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# Heatwaves and Mortality:
# A Pilot Study for the Canterbury District

2023

**Environmental Health Intelligence New Zealand**

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## Contents

## List of abbreviations

| | |
|---|---|
| CCRI | Climate Change Research Institute |
| CDHB/DHB | Canterbury District Health Board/District Health Board |
| DMT | daily mean temperature |
| $DMT_{95}$ | 95th percentile of daily mean temperature |
| EHF | Excess Heat Factor (Australian method for defining heatwaves) |
| EHI/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 |
| 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 |
| TA | Territorial authority |
| $T_{max}$ | daily maximum temperature |
| $T_{min}$ | daily minimum temperature |
| WHO | World Health Organization |
| WMO | World Meteorological Organization |

## Executive summary

Heatwaves are associated with negative impacts on public health, with outcomes ranging from dehydration to death. Climate change projections for New Zealand predict an increase in mean temperatures, maximum temperatures and hot days in the coming decades. In particular, the number of hot days (over 25°C) is projected to increase 40-100% by 2040 in New Zealand. Extreme temperatures are, therefore, 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 measuring this health impact.

In this project, we aim to investigate three different heatwave definitions to estimate the impact of heatwaves on mortality in the pilot study area of Canterbury district (formerly Canterbury District Health Board, CDHB). This pilot study covers the study period of November to March (summer months), 2000 to 2018.

We first identified heatwaves retrospectively, using three different approaches: (i) the Excess Heat Factor (EHF) approach developed in Australia, (ii) the average temperature approach defined by the Ministry for the Environment (MfE) and Stats NZ, and (iii) the 90th percentile approach used by the UK Met Office. We estimated the excess mortality during the heatwaves identified by each of these three approaches, and then compared excess mortality and other parameters across all three approaches.

Overall, across all heatwave episodes that each method identified from 2000 to 2018, the EHF approach found the highest level of excess mortality (79.6 excess deaths across 59 heatwave episodes), followed by the UK method (13.6 excess deaths across 7 heatwave episodes), with the MfE/Stats NZ method only identifying 1.1 excess deaths (across 26 heatwave episodes). Most heatwave days identified by all three approaches were found in the two summer seasons of 2015/16 and 2017/18. These two seasons also represented the worst seasons, based on excess temperature. For the 2017/18 season, all three methods found excess deaths due to heatwaves (24.1 for EHF, 16.5 for MfE/Stats, and 9.9 for the UK approach). However, no excess deaths were found due to heatwaves in the 2015/16 season (-16.5, -20.2 and -2.1 excess deaths for EHF, MfE/Stats and UK approaches respectively). When looking at the seven worst heatwave episodes (based on excess temperature) for each method across the study period, the EHF and MfE/Stats NZ approaches found a similar number of excess deaths (39.3 and 37.3 respectively), while the UK approach found 13.6 excess deaths. However, none of the above findings relating to excess mortality were statistically significant due to the small numbers of daily deaths in the Canterbury district, resulting in wide confidence intervals for estimated excess mortality.

In general, the EHF approach identified heatwaves that were long but with relatively cooler temperatures. The UK approach identified short but very hot heatwaves. The MfE/Stats NZ approach identified heatwaves of medium length and with medium temperatures.

Deciding which heatwave definition to use depends considerably on the intended audience and the desired outcomes. From a climatological standpoint, the EHF approach makes the most sense as it

includes both daily maximum ($T_{max}$) and minimum ($T_{min}$) temperatures in the same index, which can help to account for higher nighttime temperatures. Furthermore, the EHF approach considers the conditions leading up to a potential heatwave and compares this to a 95th percentile value to gain an understanding about the severity of a potential heatwave. Additionally, the EHF has been developed specifically as an indicator of health-relevant heat events and has been used in multiple countries. The UK approach might miss heatwaves that have relatively cooler temperatures but go on for longer, which is known to significantly impact public health. It also applies one temperature threshold to the whole summer period. The MfE/Stats NZ approach takes a middle-ground; however, heatwave episodes identified by this approach correlated with a low excess mortality. Nonetheless, the approach is straightforward and can easily be applied. On balance, the EHF approach appears to be the most appropriate method to use, particularly given its strong link to health outcomes due to heatwaves and wide use in other countries. Additionally, the MetService trial of heat alerts during the summer of 2022/23 has not been included in this study, but these heat alert thresholds could be evaluated in future using a similar method as this study once the required outcomes are certain.

The results of this study could be used to inform the development of a heat-health warning system in New Zealand, and could also form the basis for Environmental Health Intelligence NZ to develop a national system for monitoring heatwaves and their health impacts.

# Introduction

## Project aims

The project was a pilot study to investigate the impact of heatwaves on mortality, using the geographic area covered by the Canterbury district (formerly Canterbury District Health Board). The results contribute to developing a heat-health warning system (HHWS) for New Zealand and informing ongoing surveillance and monitoring of heatwave impacts on mortality by EHINZ.

There were two main objectives of this project:

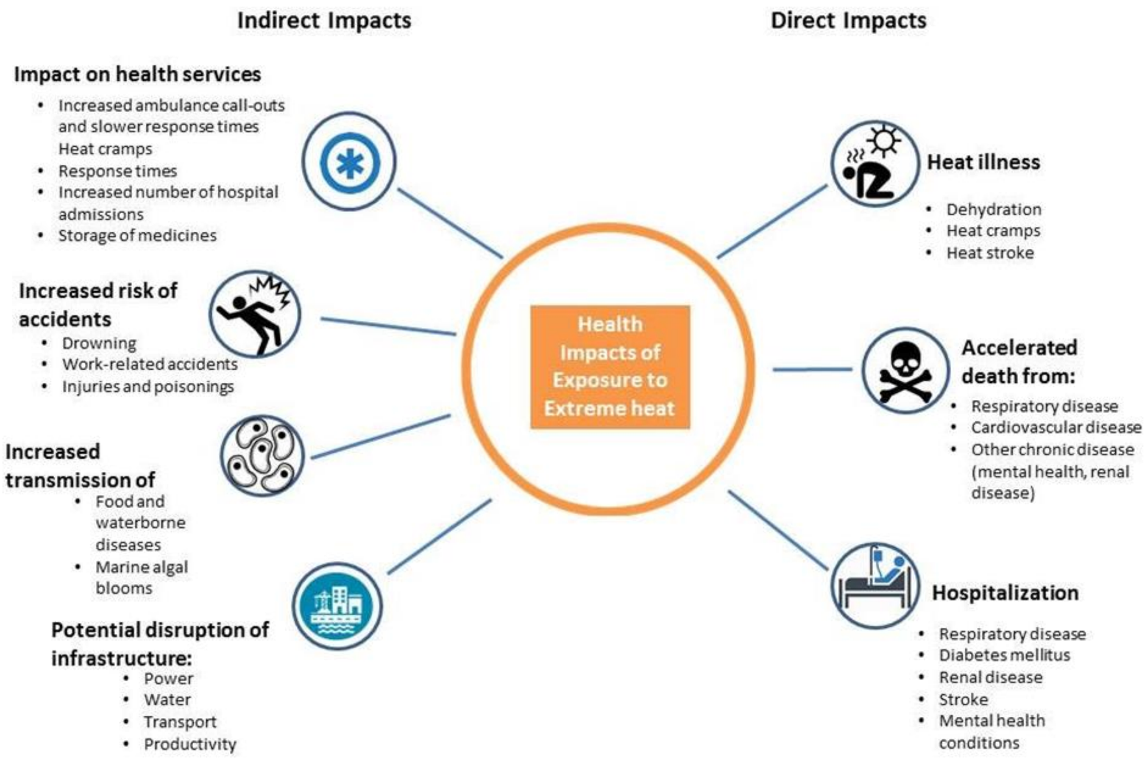
- To investigate which heatwave definition has the greatest applicability in the New Zealand context when considering impacts on mortality
- To estimate the excess mortality associated with heatwaves in Canterbury district.

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

## Heatwaves and health

Natural hazards such as heatwaves are associated with negative impacts on public health, with outcomes ranging from dehydration to death (Figure 1) (Ministry of Health 2018, WMO and WHO 2015). Extreme temperatures are associated with a rise in mortality and morbidity, particularly within some vulnerable population groups such as older adults, very young children, and those with pre-existing conditions (WMO and WHO 2015) (Table 1).

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



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

**Table 1:** Summary of key vulnerable population groups

| | | | |
|---|---|---|---|
| Older adults aged 65 years and over | Young children under 5 years old | Pregnant women and nursing mothers | People with disabilities |
| Migrants and refugees | People with pre-existing conditions | People who do not understand English | Homeless people |
| Outdoor workers | Overweight and obese people | People living alone | Low socioeconomic status |

**Source:** Department of Human Services (2009), Mayrhuber et al (2018), RCCC (2019), WMO and WHO (2015)

Climate change may increase the risk of heatwaves in the future. Climate change projections for New Zealand (Ministry for the Environment 2018) estimate increasing mean temperatures across the country. By 2040, mean temperatures are projected to increase between +0.7° and +1.0°C. 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 WMO and WHO (World Meteorological Organization and World Health Organization, 2015) 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*” (p. 1).

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 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). 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.”*

## MetService’s new heat alert system

In 2021, the MetService introduced the heat alert system, developed together with the Climate Change Research Institute (CCRI) at Te Herenga Waka – Victoria University of Wellington, and the 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 and was also run over the 2022/23 summer season in 44 locations.

When a significant 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. To define the temperature threshold for heat alert in each location, hourly temperature data as well as humidity and wind observations for each location, were used to calculate a daily maximum ‘feels like’ temperature. Based on this 'feels like’ temperature and historical data, a temperature threshold was selected by the research group for each location. A heat alert is triggered when temperatures on two consecutive days are forecast to be above this temperature threshold. 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 heat alert system was implemented late in this project and, therefore, was not included as part of this assessment of heatwave definitions.

## 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, as there is no universal heatwave definition, there is no standard methodology to derive 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.

In the next step, the newly developed heatwave definition can be used to identify alert threshold values. However, there is 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).

In the third step, weather forecasts are 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).

As a final step, implementing an HHWS should 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).

Some key considerations in setting up an HHWS include:

- 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 prevent excess mortality and morbidity (Basu and Samet 2002, Nairn and Fawcett 2015).

### Setting HHWS alert thresholds based on mortality

There is a wide range of methods to calculate alert thresholds, but WMO and WHO (2015) have advised that alert thresholds in an 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 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).

## 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 district during the study period (November to March (summer months), 2000 to 2018). This process was to:

1. identify heatwaves retrospectively, using three different approaches:
    a) the excess heat factor (EHF) approach used in Australia (Nairn and Fawcett 2015)
    b) the average temperature approach defined by the Ministry for the Environment and Stats NZ (Ministry for the Environment and Stats NZ 2020)
    c) the 90th percentile approach used by the UK Met Office (McCarthy et al 2019)
2. estimate the excess mortality during the identified heatwaves
3. compare the excess mortality and other parameters across all three approaches.

## Data and methods

The study used daily temperature and mortality data for the time period 2000 to 2018.

