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Future projections of extreme heat across Aotearoa New Zealand

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1. Introduction

The growing risks of extreme heat in a warming world have the potential to profoundly affect multiple sectors across society in all countries of the world, including Aotearoa New Zealand. Extreme heat is the deadliest climate hazard globally and can affect the health and wellbeing of communities in multiple ways (Ebi *et al* 2021, Vicedo-Cabrera *et al* 2021); exposure to even modest levels of heat stress can materially reduce milk production (Bryant *et al* 2007) and reduce sheep & beef profits in New Zealand (Bell *et al* 2021); while the economic impacts of workplace productivity losses caused by extreme heat events are likely also significant (Steffen *et al* 2019). Yet, the risks associated with extreme heat are also often chronically underestimated and in many regions of the world (Brimicombe *et al* 2021) and this is particularly true for New Zealand (Harrington 2021).

Given these considerations, the Climate Change Commission has requested the development of a heat metric to contribute to our wider adaptation monitoring efforts. Here, we present an analysis of projected changes in extreme heat nationwide under a range of future warming scenarios, with a focus on TX98p as a simple metric with which to characterise extreme heat.

2. Selecting a nationwide metric of extreme heat for New Zealand

Any selection of an extreme heat metric must confront a range of trade-offs, as well as consider the intended use of the metric (Perkins 2015, Perkins and Alexander 2013, Harrington 2021, Harrington and Frame 2022, Sai Venkata Sarath Chandra *et al* 2025). Here, our priority is to select a *single* metric which can inform the risks associated with locally extreme heat *across all locations in New Zealand* (not just one or two regions) and for a *range of seasons* (so to consider the varied impacts associated with unusually high temperatures at different times of year; Perkins and Gibson 2015). Importantly, we also want to ensure the *speed of future changes is comparable between different locations as well as across different warming scenarios*: this meant that projected changes in the metric of interest could not "saturate" before the end of the century under a high emissions pathway (Harrington and Otto 2018), such that the metric becomes uninformative when comparing different emissions scenarios (see Section 2.2 for further explanation).

Following previous examples in the peer-reviewed literature (Freychet *et al* 2021, Guo *et al* 2026, Harrington *et al* 2016), we have selected TX98p as our metric of choice: specifically, for each grid cell, we quantify the 98th percentile of daily maximum temperatures (TX) for each calendar day of the year, using a 15-day rolling window centred on the day of interest and a 1985-2014 reference period over which to calculate the baseline percentile metric. That is, for the 8th of December, we pool together all days from seven days beforehand (from Dec 01) until seven days after the day of interest (Dec 15), and for all years between 1985-2014, thereby giving us 15 x 30 = 450 data points from which to extract the 98th percentile value. We then simply count each day in the future when this calendar day-, location- and season-specific 98th percentile threshold is exceeded and refer to the total number of exceedances (in units of % of days) as TX98p.

Other choices to define extreme heat are of course available. Here, we attempt to outline the rationale for our selection.

2.1. On the use of a percentile-based metric

There is a wealth of epidemiological literature which shows that the temperature at which heat-related health impacts begin to emerge is relative to the climate one is adapted to, and thus, relative to the climatology of the location of interest (Gasparrini *et al* 2015, Tobías *et al* 2021, Vicedo-Cabrera *et al* 2021, Ebi *et al* 2021, Lüthi *et al* 2023). In nearly all regions of the world, there exists a "J-shaped" relationship between warm-season daily temperatures and excess adverse health outcomes (like morbidity or mortality), with the relative impact increasing non-linearly as temperatures reach extreme values (Lüthi *et al* 2023, Vicedo-Cabrera *et al* 2021).

The most common way in which statistical relationships between high temperature and excess mortality are presented in the epidemiological literature is through quantifying the minimum mortality temperature (or equivalently, the corresponding percentile of that MMT): this is the daily (mean or maximum) temperature at which health-related impacts are at their minimum, and above which the relative risk of mortality increases with every additional degree of warming. Viewed another way, this represents the temperature which the local population is optimally adapted to. For example, warmer regions like Southeast Asia exhibit minimum mortality temperatures which are more than 11°C higher than Northern Europe (Figure 2, Tobías *et al* 2021): yet in all places, adverse health outcomes can still emerge rapidly when local populations are exposed to *relatively extreme* high temperatures (Lo *et al* 2022, Ballester *et al* 2023, Gallo *et al* 2024). Of particular note, several case studies have identified excess deaths associated with temperatures which were low in absolute terms, but anomalously hot relative to their typically cool climates: such examples include England and Wales (Christidis *et al* 2010), the Netherlands (Folkerts *et al* 2020), southern Finland (Donaldson *et al* 2003), Stockholm, Sweden (Åström *et al* 2016) and Canada (Gasparrini *et al* 2015).

While excess mortality tends to be the focus of the heat-health epidemiological literature (in part because of the consistent records of mortality data), it is also important to recognise that for every one excess death, there are often several excess hospitalisations as well as ED presentations linked to extreme heat (Vaidyanathan *et al* 2019).