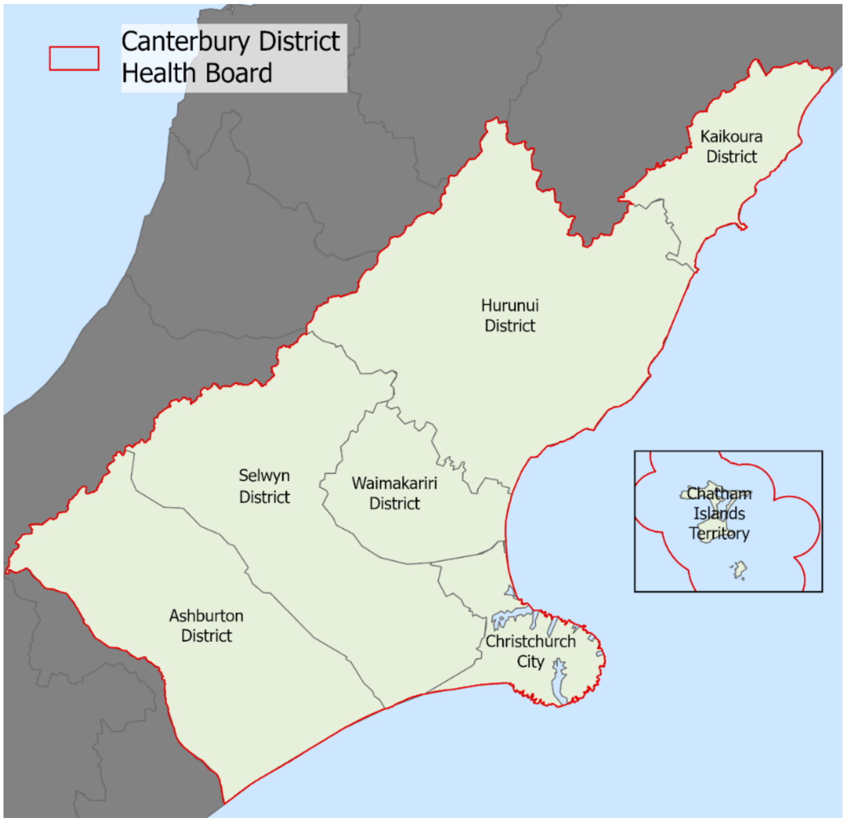
Mortality and temperature data for the Canterbury district (formerly the Canterbury District Health Board) was sourced from the Ministry of Health's (MoH's) Mortality Collection and NIWA's CliFlo database, respectively. Daily mortality data was available for the period 2000 to 2018 (the most recent data available at the time of this study), whereas daily temperature data for the selected climate stations was available for the period 1953 to the present.

The main analysis was restricted to the summer months (1 November to 31 March), between 2000 and 2018 (ie, season 2000/01 to season 2017/18).

### Study area

Canterbury district is the second largest 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 2) and provided health services to 539,631 people in 2018, according to the 2018 Census.

**Figure 2:** 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.

## 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 NIWA's CliFlo database (New Zealand's National Climate Database). The database holds data from about 6,500 climate stations, which have been operating for various periods since observations began, collecting different raw data. Subscriptions to the database are free online and are valid for two years or until 2,000,000 rows are used (whichever comes first). If the row limit or the time period is reached, the subscription can be renewed online.

CliFlo's database query form was used to download a spreadsheet of available climate stations recording relevant data in the Canterbury CliFlo climate region representing the Canterbury district. The following parameters were selected:

- Datatype: Max Min Temperature - Daily MaxMin (metcode: 201)
- Time period: 01/01/1981 – 31/12/2019

The period of 1981 to 2019 was selected as 1981–2010 represents the latest climate normal period and the period 2010–2019 further extends the record to analyse links between extreme temperature and mortality.

The Climate Normal Period is defined as a baseline period from which to measure temperature anomalies (WMO 2017). 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

The query resulted in a list of 23 climate stations, with only one station (Christchurch Aero) recording complete data for the relevant time period of 1981–2019. Therefore, the Christchurch Aero climate station was used as the designated climate station for this project. To validate the selection, the EHINZ methodology for selecting stations based on their proximity to the population-weighted centroid (EHINZ 2021) was fully carried out.

A list with all 23 stations was imported into an ArcGIS Pro project, and latitude/longitude information was converted (tool: Display xy data) 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 centroid of the Canterbury district was 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 DHB
- Currently open climate station (as of 2019)
- Long record of reliable data (ie, minimum of 10 years of data)
- One climate station per DHB

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.

Christchurch Aero (agent # 4843) started observing weather conditions 31/12/1953. Daily maximum and minimum temperature data was downloaded for the period 1981–2019.

### Measurements used from temperature data

The following temperature measurements were used from the CliFlo database:

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

In CliFlo, daily temperature readings are taken at 8am and encompass the previous 24 hours. This means that the daily maximum temperature ($T_{max}$) will have occurred on the previous day (usually in the afternoon), whereas the daily minimum temperature ($T_{min}$) will have occurred on the day of measurement (usually in the early hours of the morning). The late afternoon $T_{max,}$ therefore, precedes the early morning $T_{min}$, highlighting that the health effects of an unusually warm night following warm day temperatures are more significant than the other way round (Nairn & Fawcett 2015). The CliFlo output goes against standard climatological practice, where the 8am reading would be allocated to the previous day but rather outputs the date of the reading at the end of the measuring period. We, adjusted both $T_{max}$ and $T_{min}$ by one day to adhere to standard practices.

## Heatwave definition

Three different heatwave definitions were chosen to test their ability to recognise potential heat-related excess deaths:

1. Excess Heat Factor (EHF)

2. Ministry for the Environment and Stats NZ (MfE/Stats NZ)
3. UK (TX90p).

### Excess Heat Factor (EHF) approach

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.

The EHF approach 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) is calculated as the average of $T_{max}$ and $T_{min}$:

$$DMT = \frac{T_{max} + T_{min}}{2} \qquad 1$$

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:

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

where $T_i$ is the first day, and $DMT_{95}$ is the 95th percentile of the DMT over the 30-year reference period 1981–2010 calculated using all days of the year. For Christchurch Aero, the $DMT_{95}$ (1981–2010) was calculated to be 19.9°C. 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).

The second index is the Excess Heat Index for a heat event requiring an acclimatisation response ($EHI_{accl}$), which measures how hot the same three-day period is in comparison to the recent past (30 days).

$EHI_{accl}$ is calculated as follows:

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

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).

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

$$\text{EHF} = |\text{EHI}_{accl}| * \text{EHI}_{sig} \tag{4}$$

As evident from equation 4, the EHF must have the same sign as the $\text{EHI}_{sig}$, and will indicate a heatwave is occurring if $\text{EHI}_{sig}$ is positive. However, if $\text{EHI}_{accl}$ is also positive, this would increase the severity of the heatwave. Finally, all positive EHF values indicate heatwave conditions, which applies to all days in the three-day period in question (Nairn and Fawcett 2015).

In summary, for this pilot study, the EHF approach defined heatwaves as occurring when the average daily mean temperature of a three-day period was higher than 19.9°C.

### MfE/Stats NZ approach

The Ministry for the Environment's (MfE's) and Stats NZ's (2020) atmosphere and climate report defines heatwave days "*as three or more consecutive days with a maximum temperature of more than 5 degrees Celsius above the monthly average for 1981–2010*". It was the only definition of a heatwave published for New Zealand at the time of analysis.

To identify heatwaves with the MfE/Stats NZ approach, the average monthly maximum temperature was calculated from daily maximum temperatures ($T_{max}$) for the period 1981–2010. Heat days were identified as days with a maximum temperature of more than 5°C above the respective monthly average (Table 2). Heatwaves occurred when three or more consecutive heat days were recorded.

**Table 2:** Heatwave parameters for Christchurch Aero, 1981–2010, MfE/StatsNZ

| Month | 1981–2010 average $T_{max}$ | Heat day (+5°C) | Heatwave = 3 or more consecutive heat days |
|---|---:|---:|---|
| **January** | 22.6 | 27.6 | |
| **February** | 21.9 | 26.9 | |
| **March** | 20.3 | 25.3 | |
| **November** | 18.9 | 23.9 | |
| **December** | 21.1 | 26.1 | |

In summary, for this pilot study, the MfE/Stats NZ approach defined heat days as having a daily maximum temperature above the following temperatures: 27.6°C for January, 26.9°C for February, 25.3°C for March, 23.9°C for November and 26.1°C for December. A heatwave occurs when three or more consecutive heat days are recorded.

### UK approach

The TX90p approach is used by the UK Met Office, where a heatwave is declared when a location observes three or more days with maximum temperatures above a certain threshold. This threshold is defined by calculating the 90th percentile of the climatological distribution of daily maximum temperatures as their temperature threshold (McCarthy et al 2019). This definition was chosen due the UK climate being similar to New Zealand's temperate oceanic climate (Cfb classification in the Köppen-Geiger climate classification, Beck et al 2018).

For the UK approach, the threshold temperature was calculated as the 90th percentile of daily maximum temperatures ($T_{max}$). The 90th percentile $T_{max}$ was calculated for the 1981–2010 period using a moving 15-day window centred on each day of the year (McCarthy et al 2019, Perkins and Alexander

2013). On average, January had the highest 90th percentile $T_{max}$ at 29.2°C. The heatwave threshold temperature has therefore been set based on the 90th percentile for January days at 29.0°C (rounded; McCarthy et al 2019).

In summary, for this pilot study, the UK approach defined heat days as days with a daily maximum temperature of at least 29.0°C, and a heatwave occurred when there were three or more consecutive heat days.

## Mortality data

Mortality data was sourced from the MoH's New Zealand Mortality Collection. Total, all-cause (WMO and WHO 2015) daily mortality counts of people residing in domicile codes within the Canterbury district at the time of death during 1998–2018 were used.

Victims of the Christchurch earthquakes (22/02/2011) were excluded from the analysis based on ICD-10 code X34 (Victim of earthquake) (Table 3).

**Table 3:** Christchurch earthquake victims

| Date | Victim count |
|---|---:|
| 16/11/2010 | 1 |
| 22/02/2011 | 139 |
| 23/02/2011 | 1 |
| 24/02/2011 | 1 |
| 26/02/2011 | 1 |
| 6/03/2011 | 1 |
| 9/03/2011 | 1 |
| 10/03/2011 | 1 |
| 14/06/2011 | 1 |
| **Total** | **147** |

## 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 two 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).

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. The 95% CIs were subtracted from the baseline mortality to obtain 95% CIs for the excess mortality during the same heatwave episode.

# Results

## Mortality data

Between 2000/01 and 2017/18, there were 24,869 deaths in the Canterbury district, with a maximum of 23 and a minimum of one death per day. The average observed mortality was 9.1 deaths per day during the summer season (November–March) (Figure 3 and Figure 4).

**Figure 3:** Average observed daily number of deaths, by summer month, 2000/01–2017/18

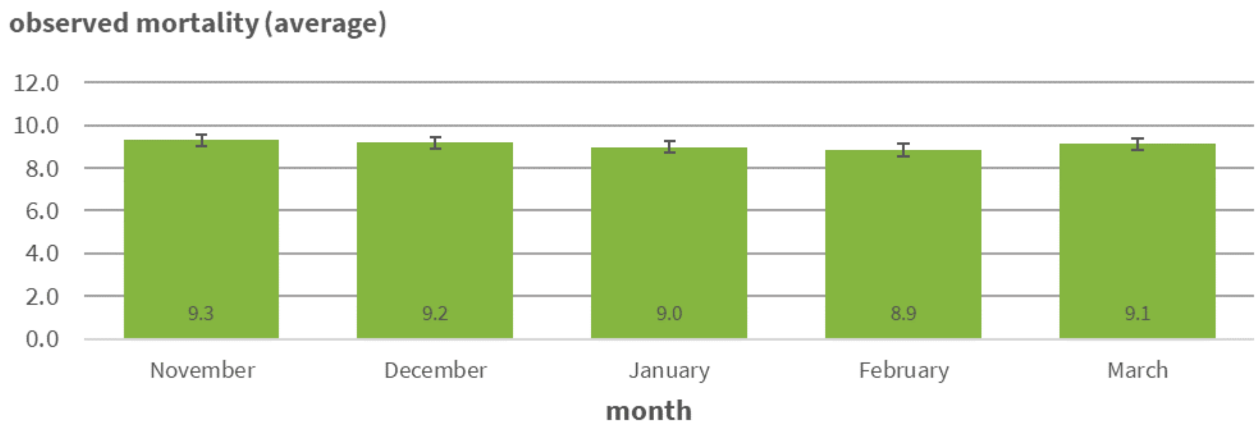
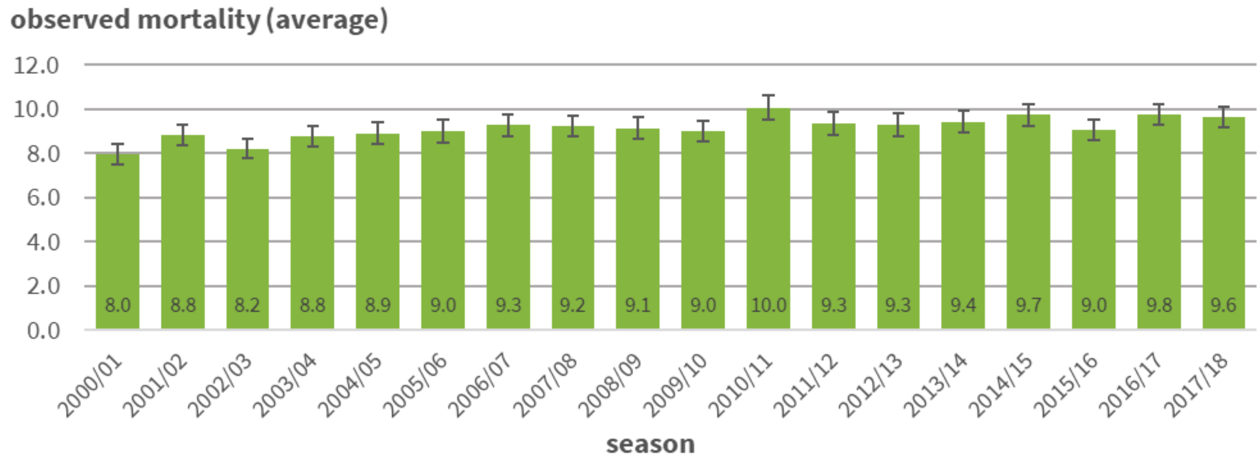


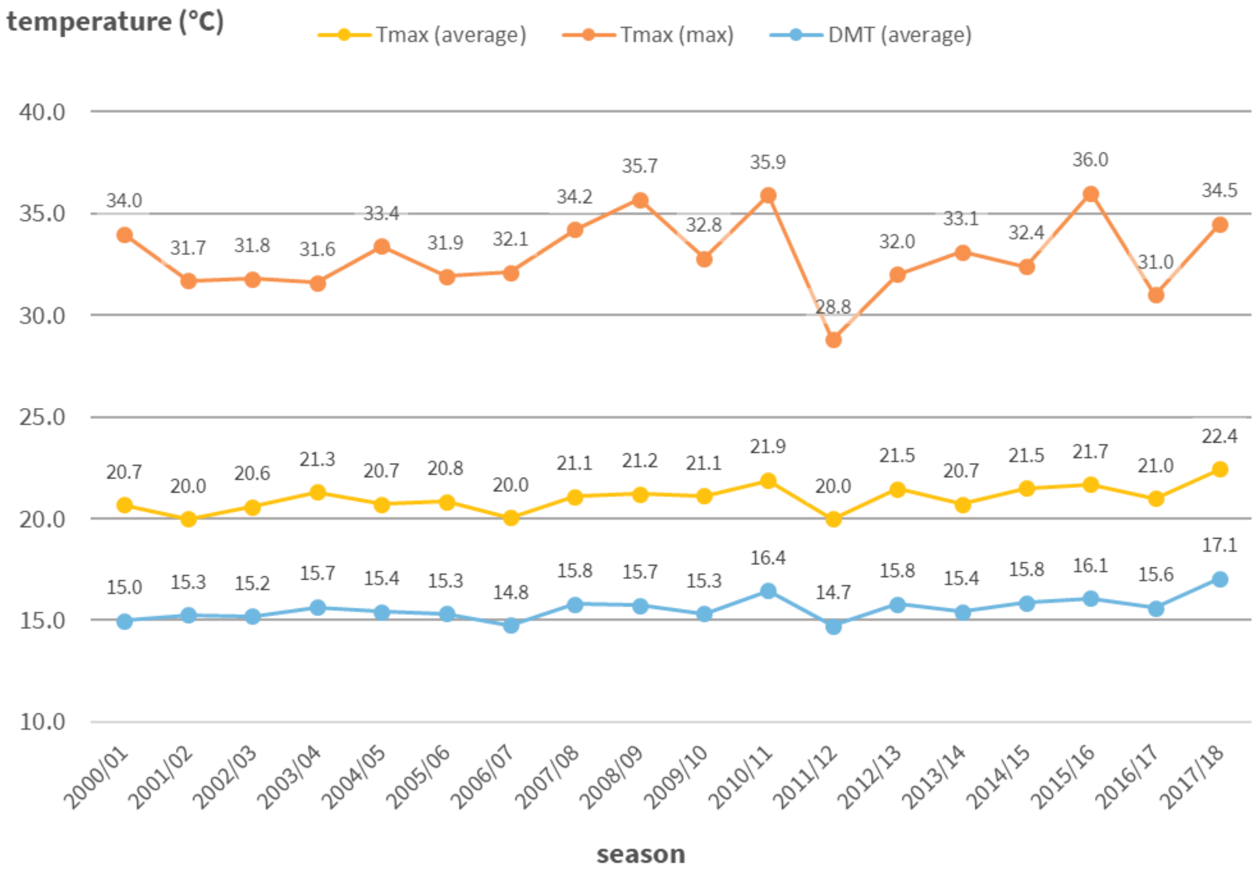
**Figure 4:** Average observed daily number of deaths in the summer season (November–March), 2000/01 to 2017/18



## Temperature data

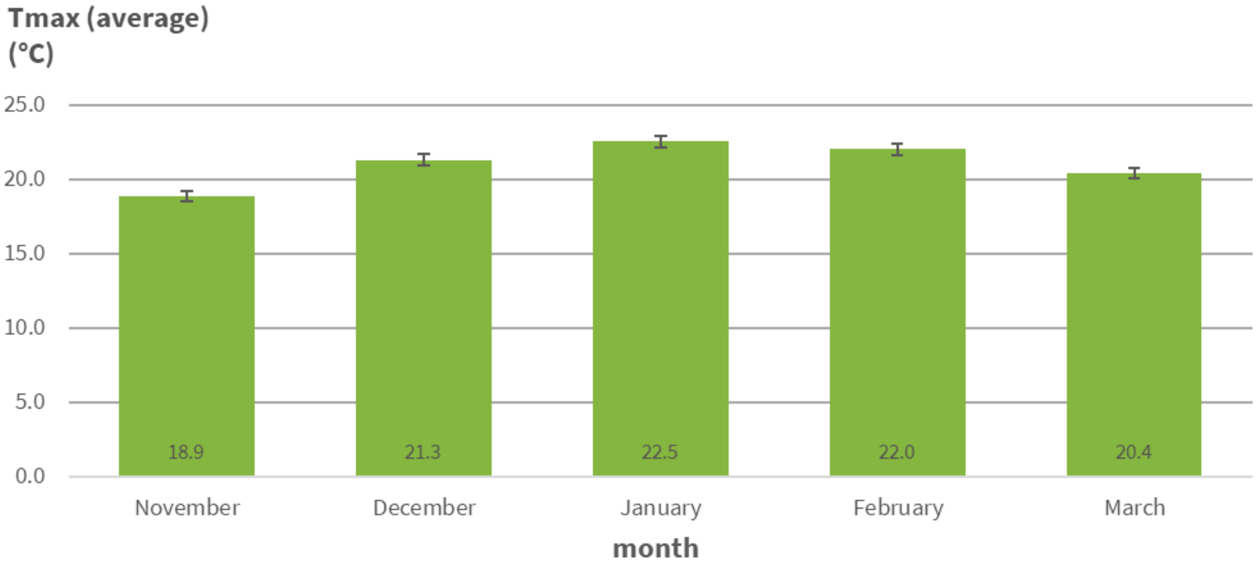
Between 2000/01 and 2017/18, the average daily mean temperature (DMT) was 15.6°C, and the average daily maximum temperature was 21.0°C. The highest recorded temperature was 36.0°C on 22/12/2015 (Figure 5). NIWA recorded the summer season 2017/18 as the hottest summer on record since 1909 (NIWA nd), which is also reflected in the highest average $T_{max}$ in the study period.

**Figure 5:** Average of daily mean temperature (DMT (average)), daily maximum temperature ($T_{max}$ (average)), and highest recorded daily temperature ($T_{max}$ (max)), per summer season, 2000/01 – 2017/18



On average, January had the highest average daily maximum temperature ($T_{max}$) in the study period (22.5°C), followed by February (22.0°C) and December (21.3°C) (Figure 6).

**Figure 6:** Average daily maximum temperature ($T_{max}$(average)), by summer month, 2000/01 – 2017/18



## Heatwave episodes and heatwave days

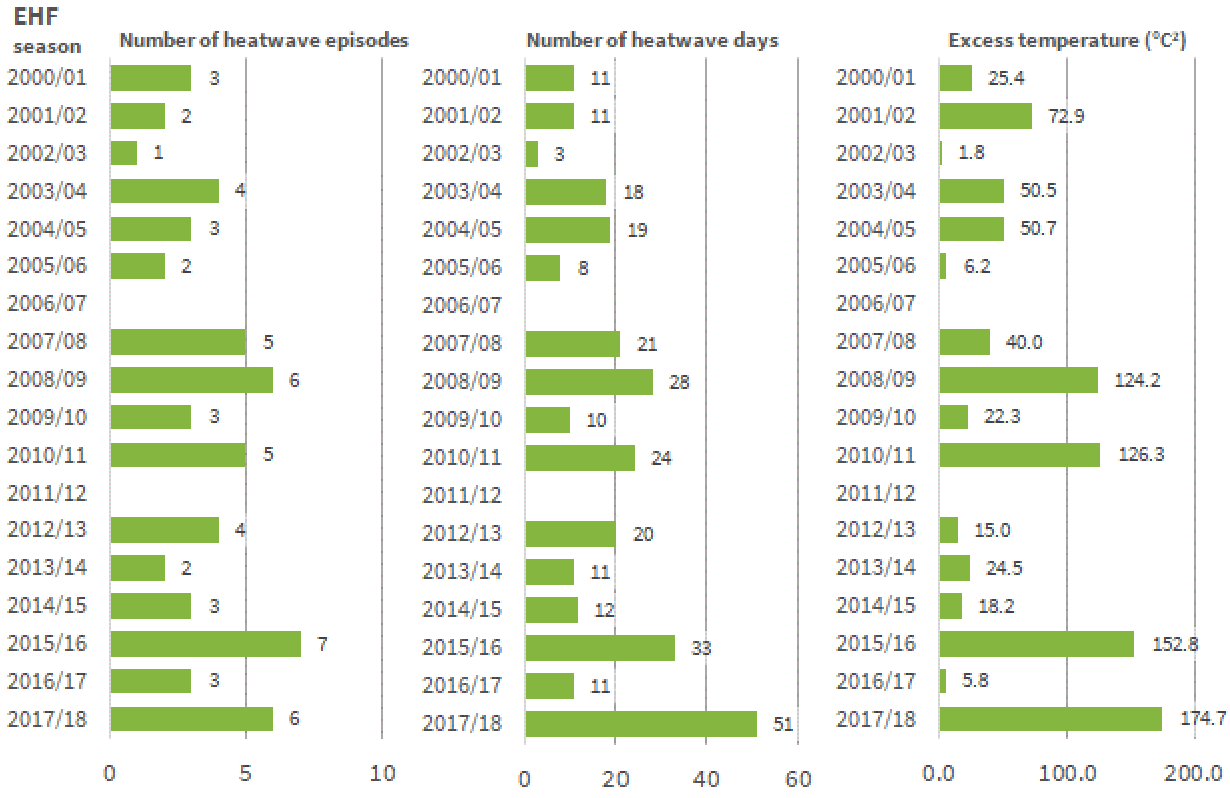
The following section describes the effects of applying the three different definitions to identify heatwave episodes and heatwave days for all three approaches, as well as a comparison.