2.2. Why not use TX90p?

When selecting a single, easy-to-understand metric of worsening extreme heat, the choice of which percentile threshold to use is important (though ultimately subjective). Many other studies in the available literature use TX90p, which is equivalent to TX98p but, as the name suggests, counts the number of exceedances of the (local, seasonally adjusted) 90th percentile of daily maximum temperatures. The reason for our choice to use a rarer percentile threshold reflects two considerations: first, we want to focus only on the most impactful types of extreme heat (which are inevitably associated with rarer temperatures); second, we are mindful of a statistical artefact called risk ratio saturation (Harrington *et al* 2018, Harrington and Otto 2018, Gampe *et al* 2024).

When looking at future changes in the frequency of extreme heat, where the definition of what constitutes an extreme hot day is a fixed threshold (whether a locally-specific percentile threshold or otherwise), the most common framework to present future changes in risk is by focusing on risk ratios (sometimes also called probability ratios): this is a metric which answers the question, "*how many times more often do we see the extreme event of interest occur now, relative to the past?*" (see also Figure SPM.6 from the IPCC's Sixth Assessment Report Working Group 1 Summary for Policymakers (IPCC 2021)).

For example, when considering TX90p, we expect this 90th percentile threshold to be exceeded on 10% of all days in the reference period by definition. But suppose in a warmer future, that number increases to 20% of all days: this is equivalent to a risk ratio of 2 (or "*twice as many extreme hot days now occur relative to the reference period*"). And then if enough warming were to occur in the future such that *all* days of the year were above the historical 90th percentile threshold, then the risk ratio would reach its maximum value of 10.

Next, consider the same question but for a higher 98th percentile threshold: 2% of all days exceed this threshold in the reference period; in the future, a risk ratio of 2 would occur when 4% of all days exceed that threshold; while the maximum risk ratio that can occur is 50 (i.e. when 100% of all days exceed the threshold).

Thus, it is important to acknowledge that any percentile-based metric of extreme heat has its own maximum risk ratio, which in turn differs depending on the baseline rarity of the threshold (= 100 / % days exceeding threshold in the reference period). However, for less extreme metrics like TX90p, risk ratios begin to saturate near this maximum value at much lower levels of warming (Harrington and Otto 2018), *meaning the relative impact of additional warming* (say, the impact of a 4°C world relative to a 3°C world) *can no longer be distinguished using that metric* (Fischer and Knutti 2015). It is for these reasons, combined with the authors understanding of the relative rate of projected changes in extreme heat over New Zealand (following Lewis *et al* 2025), that TX98p was selected as the metric of choice.

2.3. Why not a combined metric of heat and humidity to more meaningfully represent heat stress?

Methodological assumptions underpinning different metrics of "heat stress" or "dangerous" heat are currently the subject of robust scrutiny within the research community (Kong and Huber 2022), particularly in the context of climate change and human health (Vanos *et al* 2020, Baldwin *et al* 2023). Some climate scientists have focused on developing very simple metrics, so to ensure climate model representations of heat stress rely primarily on variables which are relatively well-simulated (like temperature and humidity at the daily scale) without needing to also perform multi-dimensional bias-corrections for a range of other, poorly-simulated factors (like wind speed, cloudiness or diurnal variations in temperature and humidity; Fischer and Knutti 2013). Conversely, health researchers have emphasised that the adverse health outcomes of extreme heat simply cannot be quantified without accounting for this diverse range of other confounding factors (Vanos *et al* 2020, Baldwin *et al* 2023).

Here, we have opted for a metric which only relies on daily maximum temperature data for several reasons. First, recent research has concluded that the metric which best approximates the relationship between heat stress and adverse health outcomes can vary *significantly* country-to-country, even in regions with otherwise comparable climates (Lo *et al* 2023). Second, statistical downscaling of the CCAM climate model output to a 5km x 5km resolution used in this analysis first included a bias correction step for the daily maximum temperature output *but not* the relative humidity output (because of the lack of historical station observations for the latter): consequently, the two output variables can no longer be combined to estimate wet-bulb temperature or some other proxy for heat stress without misrepresenting the statistical relationship between the two variables (Zscheischler *et al* 2019).

Third, our choice to only focus on ambient temperature data is consistent with the majority of heatwave definitions used in other countries worldwide, including the heatwave warning systems used by Australia and the United Kingdom (Sai Venkata Sarath Chandra *et al* 2025). This, in turn, partly relates to the fact that operational weather forecast models are typically more error-prone when trying to predict daily maximum *apparent* temperature (i.e. including humidity in the metric): this was one of the reasons why New Zealand's MetService moved away from the inclusion of humid heat metrics as part of their heat alert pilot programme, instead considering the persistence of unusually high temperatures over several days (and nights) as an alternative proxy for humid heat which can be forecasted more reliably (Harrington and Frame 2022).

3. Data and Methods

3.1. Climate model data

We examine heat extremes using the outputs of six models from the CMIP6 ensemble (Eyring *et al* 2016) which have been dynamically downscaled from their native resolutions to a resolution of 12 x 12 km over New Zealand using the variable-resolution Conformal Cubic Atmospheric Model (CCAM; see Gibson *et al* 2023, 2024a, 2024b). The downscaling procedure adds significant value to the simulation of daily maximum temperatures (as well as other variables) relative to the host GCMs (Gibson *et al* 2024b).