### Excess Heat Factor (EHF) approach

The Excess Heat Factor (EHF) approach identified the most heatwaves and associated heatwave days during the research period (Figure 7). Between 2000/01 and 2017/18, this approach identified 291 heatwave days across 59 heatwave episodes. On average, there were 3.3 heatwave episodes per year. Excess heat was calculated as the sum of the (positive) EHF values for each heatwave episode, taking duration and temperature into consideration.

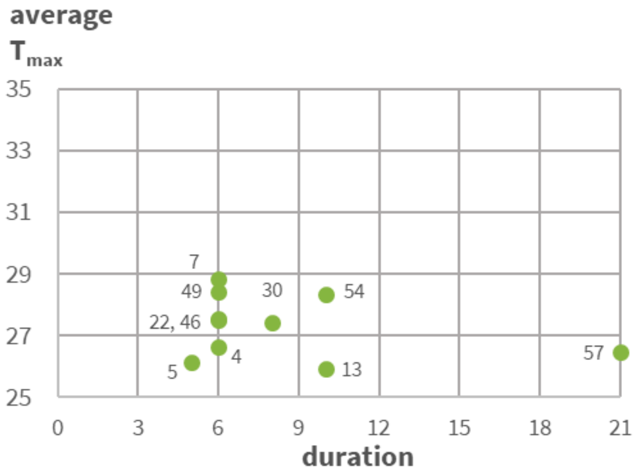
The 2017/18 summer season had the most heatwave days (51 days) across six episodes. This was followed by the 2015/16 summer season, with 33 heatwave days across seven episodes. Heatwave episodes in the 2017/18 season (8.5 days on average) were considerably longer than in 2015/16 (4.7 days on average).

**Figure 7:** Number of heatwave episodes and heatwave days, and excess heat during heatwave episodes, EHF approach, 2000/01–2017/18



The ten worst heatwave episodes using the EHF approach were ranked based on excess temperature (Figure 8), which equals the value of the Excess Heat Factor (EHF). Episode 57 (season 2017/18) had the highest excess temperature (113.4°C$^2$), even though it had a relatively lower average daily maximum temperature ($T_{max}$) compared to other episodes. It was, however, the longest heatwave episode identified via the EHF approach.

**Figure 8:** Ten worst heatwave episodes (based on excess temperature) using the EHF approach, duration (days) and average daily maximum temperature ($T_{max}$), 2000/01 – 2017/18



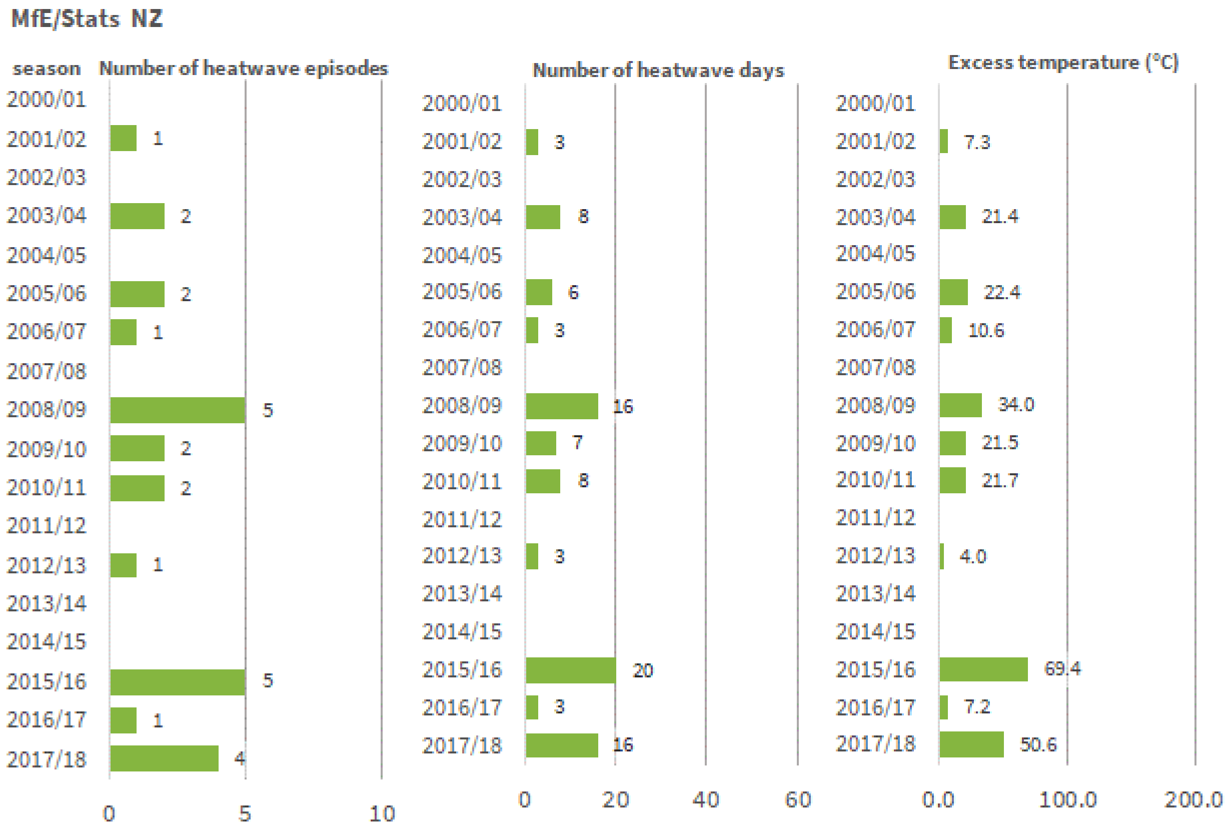
| episode | duration | excess temperature | $T_{max}$ (average) | season |
|---|---|---|---|---|
| 57 | 21 | 113.4 | 26.5 | 2017/18 |
| 30 | 8 | 89.7 | 27.4 | 2010/11 |
| 22 | 6 | 87.8 | 27.5 | 2008/09 |
| 46 | 6 | 62.9 | 27.5 | 2015/16 |
| 54 | 10 | 53.9 | 28.3 | 2017/18 |
| 49 | 6 | 51.6 | 28.4 | 2015/16 |
| 4 | 6 | 44.3 | 26.6 | 2001/02 |
| 13 | 10 | 41.6 | 25.9 | 2004/05 |
| 7 | 6 | 37.3 | 28.8 | 2003/04 |
| 5 | 5 | 28.6 | 26.1 | 2001/02 |

### MfE/Stats NZ approach

The MfE/Stats NZ approach identified 93 heatwave days across 26 heatwave episodes (Figure 9). On average, there were 1.4 heatwave episodes per year.

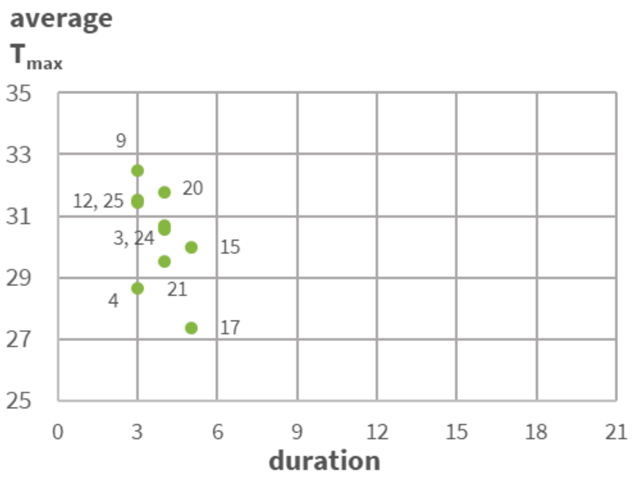
The 2015/16 summer season had the most heatwave days (20 days) across five episodes. This was followed by the 2017/18 summer season, with 16 heatwave days across four episodes.

**Figure 9:** Number of heatwave episodes and heatwave days, and excess heat during heatwave episodes, MfE/Stats NZ approach, 2000/01 – 2017/18



The ten worst heatwave episodes using the MfE/Stats NZ approach were ranked based on excess temperature (Figure 10). Excess heat was calculated as the cumulative temperature above the threshold for each heatwave episode, therefore taking duration and temperature into consideration. Episode 20 (season 2015/16) had the highest excess temperature (19.5°C) with a duration of only four days but a very high average daily maximum temperature ($T_{max}$) of 31.8°C.

**Figure 10:** Ten worst heatwave episodes (based on excess temperature) using the MfE/Stats NZ approach, duration (days) and average daily maximum temperature ($T_{max}$), 2000/01 – 2017/18



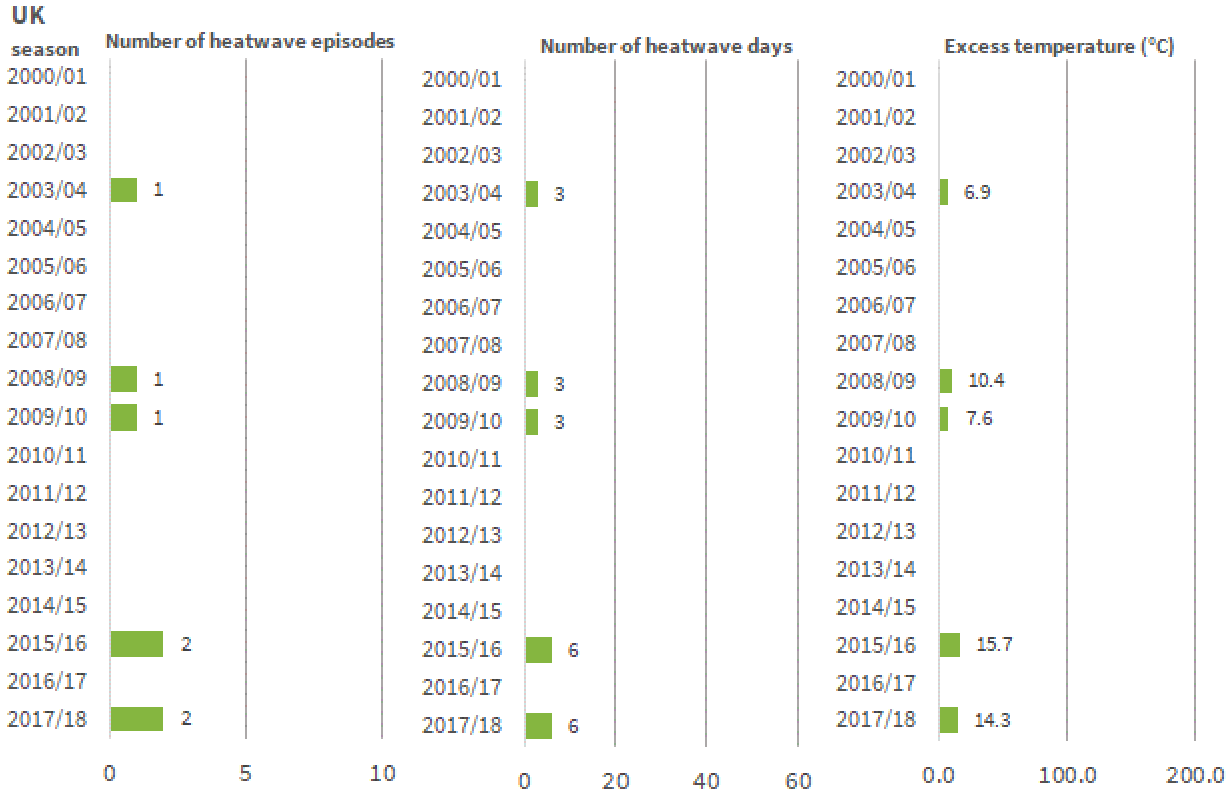
| episode | duration | excess temperature | $T_{max}$ (average) | season |
|---|---|---|---|---|
| 20 | 4 | 19.5 | 31.8 | 2015/16 |
| 15 | 5 | 19.4 | 30.0 | 2010/11 |
| 24 | 4 | 17.9 | 30.6 | 2017/18 |
| 17 | 5 | 17.3 | 27.4 | 2015/16 |
| 21 | 4 | 16.9 | 29.5 | 2015/16 |
| 9 | 3 | 14.6 | 32.5 | 2008/09 |
| 4 | 3 | 14.2 | 28.6 | 2005/06 |
| 3 | 4 | 12.4 | 30.7 | 2003/04 |
| 25 | 3 | 12.2 | 31.4 | 2017/18 |
| 12 | 3 | 11.8 | 31.5 | 2009/10 |

### UK approach

The UK approach identified the fewest heatwave episodes and associated heatwave days. It measured 21 heatwave days across seven heatwave episodes, each with a duration of three days (Figure 11). On average, there were 0.4 heatwave episodes per year.

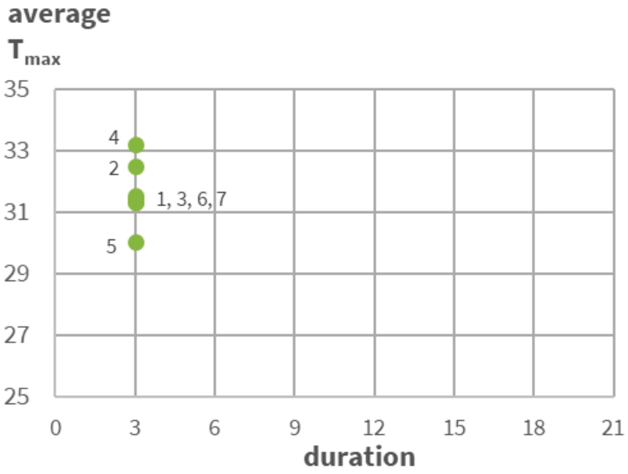
The 2015/16 and 2017/18 summer seasons had the most heatwave days (three days) across three episodes, with the 2015/16 season having a higher excess temperature.

**Figure 11:** Number of heatwave episodes and heatwave days, and excess heat during heatwave episodes, UK approach, 2000/01 – 2017/18



As the UK approach only identified seven heatwave episodes across the study period, these were all ranked based on excess temperature (Figure 12). Excess temperature was calculated as the cumulative temperature above the threshold for each heatwave episode, therefore taking duration and temperature into consideration. Episode 4 (season 2015/16) had the highest excess temperature (12.6°C) with a duration of only three days but a very high average daily maximum temperature ($T_{max}$) of 33.2°C.

**Figure 12:** Seven heatwave episodes identified using the UK approach, duration (days) and average daily maximum temperature ($T_{max}$), 2000/01 – 2017/18



| episode | duration | excess temperature | $T_{max}$ (average) | season |
|---:|---:|---:|---:|---|
| 4 | 3 | 12.6 | 33.2 | 2015/16 |
| 2 | 3 | 10.4 | 32.5 | 2008/09 |
| 3 | 3 | 7.6 | 31.5 | 2009/10 |
| 7 | 3 | 7.3 | 31.4 | 2017/18 |
| 6 | 3 | 7.0 | 31.3 | 2017/18 |
| 1 | 3 | 6.9 | 31.3 | 2003/04 |
| 5 | 3 | 3.1 | 30.0 | 2015/16 |
| na | | | | |
| na | | | | |
| na | | | | |

Note: Only seven heatwave episodes were identified over the study period using the UK approach, so only seven episodes are presented here, rather than the ten worst heatwave episodes as previously presented for the EHF and MfE/Stats NZ approaches.

### Comparison of three approaches for identifying heatwaves

The EHF approach identified heatwave episodes in almost 90% (16/18) of all studied seasons, whereas the MfE/Stats NZ and the UK approach only identified heatwave events in two-thirds (11/18 seasons) and one-third of seasons (5/18 seasons) respectively.

Across all approaches, 37.5% of all identified heatwave days occurred in January, 29.4% in February and 20.5% in December (Figure 13).

**Figure 13:** Distribution of heatwave days by month (percentage of heatwave days, among all heatwave days), 2000/01 to 2017/18

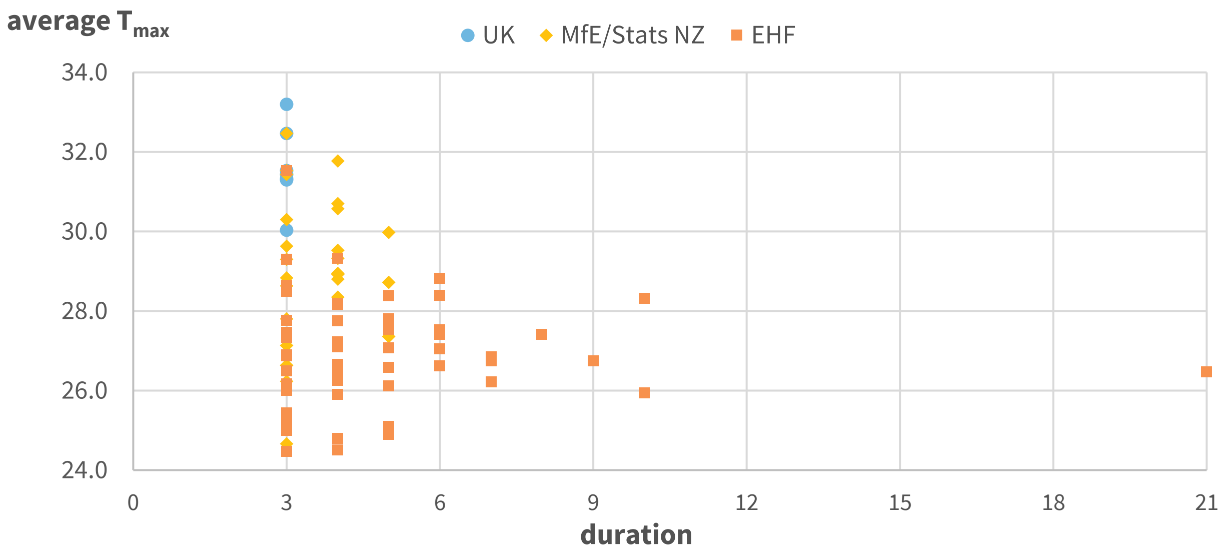
Across the study period, 21 heatwave days were identified by all three approaches (Table 4), representing the heatwave days identified by the strict UK approach. When looking at heatwave days identified by the EHF and the MfE/Stats NZ approach, there were 67 shared days across the study period. Most heatwave days identified by either all three approaches or the EHF and MfE/Stats NZ approach can be found in the seasons 2017/18 and 2015/16, which was to be expected as all three approaches identified the most heatwave episodes and days in these seasons.

**Table 4:** Comparison of mutually identified heatwave days, 2000/01 – 2017/18

| season | EHF – MfE/Stats NZ – UK | EHF – MfE/Stats NZ |
|---|---|---|
| **2000/01** | | |
| **2001/02** | | 3 |
| **2002/03** | 3 | |
| **2003/04** | | 4 |
| **2004/05** | | |
| **2005/06** | | 3 |
| **2006/07** | | |
| **2007/08** | | |
| **2008/09** | 3 | 7 |
| **2009/10** | 3 | 7 |
| **2010/11** | | 5 |
| **2011/12** | | |
| **2012/13** | | |
| **2013/14** | | |
| **2014/15** | | |
| **2015/16** | 6 | 19 |
| **2016/17** | | 3 |
| **2017/18** | 6 | 16 |
| **Total** | **21** | **67** |

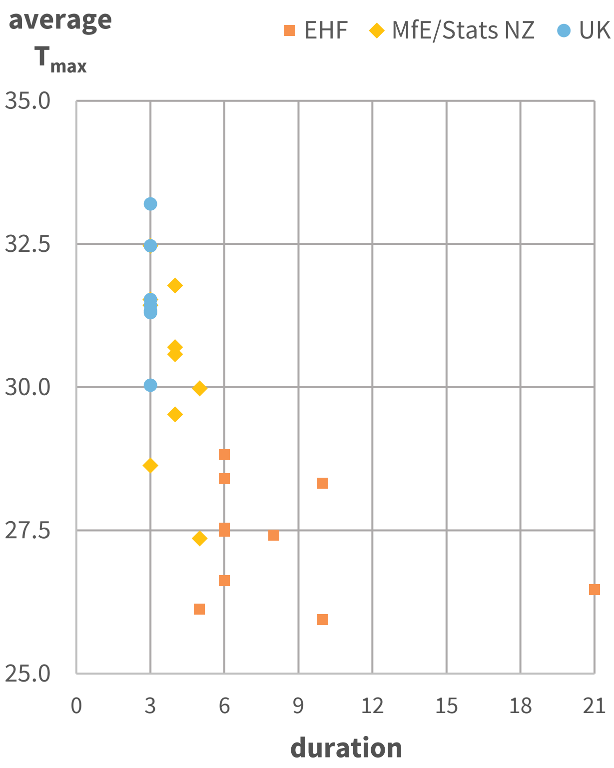
The distribution of the duration of heatwave episodes versus the average daily maximum temperatures ($T_{max}$), shows that the UK approach tends to identify short but very hot heatwaves (Figure 14). The EHF approach, on the other hand, identifies longer and relatively cooler heatwaves. The MfE/Stats NZ approach identifies heatwaves with medium duration and medium $T_{max}$.

**Figure 14:** Comparison of heatwave duration (days) versus average $T_{max}$



When looking at only the worst heatwave episodes identified by all three approaches (based on excess temperature, see Figures 8, 10 and 12), the seasons 2015/16 and 2017/18 had the highest number of episodes (Figure 15). This is consistent with results from NIWA's seven station temperature series (Ministry for the Environment and Stats NZ 2020), which found the years 1998, 1999, 2016, 2018, and 2019 were the five warmest years on record since measurements began in 1909.

**Figure 15:** Duration (days) and average $T_{max}$ for the worst heatwave episodes, 2000/01 – 2017/18



| season | number of worst episodes |
|---|---|
| 2000/01 | |
| 2001/02 | 2 |
| 2002/03 | |
| 2003/04 | 3 |
| 2004/05 | 1 |
| 2005/06 | 1 |
| 2006/07 | |
| 2007/08 | |
| 2008/09 | 3 |
| 2009/10 | 2 |
| 2010/11 | 2 |
| 2011/12 | |
| 2012/13 | |
| 2013/14 | |
| 2014/15 | |
| 2015/16 | 7 |
| 2016/17 | |
| 2017/18 | 6 |

## Association between heatwave episodes and mortality

As previously mentioned, the worst heatwave episodes (based on excess temperature) occurred during the summer seasons of 2015/16 (Figure 16) and 2017/18 (Figure 17).

In the 2015/16 season, the longest heatwave identified by the EHF approach had a duration of six days (Figure 16). The EHF approach identified seven heatwaves in the 2015/16 season, while the MfE/Stats NZ approach identified five heatwaves, and the UK approach identified two heatwaves.

In the 2017/18 season, the above-average temperatures were especially picked up by the EHF approach (Figure 17), which recorded the longest heatwave of this study in January 2018, with a duration of 21 days. In this 2017/18 season, the EHF approach identified six heatwaves overall, followed by the MfE/Stats NZ approach (four heatwaves) and the UK approach (two heatwaves).