Furthermore, we use a bias-corrected version of this data set, which has daily maximum temperature data available at a 5 km × 5 km horizontal resolution. The bias correction which was performed, presented, and evaluated in Campbell et al. (2024; see https://bit.ly/3PGOeNG), and uses trend preserving quantile mapping of daily maximum temperature with respect to the Virtual Climate Station Network (VCSN) as the observational reference product (Tait *et al* 2006, 2012).

Throughout this analysis, we use 'Historical' model simulations spanning 1985–2014 as a baseline reference period, while examining projected changes which occur across the 2015–2099 future period under three different SSP scenarios: SSP1-2.6, SSP2-4.5 and SSP3-7.0, to account for the effects of scenario uncertainty on future heat extremes. Further guidance information about the underlying model simulations can be found here, https://bit.ly/47xVjGn.

3.2. Determining a baseline value and changes in TX98p

For each calendar day of the year, we use a 15-day rolling window centred on each day of interest and a 1985-2014 reference period, and six downscaled climate model simulations over which to calculate TX98p. For each day of the year, we pool together all days from seven days beforehand until seven days after the day of interest, for all years between 1985-2014 (giving us 15 x 30 = 450 data points per model simulation) and for all six model simulations, yielding 450 x 6 = 2700 data points from which to extract the 98^{th} percentile value. This 98^{th} percentile value is a day-, location-, and season-specific threshold.

We then examine changes in the number of exceedances of these historically determined thresholds under the three future SSP scenarios in units of % of days above TX98p. If 2% of days over some time span in the future are above Tx98p then there is no change in the frequency of TX98p days in the future. If 4% of days over some time span in the future are above TX98p then there has been a doubling in the frequency of TX98p days. This corresponds to a risk ratio of hot days in the future to hot days in the historical period of 2 which we will use in the following plots of future projections.

Unless stated otherwise, all results are hereafter presented as the multi-model mean of the six-model CCAM ensemble.

4. Results

4.1. Annual TX98p projections across different warming scenarios

We show the risk ratios of TX98p temperatures to occur on any day of the year under an SSP1-2.6 scenario across various time horizons in Figure 1. Even within the nearest time horizon 2020-2040 there is a significant increase in risk of TX98p temperatures with the majority of the North Island having a risk ratio greater than 2, and the majority of the South Island having a risk ratio greater than 1.5. This change is not totally homogenous with areas on the north and west of the South Island having risk ratios greater than 2, while the Wellington and Taranaki regions experience lower risk ratios than the rest of the North Island. The risk of TX98p temperatures increases again over the next time horizon 2040-2060, with the northern North Island having a risk ratio between 3 and 5, with the remainder of the country having a risk ratio between 2 and 3. Global mean surface temperatures peak around 2050 under SSP1-2.6 (O'Neill *et al* 2016) and continue to decrease slightly thereafter: consequently, risk ratios in 2060-2080 are only slightly elevated again, with regions of the far north and the Southern Alps reaching risk ratios of 3-5. In the end of century period 2080-2100 these risk ratios begin declining with the majority of the South Island having a risk ratio of 2-3 and the North Island having risk ratios between 2 and 3 in the south and central areas, and 3-5 in the northern and some coastal areas.

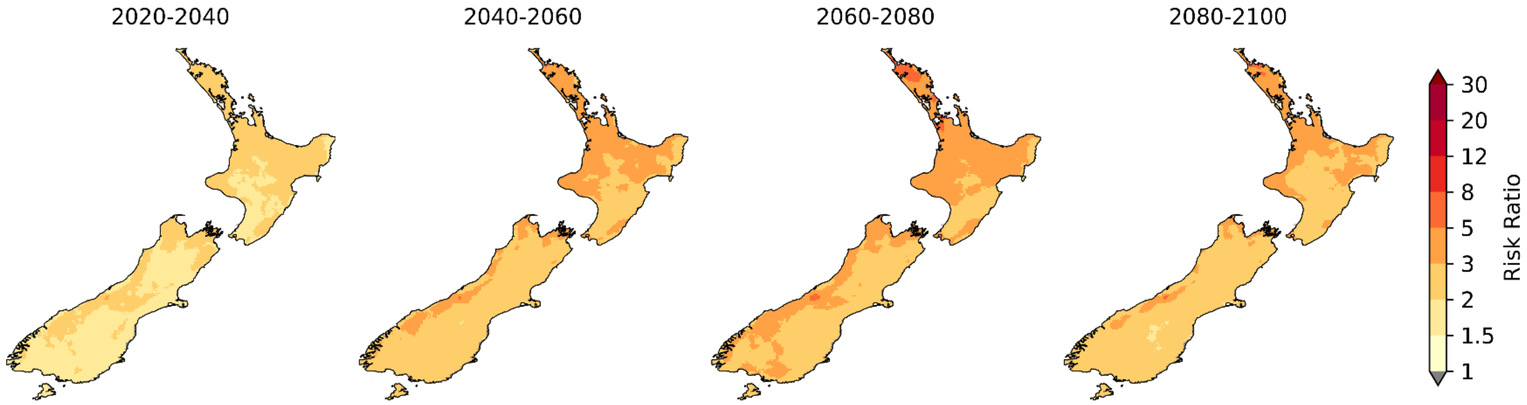

Figure 1: Twenty-first century risk ratios of TX98p under an SSP1-2.6 scenario, considering all days of the year. All risk ratios are presented relative to 1985-2014.