**Figure 16:** Heatwave episodes during the 2015/16 season, observed and baseline mortality, and $T_{max}$ for all three approaches

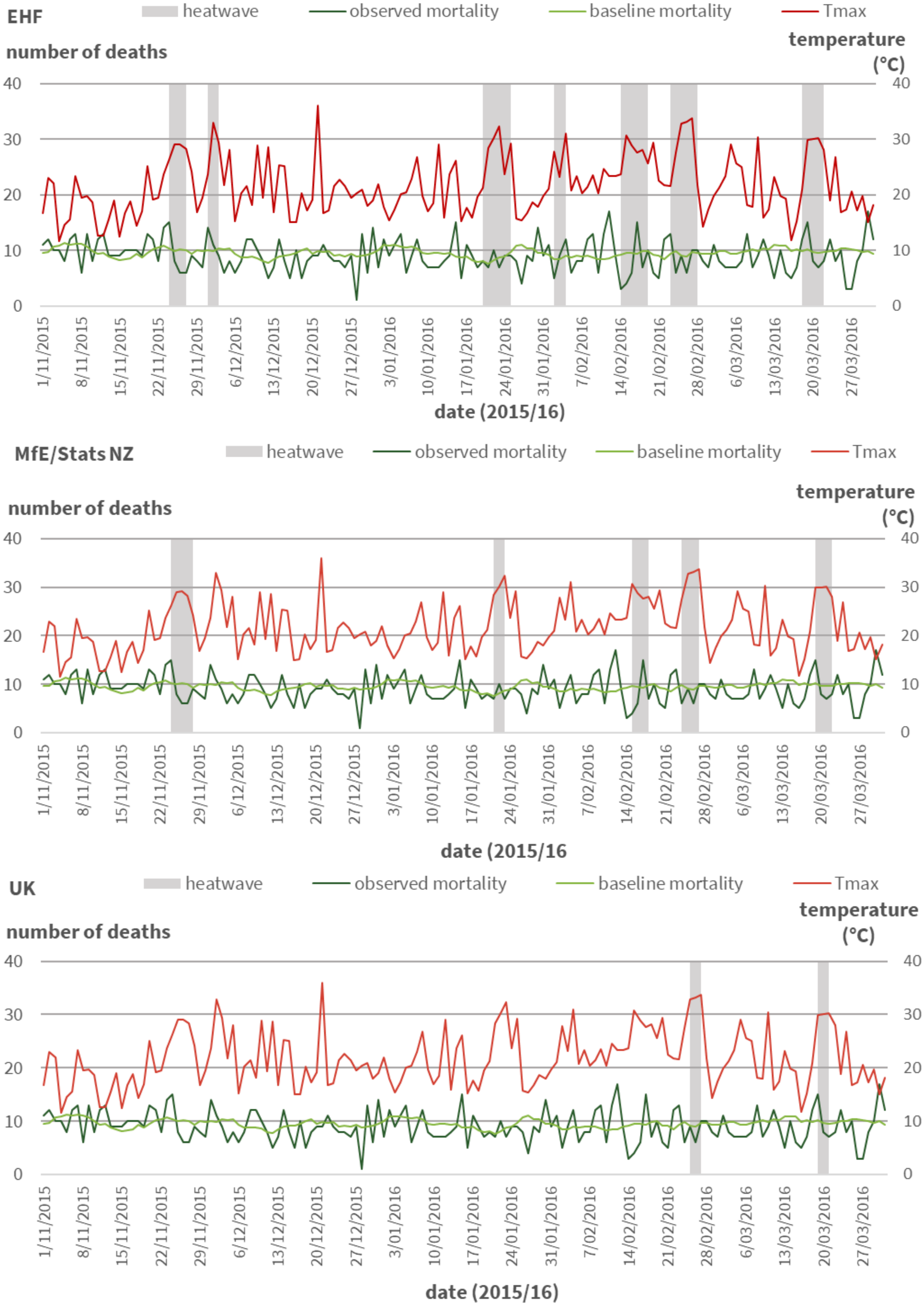
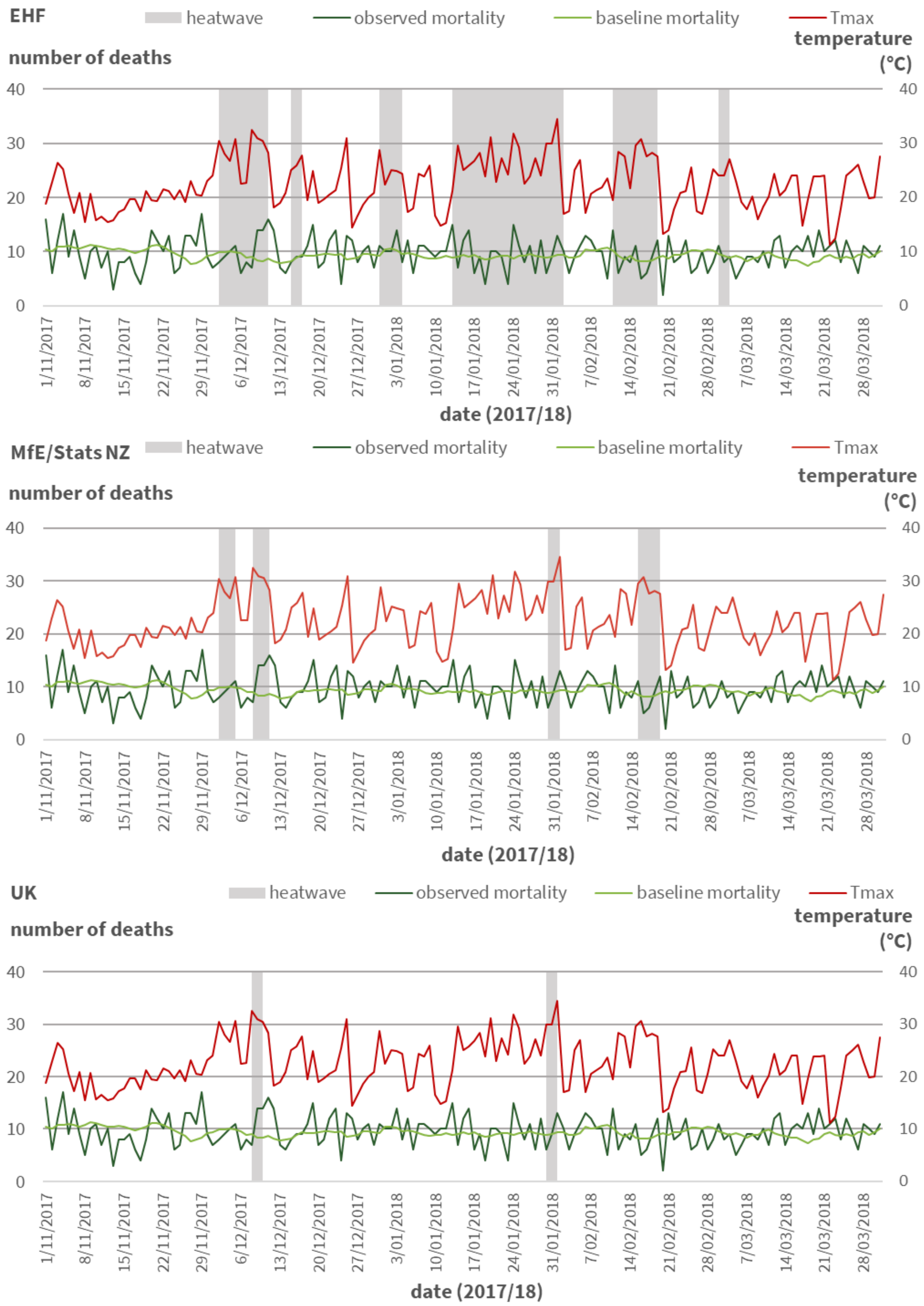


**Figure 17:** Heatwave episodes during the 2017/18 season, observed and baseline mortality, and $T_{max}$ for all three approaches



## Estimating excess mortality

A retrospective analysis of the summer seasons from 2000/01 to 2017/18 was carried out to quantify excess mortality during heatwave episodes. The following sections discuss the association between heatwave episodes identified by three different approaches and excess mortality.

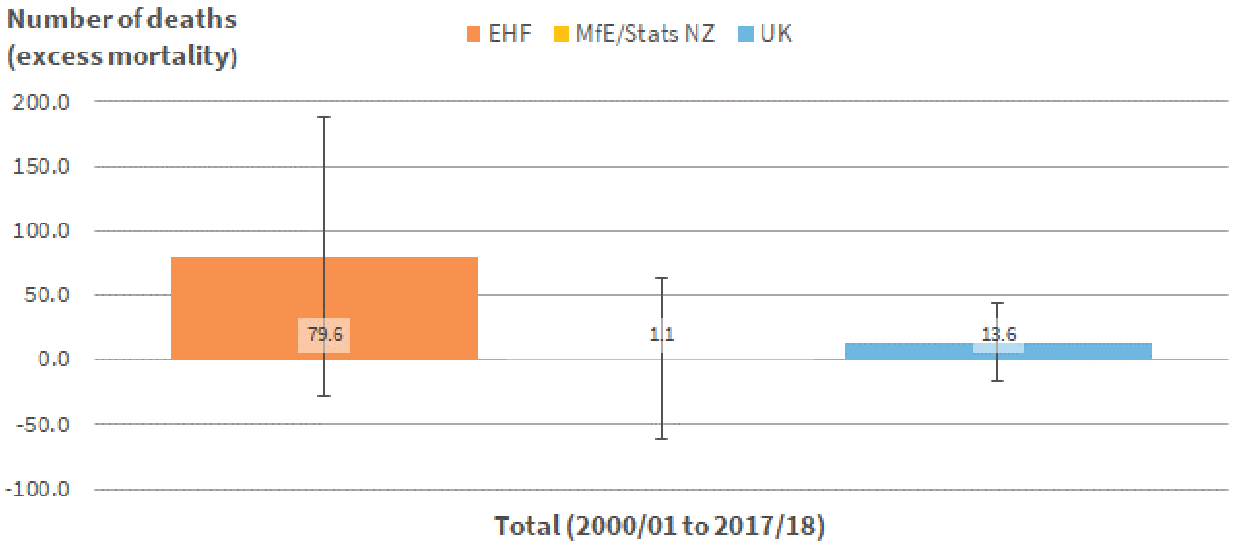
### Excess mortality across study period (2000/01–2017/2018)

Overall, the EHF approach had the highest estimated number of excess deaths on identified heatwave days across the study period (79.6, 95% confidence interval -28.6 – 187.8) (Table 5, Figure 18), although it also identified the most heatwave days. Even though the UK approach identified the least amount of heatwave days, it resulted in an estimated 13.6 (-16.0 – 43.2) excess deaths, whereas the MfE/Stats NZ approach only resulted in an estimated 1.1 (-61.4 – 63.7) excess deaths. This might be the result of the UK approach strictly identifying the hottest days of the year, therefore identifying heatwave days with the highest impact on health. However, none of these results are statistically significant due to low mortality numbers and therefore, wide confidence intervals.

**Table 5:** Summary of key heatwave and mortality variables for each heatwave approach (on heatwave days), total (2000/01 to 2017/18)

| Method | Heatwave episodes | Heatwave days | Baseline mortality | Observed mortality | Excess mortality |
|---|---|---|---|---|---|
| **EHF** | 59 | 291 | 2610.4 | 2690 | 79.6 (-28.6 to 187.8) |
| **MfE** | 23 | 93 | 855.9 | 857 | 1.1 (-61.4 to 63.7) |
| **UK** | 7 | 21 | 194.4 | 208 | 13.6 (-16.0 to 43.2) |

**Figure 18:** Number of cumulative excess deaths during heatwave episodes, total (2000/01 to 2017/18)



### Excess mortality for 2015/16 and 2017/18 seasons

The number of excess deaths between 2015/16 (Table 6) and 2017/18 (Table 7) shows a marked difference (Figure 19). In the 2015/16 season, no excess deaths were estimated by any approach. By contrast, excess deaths occurred for each approach during 2017/18 (albeit not statistically significant). This difference likely highlights that the summer of 2017/18 was the hottest summer on record (NIWA nd) when prolonged above-average temperatures would have contributed to an increase in mortality.

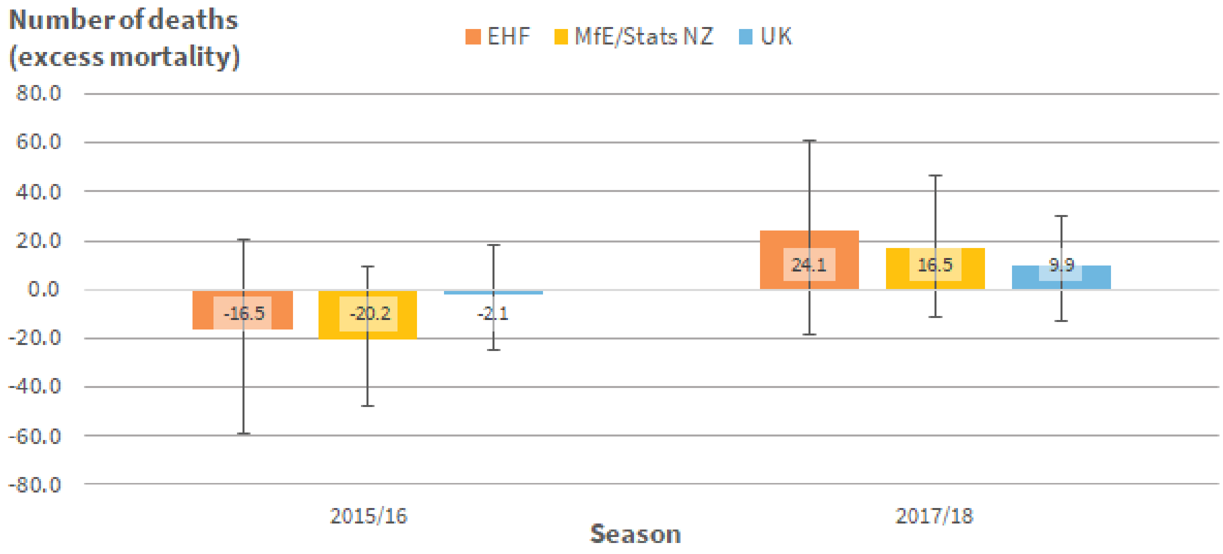
**Table 6:** Heatwave characteristics for each approach, 2015/16 season

| Method | Heatwave episodes | Observed mortality | Baseline mortality | Excess mortality |
|---|---|---|---|---|
| EHF | 24/11/2015 – 27/11/2015 | 35 | 40.5 | -5.5 (-332.7 – 21.7) |
| | 01/12/2015 – 03/12/2015 | 34 | 30.3 | 3.7 (-15.0 – 22.5) |
| | 20/01/2016 – 25/01/2016 | 50 | 51.3 | -1.3 (-8.9 – 6.3) |
| | 02/02/2016 – 04/02/2016 | 26 | 25.9 | 0.1 (-26.0 – 26.3) |
| | 14/02/2016 – 19/02/2016 | 45 | 57.4 | -12.4 (-40.2 – 15.4) |
| | 23/02/2016 – 28/02/2016 | 54 | 56.3 | -2.3 (-19.2 – 14.6) |
| | 18/03/2016 – 22/03/2016 | 50 | 48.9 | 1.1 (-19.9 – 22.2) |
| | **Total** | **294** | **310.5** | **-16.5 (-53.3 – 20.3)** |
| MfE/Stats NZ | 24/11/2015 – 28/11/2015 | 44 | 49.8 | -5.8 (-28.8 – 17.2) |
| | 21/01/2016 – 23/01/2016 | 24 | 24.6 | -0.6 (-13.5 – 12.3) |
| | 15/02/2016 – 18/02/2016 | 32 | 38.3 | -6.3 (-37.0 – 24.5) |
| | 24/02/2016 – 27/02/2016 | 31 | 37.4 | -6.4 (-19.6 – 6.7) |
| | 19/03/2016 – 22/03/2016 | 38 | 39.1 | -1.1 (-24.6 – 22.5) |
| | **Total** | **169** | **189.2** | **-20.2 (-50.0 – 9.7)** |
| UK | 25/02/2016 – 27/02/2016 | 25 | 27.7 | -2.7 (-18.2 – 12.9) |
| | 19/03/2016 – 21/03/2016 | 30 | 29.4 | 0.6 (-31.9 – 33.1) |
| | **Total** | **55** | **57.1** | **-2.1 (-22.2 – 18.0)** |

**Table 7:** Heatwave characteristics for each approach, 2017/18 season

| Method | Heatwave episodes | Observed mortality | Baseline mortality | Excess mortality |
|---|---|---|---|---|
| EHF | 02/12/2017 – 11/12/2017 | 103 | 92.8 | 10.2 (-13.9 – 34.3) |
| | 15/12/2017 – 17/12/2017 | 26 | 26.4 | -0.4 (-4.7 – 3.9) |
| | 31/12/2017 – 04/01/2018 | 53 | 49.9 | 3.1 (-10.5 – 16.7) |
| | 13/01/2018 – 02/02/2018 | 201 | 191.0 | 10.0 (-21.5 – 41.5) |
| | 11/02/2018 – 19/02/2018 | 80 | 79.1 | 0.9 (-20.0 – 21.7) |
| | 02/03/2018 – 04/03/2018 | 28 | 27.7 | 0.3 (-11.1 – 11.7) |
| | **Total** | **491** | **466.9** | **24.1 (-18.2 – 66.3)** |
| MfE/Stats NZ | 02/12/2017 – 05/12/2017 | 38 | 39.8 | -1.8 (-10.0 – 6.4) |
| | 08/12/2017 – 11/12/2017 | 51 | 34.4 | 16.6 (-8.6 – 41.7) |
| | 30/01/2018 – 01/02/2018 | 28 | 27.4 | 0.6 (-25.5 – 26.8) |
| | 15/02/2018 – 19/02/2018 | 43 | 41.9 | 1.1 (-17.9 – 20.0) |
| | **Total** | **160** | **143.5** | **16.5 (-11.0 – 44.0)** |
| UK | 08/12/2017 – 10/12/2017 | 35 | 25.7 | 9.3 (-20.8 – 19.3) |
| | 30/01/2018 – 01/02/2018 | 28 | 27.4 | 0.6 (-25.5 – 9.4) |
| | **Total** | **63** | **53.1** | **9.9 (-12.9 – 13.7)** |

**Figure 19:** Number of excess deaths, 2015/16 and 2017/18



### Excess mortality for the seven worst heatwave episodes during 2001–2018

Figure 20 focuses on the seven worst episodes (based on excess temperature) identified by each approach (as the UK approach identified a total of seven episodes throughout the study period). The EHF approach identified the highest number of excess deaths during the seven worst episodes (39.3, -16.6 – 95.2). The MfE/Stats NZ approach identified a similar number of excess deaths (37.3, -7.2 – 81.8). The UK approach identified the smallest number of excess deaths (13.6, -16.0 – 43.2) (Figure 20).

**Figure 20:** Number of excess deaths during the seven worst heatwave episodes identified by each approach, 2000/01 to 2017/18

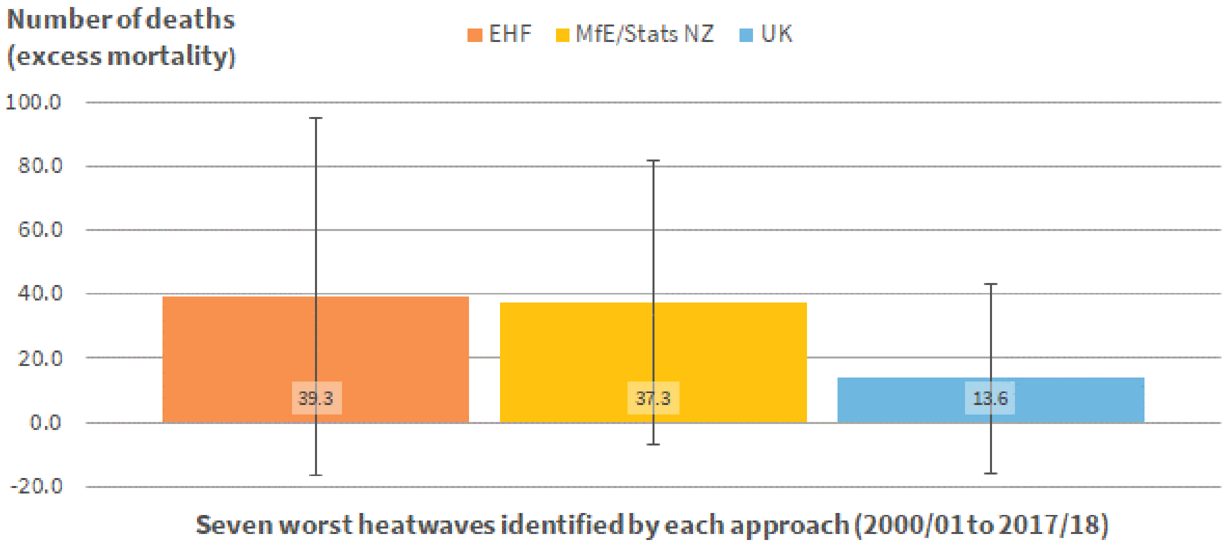


**Table 8:** Heatwave characteristics for the seven worst heatwave episodes by each approach, 2017/18 season

| Method | Heatwave episodes | Observed mortality | Baseline mortality | Excess mortality |
|---|---|---|---|---|
| **EHF** | 29/11/2001 – 04/12/2001 | 43 | 53.4 | -10.4 (-32.3 – 11.6) |
| | 05/01/2009 – 10/01/2009 | 62 | 54.1 | 7.9 (-12.3 – 28.0) |
| | 16/12/2010 – 23/12/2010 | 94 | 68.9 | 25.1 (-10.7 – 61.0) |
| | 20/01/2016 – 25/01/2016 | 50 | 51.3 | -1.3 (-8.9 – 6.3) |
| | 23/02/2016 – 28/02/2016 | 54 | 56.3 | -2.3 (-19.2 – 14.6) |
| | 02/12/2017 – 11/12/2017 | 103 | 92.8 | 10.2 (-13.9 – 34.3) |
| | 13/01/2018 – 02/02/2018 | 201 | 191.0 | 10.0 (-21.5 – 41.5) |
| | **Total** | **607** | **567.7** | **39.3 (-16.6 – 95.2)** |
| **MfE/Stats NZ** | 10/11/2005 – 12/11/2005 | 31 | 28.0 | 3.0 (-1.3 – 7.3) |
| | 07/01/2009 – 09/01/2009 | 37 | 26.4 | 10.6 (-4.9 – 26.1) |
| | 18/12/2010 – 22/12/2010 | 63 | 42.5 | 20.5 (-22.0 – 63.0) |
| | 24/11/2015 – 28/11/2015 | 44 | 49.8 | -5.8 (-28.8 – 17.2) |
| | 24/02/2016 – 27/02/2016 | 31 | 37.4 | -6.4 (-19.6 – 6.7) |
| | 19/03/2016 – 22/03/2016 | 38 | 39.1 | -1.1 (-24.6 – 22.5) |
| | 08/12/2017 – 11/12/2017 | 51 | 34.4 | 16.6 (-8.6 – 41.7) |
| | **Total** | **295** | **257.7** | **37.3 (-7.2 – 81.8)** |
| **UK** | 01/01/2004 – 03/01/2004 | 23 | 28.9 | -5.9 (-29.9 – 18.0) |
| | 07/01/2009 – 09/01/2009 | 37 | 26.4 | 10.6 (-4.9 – 26.1) |
| | 01/01/2010 – 03/01/2010 | 30 | 28.9 | 1.1 (-13.8 – 16.0) |
| | 25/02/2016 – 27/02/2016 | 25 | 27.7 | -2.7 (-18.2 – 12.9) |
| | 19/03/2016 – 21/03/2016 | 30 | 29.4 | 0.6 (-31.9 – 33.1) |
| | 08/12/2017 – 10/12/2017 | 35 | 25.7 | 9.3 (-20.8 – 39.4) |
| | 30/01/2018 – 01/02/2018 | 28 | 27.4 | 0.6 (-25.5 – 26.8) |
| | **Total** | **208** | **194.4** | **13.6 (-16.0 – 43.2)** |

# Discussion

## Heatwaves were likely to have had a health impact in the Canterbury district in 2017/18

Across the study period of 2000–2018, there were 21 heatwave days identified by all three heatwave approaches in the Canterbury district. The number of excess deaths due to heatwaves over this time period varied depending on the approach used to define heatwaves. Across all heatwave episodes that each approach identified from 2000 to 2018, the EHF approach found the highest level of excess mortality (79.6 excess deaths across 59 heatwave episodes), followed by the UK approach (13.6 excess deaths across seven heatwave episodes), with the MfE/Stats NZ approach only identifying 1.1 excess deaths (across 26 heatwave episodes).