Figure 2 is the same as Figure 1 but for climate projections under and SSP2-4.5 scenario. Under SSP2-4.5 risk ratios of TX98p temperatures in the 2040-2060 time horizon exceeding any reached under SSP1-2.6, which is reasonable given the faster and continuous warming rate of the scenario. By 2060-2080, risk ratios in the upper North Island begin reach 8-12, indicating that temperatures that occurred 2% of the time in the historical period now occur 16-24% of the time. The remainder of the North Island and the western half of the South island have risk ratios between 5-8, while the eastern half of the South Island has risk ratios between 3 and 5. In the end of century period 2080-2100 we begin to see a region in the far north with risk ratios exceeding 12, with larger areas of the North Island have risk ratios between 8 and 12, and the remainder of the North Island and the majority of the south island having risk ratios between 5 and 8.

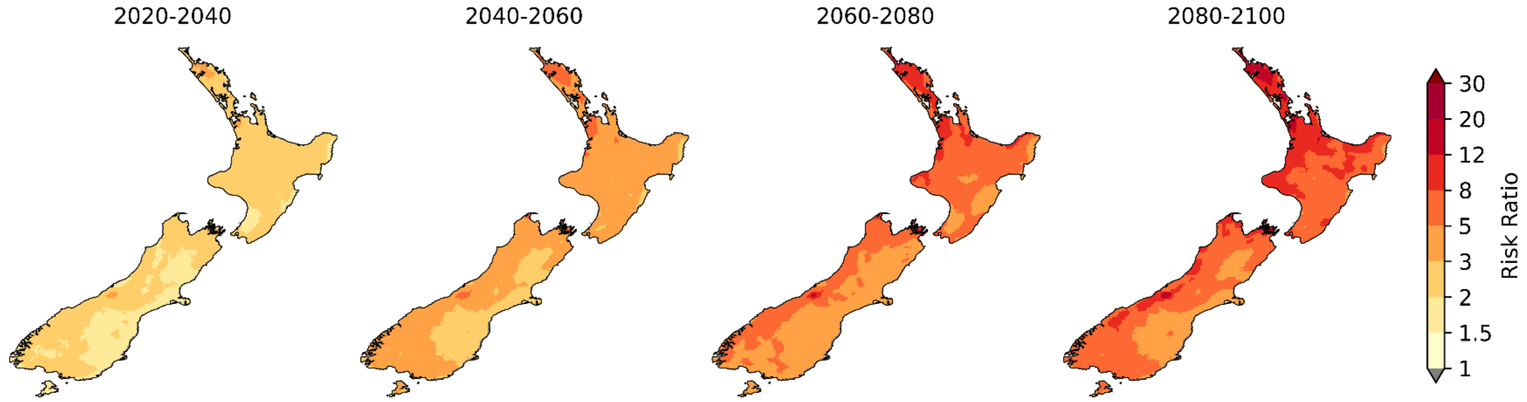

Figure 2: Twenty-first century risk ratios of TX98p under an SSP2-4.5 scenario, considering all days of the year. All risk ratios are presented relative to 1985-2014.

Under SSP3-7.0 risk ratios in the 2060-2080 time horizon already begin to exceed those seen under SSP2-4.5 in the end of century period across the country with a greater area of the upper north island beginning to have risk ratios between 12 and 20. The end of century period under SSP3-7.0 provides the most dramatic results, with the upper north island having risk ratios of TX98p days between 20 and 30, meaning 40-60% of days are above the historical TX98p threshold. The remainder of the North island and the western half of the South Island exhibit risk ratios between 12 and 20, while the remainder of the South Island has risk ratios between 5 and 12.

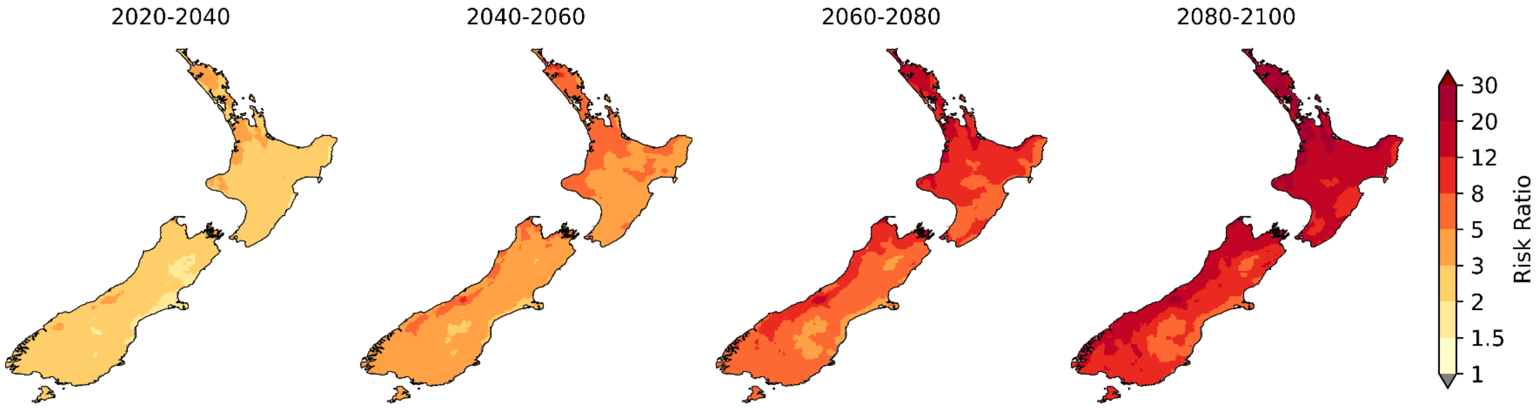

Figure 3: Twenty-first century risk ratios of TX98p under an SSP3-7.0 scenario, considering all days of the year. All risk ratios are presented relative to 1985-2014.

The geographic patterns of change emerging across all scenarios are consistent with results previously found by Gibson *et al* (2025; their Figure 8) and Lewis *et al* (2025; their Figure 2): in essence, there is much less day-to-day variability in daily maximum temperatures in northern regions of the country, such that the same mean warming signal inherently results in many more exceedances of historically extreme percentile thresholds when compared with other regions in the country with high levels of daily (and interannual) temperature variability. The reader is also referred to Section 5 of Harrington & Frame (2022) for further explanation.

4.2. Seasonal variations in TX98p projections

So far, we have examined the risk ratios of TX98p across all days of the year, with increasing risk found in increasingly warm SSP scenarios. One other aspect of the future changes in TX98p exceedances we are also particular interested in exceedances which occur in the summertime, as these will be the greatest absolute temperatures that New Zealander's will be exposed to throughout the year, and thus carry the greatest heat-related impacts. To determine if changes in summertime exceedances of TX98p are significantly different to exceedances which occur throughout all days of the year, we contrast risk ratios of TX98p exceedances in both summertime (specifically exceedances which occur in December, January, and February (DJF)), and wintertime (specifically exceedances which occur in June, July, and August (JJA)), as these are the two most dissimilar seasons. These are shown Figures 4 and 5 respectively for an SSP3-7.0 scenario, with analogous figures for SSP1-2.6 and SSP2-4.5 in the appendix. Comparing the risk ratios of TX98p for individual seasons (Figure 4 & 5) relative to corresponding results for all days of the year (Figure 3), we conclude that there are no meaningful differences in the rate of change of TX98p between summertime, wintertime, and considering all days of the year.

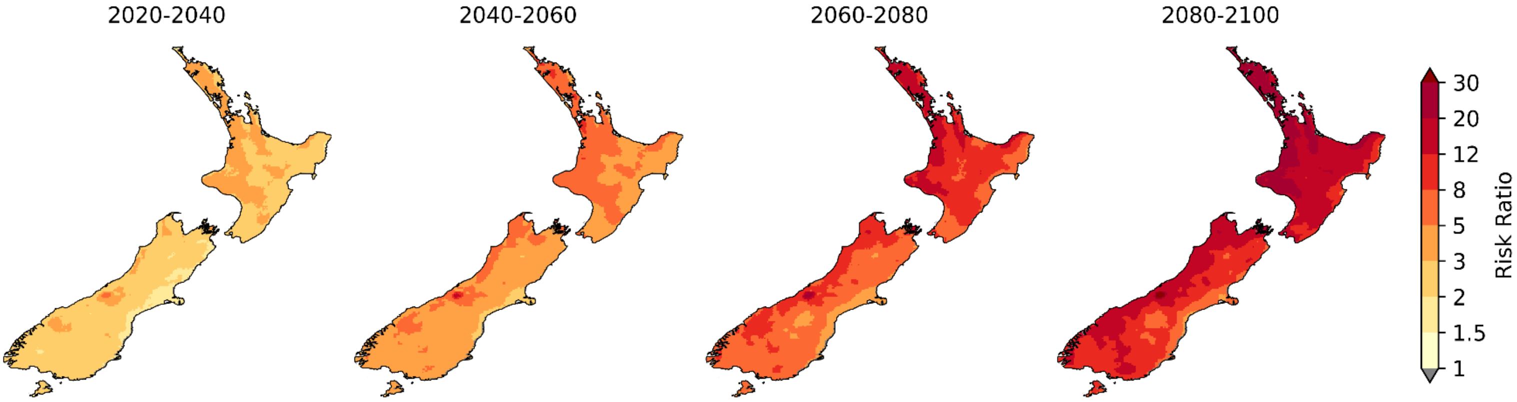

Figure 4: Twenty-first century risk ratios of TX98p temperatures under an SSP3-7.0 scenario, considering all days in December, January & February (DJF). All risk ratios are presented relative to 1985-2014.