Most heatwave days identified by all three approaches were in the two summer seasons of 2015/16 and 2017/18. These two seasons also represented the worst heatwave seasons, based on excess temperature. For the 2017/18 season, all three approaches found an excess of deaths due to heatwaves (24.1 for EHF, 16.5 for MfE/Stats, and 9.9 for UK approach). However, no excess deaths were found due to heatwaves in the 2015/16 season (-16.5, -20.2 and -2.1 excess deaths for EHF, MfE/Stats and UK approaches respectively).

When looking at the seven worst heatwave episodes (based on excess heat) for each approach across the study period, the EHF and MfE/Stats NZ approaches found a similar number of excess deaths (39.3 and 37.3 respectively), while the UK approach found 13.6 excess deaths.

It should be noted that none of the above findings were statistically significant. Because of a small number of deaths in the Canterbury district (only about nine deaths per day), the estimates of excess deaths had wide 95% confidence intervals that overlapped zero.

## Selecting an approach for defining heatwave episodes

Deciding which heatwave definition to use depends considerably on the intended audience and the desired outcomes. For example, heatwave definitions can be used when setting up early warning systems and/or to monitor the health impacts of heatwaves on the population. The considerations for the selection of heatwave definition may differ depending on the proposed use.

For both early warning systems and monitoring purposes, selecting the 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). Additionally, when setting up a heat-health warning system, 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.

Among the three heatwave definitions compared in this study, the MfE/Stats NZ and the UK approaches take only the daily maximum temperature ($T_{max}$) into account, whereas the EHF approach uses both the daily maximum ($T_{max}$) and daily minimum ($T_{min}$) temperatures in its calculations, to allow for high minimum temperatures and therefore accumulated heat load, which can have a health impact (Kanti et al 2022). The three approaches use the 1981–2010 Climate Normal Period as a benchmark in their analysis and identified heatwaves in the hottest summer on record, 2017/18. Furthermore, all three approaches agreed that the worst episodes based on excess temperature occurred in seasons 2015/16 and 2017/18.

In general, the EHF approach identified heatwaves that were long but with relatively cooler temperatures. The UK approach identified short but very hot heatwaves. This was expected, as by definition of the 90th percentile, the temperature threshold of the UK approach is not often exceeded (McCarthy et al 2019). In the middle, the MfE/Stats NZ approach identified heatwaves that were of medium length and with medium temperatures. Excess mortality was highest with the EHF approach, which might in part be related to it identifying the most heatwave days.

From a climatological standpoint, the EHF approach makes the most sense as it includes 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 also intrinsically includes humidity, according to the authors (Nairn and Fawcett 2015, Wondmagegn et al 2021). Furthermore, the EHF approach considers the conditions leading up to a potential heatwave and compares this to a 95th percentile value to gain an understanding of the severity of a potential heatwave.

Additionally, the EHF has been developed as an indicator of health-relevant heat events (Oliveira et al 2022), 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 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), and 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). When used for public warnings, the option of using a more severe category from the EHF is available, through the EHF severity metric (Nairn et al 2018, Hatvani-Kovacs et al 2016).

Given that the EHF approach identifies many episodes and days per season (seven episodes in 2015/16 for example), it 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. Furthermore, this methodology, application, and communication is slightly more complicated than the rather more straightforward MfE/Stats NZ and UK approaches. This suggests that the EHF is a useful measure for monitoring the health impacts of heatwaves, but if used for a heat alert system, a subset of the alerts (eg moderate/severe) may need to be considered (Varghese et al 2019).

By contrast, the UK approach might miss heatwaves that have relatively cooler temperatures but go on for longer, which is known to have a significant impact on public health. However, the UK has a similar climate to New Zealand, and therefore the UK approach might be usefully considered here. One downside of this approach is that it applies one temperature threshold to the whole summer period rather than using monthly thresholds.

The MfE/Stats NZ approach takes a middle ground. However, the heatwave episodes identified by this approach correlated with a very low excess mortality overall (1.1 excess deaths over the study period), which may make it less useful from a health perspective. Nonetheless, the approach is straightforward and can easily be applied.

## Potential applications of this study

There are two main potential applications of this study for public health action. Firstly, the results may help to inform the development of a heat-health warning system in New Zealand. These systems are being 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 ED departments. For example, the Australian Bureau of Meterology has used the EHF to publicly release national 7-day heatwave severity maps since 2014 (Nairn et al 2018). Of note, in New Zealand, the MetService has been recently trialling a new heat alert system during the 2021/2022 and 2022/23 summer seasons. This heat alert system is based on temperature, humidity and wind to calculate a ‘feels like’ temperature, which is measured against a daily maximum temperature threshold for the location. These calculations are likely more complex than the approaches trialled here (given the additional variables of humidity and wind used in analysis). It is unknown how the hot days and heatwaves identified through the MetService’s system relate to those identified through the three approaches trialled in this study or how the identified hot days link to health outcomes.

Secondly, Environmental Health Intelligence NZ (EHINZ) could use these results to develop 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. NIWA temperature data could be used to identify heatwaves in each summer season for geographic areas (such as territorial authorities or urban areas) across New Zealand. Excess mortality could then potentially be estimated nationally and for each district and/or for specific districts where heatwaves are likely to be a problem. It should be noted that smaller population sizes may limit the statistically significant excess deaths that can be identified regionally.

## Further considerations

If 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 be considered before implementation.

### Low numbers

Excess mortality results for each heatwave approach resulted in values that were not statistically significant. This might be due to relatively low daily numbers of observed mortality and/or a low impact of heat on mortality. Further analysis around excess mortality and the link with temperature might be useful, particularly to expand the analysis to include a larger population. The Canterbury district had about nine deaths per day in the summer season, and about 3500–4000 deaths per year. By contrast, New Zealand generally has more than 30,000 deaths per year, so carrying out a similar analysis for the whole of New Zealand might allow for increased numbers of deaths, and therefore hopefully more precise estimates for excess deaths, at the national level.

### Alternate heatwave definitions for consideration

Some refinements to the above approaches for defining heatwaves could potentially be considered. For example, for the EHF approach, some studies have categorised heatwaves based on EHF severity categories (eg no heatwave; low-intensity, moderate-severity, high-severity), and may only use certain categories used for public alerts (Varghese el al 2019).

For the UK approach, varying monthly temperature thresholds might be useful to test, to be similar to the MfE/Stats NZ approach. This would ensure that heatwaves in the cooler summer months are not missed. Additionally, for the MfE/Stats NZ approach, it might be useful to alter the approach to include $T_{min}$ in the calculation to account for nighttime temperatures.

Additionally, the recent MetService trial of heat alerts was implemented late in this project, and has not been included in this analysis. However, this method may need future evaluation against mortality data once the required outcomes for a heat alert system are certain. The same approach as used in this project could be used to evaluate the MetService heat alerts, as long as appropriate data was available.

### Baseline mortality calculations

The methodology for the baseline mortality calculations could also have an effect on the results. Different methods could lead to varying baseline values, consequently affecting excess mortality values (Rustemeyer and Howells 2021). For example, it might be useful to analyse the impact of all three heatwave approaches using a longer baseline of 5 years prior (Rustemeyer and Howells 2021). This would decrease the study period as more years are needed to calculate a baseline mortality, although any heatwave impact on mortality may become more visible.

### Time lag

We did not investigate the effect of time lag on mortality, however, 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).

### Potential confounding factors

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).

We also did not investigate the effect of Urban Heat Islands on excess mortality as we only analysed mortality data for the total Canterbury district. Urban areas experience higher temperatures compared to more rural areas due to the built environment. The population in urban areas is therefore exposed to higher temperatures making them more vulnerable in heatwave conditions.

### Climate Normal Period

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 will result in most days being identified as heatwave days. This study uses the 1981–2010 Climate Normal Period, the latest available period at the start of the study, which should be re-analysed with the most current period, 1991–2020, in a future update.

### Geographic areas

If the results of this project are implemented at the national level, further work would be required to determine the most appropriate geographic level to carry out analyses (such as territorial authorities or urban areas). This decision may be based on data availability (eg climate data), utility by end-users, and appropriateness of climatic regions.

### 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 social vulnerability to heatwaves alongside any further analysis, for example using the Social Vulnerability Indicators (SVIs) for natural hazards that EHINZ has developed (Mason et al, 2021), and/or using these SVIs to create a heat vulnerability index. These types of indicators could be used to identify areas in New Zealand with highly vulnerable populations (such as young children and older adults), who may be most likely to benefit from a heat-health warning system and/or education and public health preventive action during the summer season.

## Conclusion

This project analysed the association between heatwaves and mortality counts across the Canterbury district between 2000/01 and 2017/18, using three heatwave definitions. Excess mortality was calculated for each approach and its identified heatwave episodes. By comparing the approaches and their findings, we found that heatwave characteristics can vary widely depending on the definition used. Each approach resulted in heatwaves that were distinctly different from each other in terms of duration and average daily maximum temperature ($T_{max}$), and therefore the number of heatwave episodes and days for each approach differed as well. Due to the difference in the number of heatwave episodes and days, excess mortality varied across approaches. The Excess Heat Factor (EHF) approach identified the most heatwave days, which also resulted in the highest excess mortality.

Deciding which heatwave definition to use may depend on the intended audience and the desired outcomes. The UK approach, for example, takes an acute and higher-risk approach, it identifies a few short, but very hot heatwave episodes. The EHF approach identifies a greater number of heatwaves that were long but with relatively cooler temperatures. The MfE/Stats NZ approach identifies an intermediate number of heatwaves with medium length, and medium temperatures. Additionally, the MetService trial of heat alerts was implemented late in this project, so was not able to be included; however, these heat alert thresholds may need future evaluation against mortality data once the required outcomes are certain.

On balance, the EHF approach appears to be the most appropriate method to use. It identified the greatest number of heatwaves and the highest excess mortality from heatwaves. It has been used elsewhere in the world, and has been shown to work well in a range of countries, including mid-latitude countries where humidity tends not to be too high. The results of this study could be used to inform the development of a heat-health warning system in New Zealand, and could also form the basis for Environmental Health Intelligence NZ to develop a national system for monitoring heatwaves and their health impacts.

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