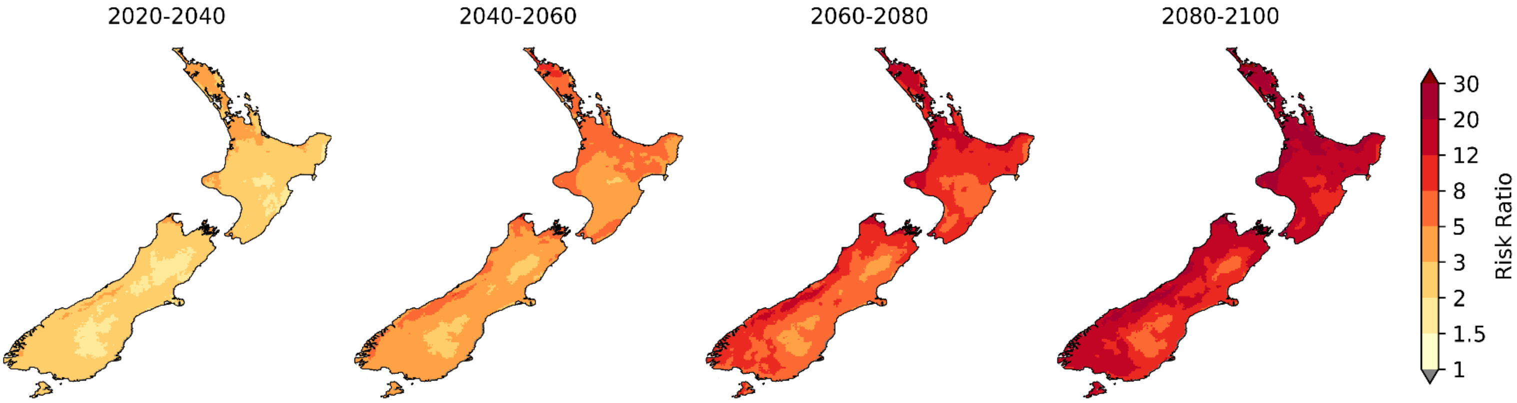

Figure 5: Twenty-first century risk ratios of TX98p temperatures under an SSP3-7.0 scenario, considering all days in June, July & August (JJA). All risk ratios are presented relative to 1985-2014.

5. Summary and future considerations

Here, we have introduced a nationwide heat metric for New Zealand, TX98p, with supporting rationale based on existing scientific literature and the criteria provided to us by the Climate Change Commission. We have presented future projections of TX98p using dynamically downscaled and bias-corrected climate model output, spanning three warming scenarios (SSP1-2.6, SSP2-4.5, and SSP3-7.0), to contextualise future changes in heat-related hazards.

Heat related risks in New Zealand are set to substantially increase in the future, irrespective of the exact amount of warming that will happen over the 21st century. Even under a warming scenario consistent with rapid efforts to reduce emissions (SSP1-2.6), extreme hot days are projected occur 2-5 times more often by 2040, relative to 1985-2014. Warmer SSP scenarios exhibit significantly greater increases in TX98p: risk ratios exceed 12 by the end of the century under SSP2-4.5, while they exceed 20 under SSP3-7.0 in northern regions of the country.

We conclude with a series of suggestions for decision-makers to consider, which we believe will (1) strengthen our understanding of the current and future risks associated with extreme heat in Aotearoa, as well as (2) help to reduce the future impacts from worsening heat-related hazards.

Suggestions to improve our understanding of the risks from extreme heat:

1) Determine which ministry within the Government holds responsibility for making decisions relating to the definition of heatwaves, as well as coordinating efforts to manage the risks from extreme heat in New Zealand.

2) Establish a formal definition of a heatwave.
3) Allocate resources to properly integrate our existing heat alert pilot system into the formal Severe Weather Warning system within MetService. Doing so would bring New Zealand into alignment with existing efforts in the UK, Australia and many other countries worldwide.
4) Develop a suite of different heat-related impact metrics to monitor over time, not just one, with each being tailored to individual sectors. In addition to the TX98p metric we've introduced in this analysis, we recommend the development of one metric which best characterises the physiological effects of heat stress in pastoral agriculture (Woodward *et al* 2025); one which best captures the elevated vulnerability of older people, children under five and which is representative of indoor settings; and one which captures the added effect of humidity for northern regions of the country.
5) Introduce summertime heat-health surveillance and monitoring systems for GP clinics and hospital emergency departments, particularly given the many different ways in which the adverse health outcomes of extreme heat can present themselves (Ebi *et al* 2021)

Policy-relevant suggestions to reduce the future impacts of extreme heat:

6) Learn from initiatives like the recent establishment of Heat Risk Commission in the UK, as well as past government inquiries or reviews from elsewhere in the world (e.g. https://bit.ly/4sTaEtJ).
7) NEMA and the Ministry of Health should work together to develop targeted emergency response plans for heatwave events, particularly using the 1973 Canterbury heatwave and the storyline scenario identified by Lewis *et al* (2025) as a basis for stress test exercises (including considering the risks of electricity outages and impacts on transport infrastructure).
8) Introduce an opt-in heat vulnerability register, along with council-initiated planning to respond during heatwave events. This could follow the example of the CHALEX registry in France, which was introduced in the aftermath of the devastating 2003 European heatwaves (Robine *et al* 2008): there, registrants (people aged 75 and older, disabled people, people with health problems and isolated people) receive cooling advice, a phone check up every two days during heat emergencies, and transportation to a cooling centre if necessary (Kearl and Vogel 2023). In Aotearoa, the focus could initially be focused on maximising benefit for Māori & Pasifika communities, aged residential care facilities and early childhood education centres.
9) Quantify the economic productivity losses associated with individual heatwave events as well as increasingly chronic experiences of extreme high temperatures, like efforts to quantify the economic impacts of the 2009 heatwave in south-east Australia (Steffen *et al* 2019).
10) There needs to be a targeted effort to improve evidence-gathering of the specific risks from humid heat stress, particularly over the North Island (Harrington and Frame 2022).

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Appendix

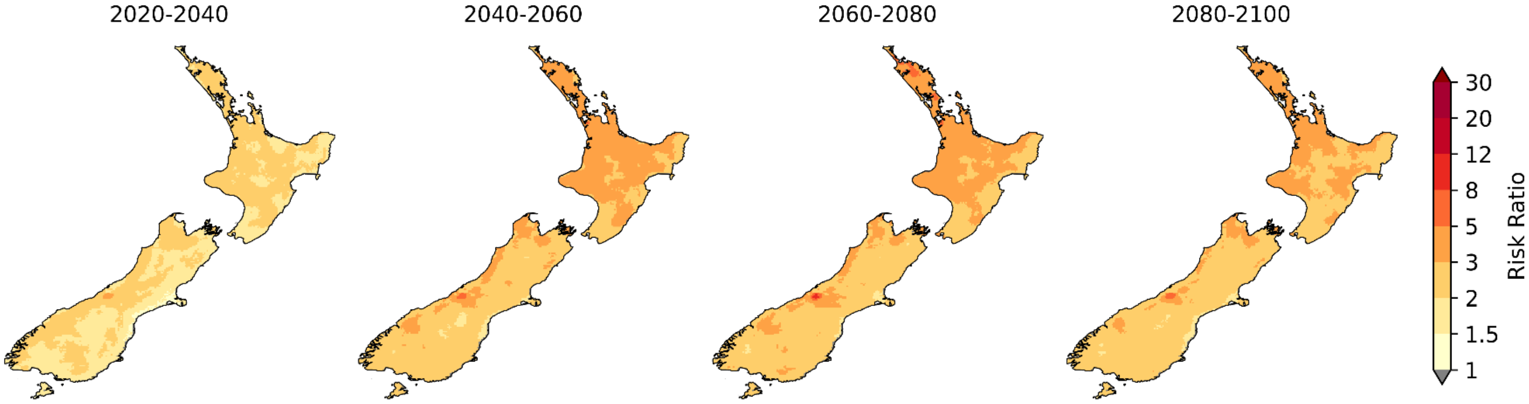

Figure A1: Twenty-first century risk ratios of TX98p under an SSP1-2.6 scenario, considering all days in DJF. All risk ratios are presented relative to 1985-2014.

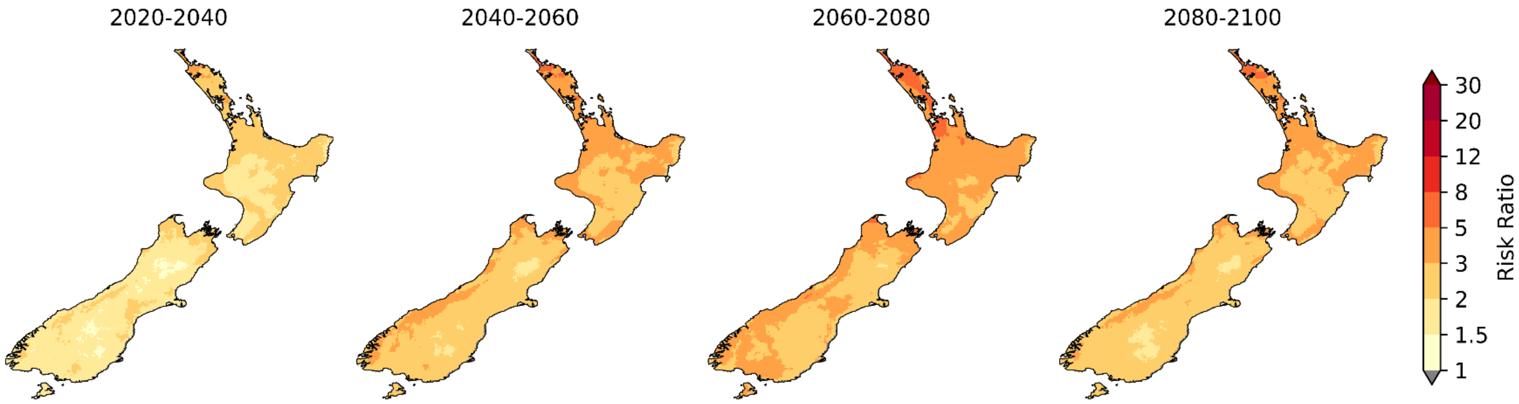

Figure A2: Twenty-first century risk ratios of TX98p under an SSP1-2.6 scenario, considering all days in JJA. All risk ratios are presented relative to 1985-2014.

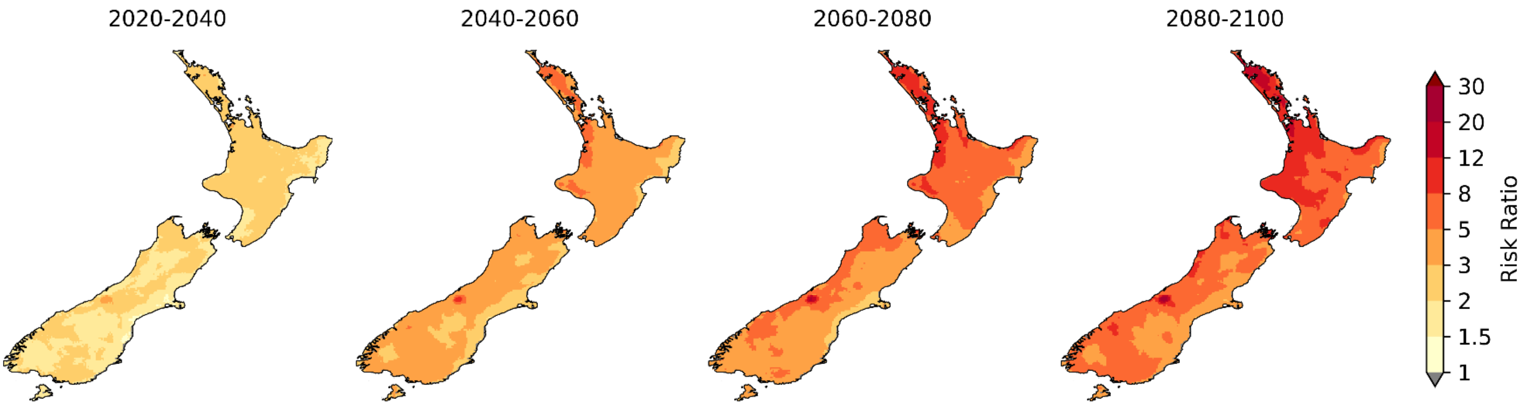

Figure A3: Twenty-first century risk ratios of TX98p under an SSP2-4.5 scenario, considering all days in DJF. All risk ratios are presented relative to 1985-2014.

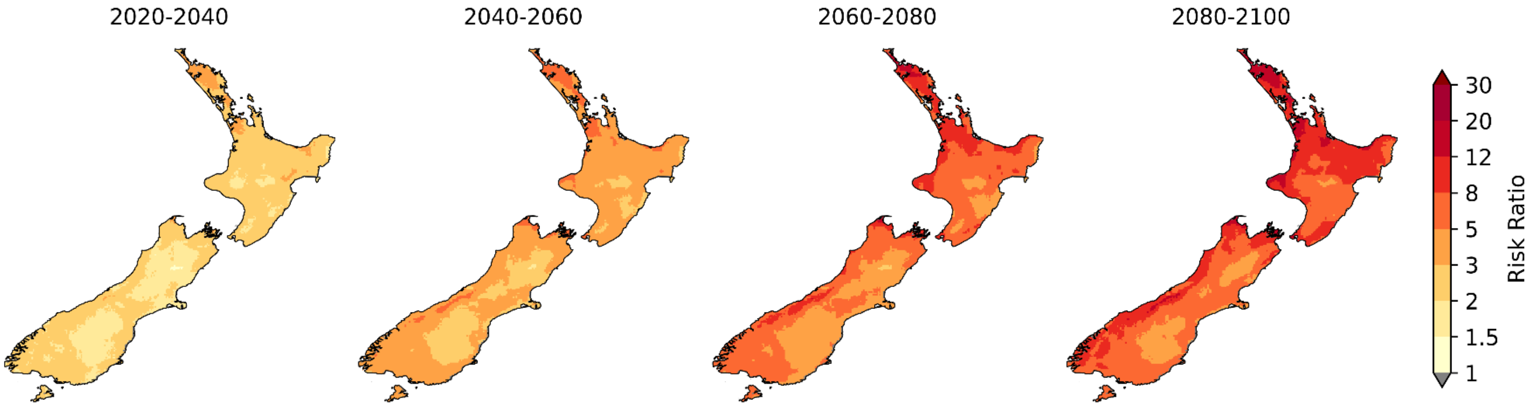

Figure A4: Twenty-first century risk ratios of TX98p under an SSP2-4.5 scenario, considering all days in JJA. All risk ratios are presented relative to 1985-2014.