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Extreme heat in New Zealand: a synthesis

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Abstract
Extreme heatwaves are among the fastest-changing meteorological hazards in a warming world. While likely also true for New Zealand, significant knowledge gaps exist relating to the current and future risks associated with extreme heat. Using high-quality station observations dating back to at least 1972, this study presents the first detailed synthesis of the severity, frequency, and persistence of extreme heat experienced by local communities in New Zealand. Results show the hottest days of the year have warmed by more than 0.5 °C over the last 20 years for many populated regions, a rate which exceeds average annual changes across the country. When evaluating the risks associated with unusually extreme events, complex regional differences emerge. While the East Coast of both islands witness higher absolute temperatures during local heatwaves, lower levels of day-to-day temperature variability in the northern half of the North Island will translate to larger risks with further warming over the twenty-first century.

Keywords Extreme heat · Emergence · Heat-related health risks · Climate change

1 Introduction

Whether focusing on communities living in hot, tropical climates or those in cooler, mid-latitude climates, there exists clear evidence of the manifold risks associated with extremely high temperatures, including for human health (Gasparrini et al. 2015; Vicedo-Cabrera et al. 2021), animal welfare (Bryant et al. 2007; Dunn et al. 2014) and economic productivity (Steffen et al. 2019). Similar stark evidence shows both the frequency and intensity of extreme heat events are increasing worldwide, in response to anthropogenic climate change (Vogel et al. 2019; Harrington 2021a; Philip et al. 2021). Despite this globally ubiquitous evidence base, extreme heat remains surprisingly understudied in New Zealand. For example, the primary metric used to characterise extreme heat across the country—including for

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central and local government risk assessments (MfE 2018)—involves identifying exceedances of 25 °C, despite a lack of evidence to justify that choice (Harrington 2021b).

Understanding how local high-temperature extremes will change with further global warming is also complicated by the limited ability of coarse-resolution climate models to capture the nuanced microclimates of New Zealand, a relatively small, mountainous country surrounded by ocean (Flato et al. 2013; Williams et al. 2016). However, the challenges of climate model fidelity overlook potentially powerful insights that can be drawn from more effectively interrogating simple observational datasets (Ranasinghe et al. 2021).

This analysis will use daily maximum and minimum temperature observations from thirty high-quality, long-duration weather stations to improve the basis for risk assessments associated with locally extreme heat in New Zealand. Specifically, this analysis will quantify how the frequency, intensity, and persistence of extreme heat events vary for different regions across the country, while also examining how regional diversity in these characteristics of extreme heat can be better accounted for in future metrics of extreme heat risk.

1.1 Data selection

Quality-controlled daily maximum and minimum temperature data were extracted for thirty geographically diverse weather stations (see Fig. 1) from the freely-available database (https://data.mfe.govt.nz/table/105056-daily-temperature-1909-2019/), made available by New Zealand's Ministry for the Environment as part of their *Our Climate and Atmosphere 2020* report (MfE 2020). Time-series of daily temperature maxima and minima were available for the period spanning 1972 to 2019 (inclusive) for all thirty stations: some stations also had additional data dating back to as early as 1928, albeit with increasingly high numbers of "missing data" days (see Supplementary Table 1). Further information on quality-control procedures relating to these station observations can be found here, https://bit.ly/3bS8zMi.

To ensure a focus on the risks associated with the present-day climate, we restrict our analysis to the 40-year period spanning 1980–2019 when calculating local heatwave thresholds in Sections 2 and 3 but otherwise consider all available data when examining historical trends of high-temperature extremes in Section 4. Section 5 offers a pseudo-global warming analysis to highlight the importance of interannual variability when interpreting future heat risks before a synthesis, and summary is presented in Sections 6 and 7.

2 Baseline exposure to extreme heat over multi-day timescales

Past assessments of high temperatures in New Zealand have mostly focused on the climatological frequency of "hot days," whereby any day was considered "hot" if temperatures exceeded 25 °C, regardless of location. Of course, characterising extreme heat in such a binary framework obscures second-order differences between locations, while also failing to capture potentially significant differences between the adverse effects of a 26 °C day versus a 36 °C day.

Figure 2 explores these details further by presenting exceedance distributions of daily maximum temperature statistics for four selected locations: Auckland, Christchurch, Hamilton, and Napier. These stations were chosen on the basis of spanning different climatic zones while also being relatively large cities (results for all thirty stations are presented in the supplementary information). The thick green line in each figure panel

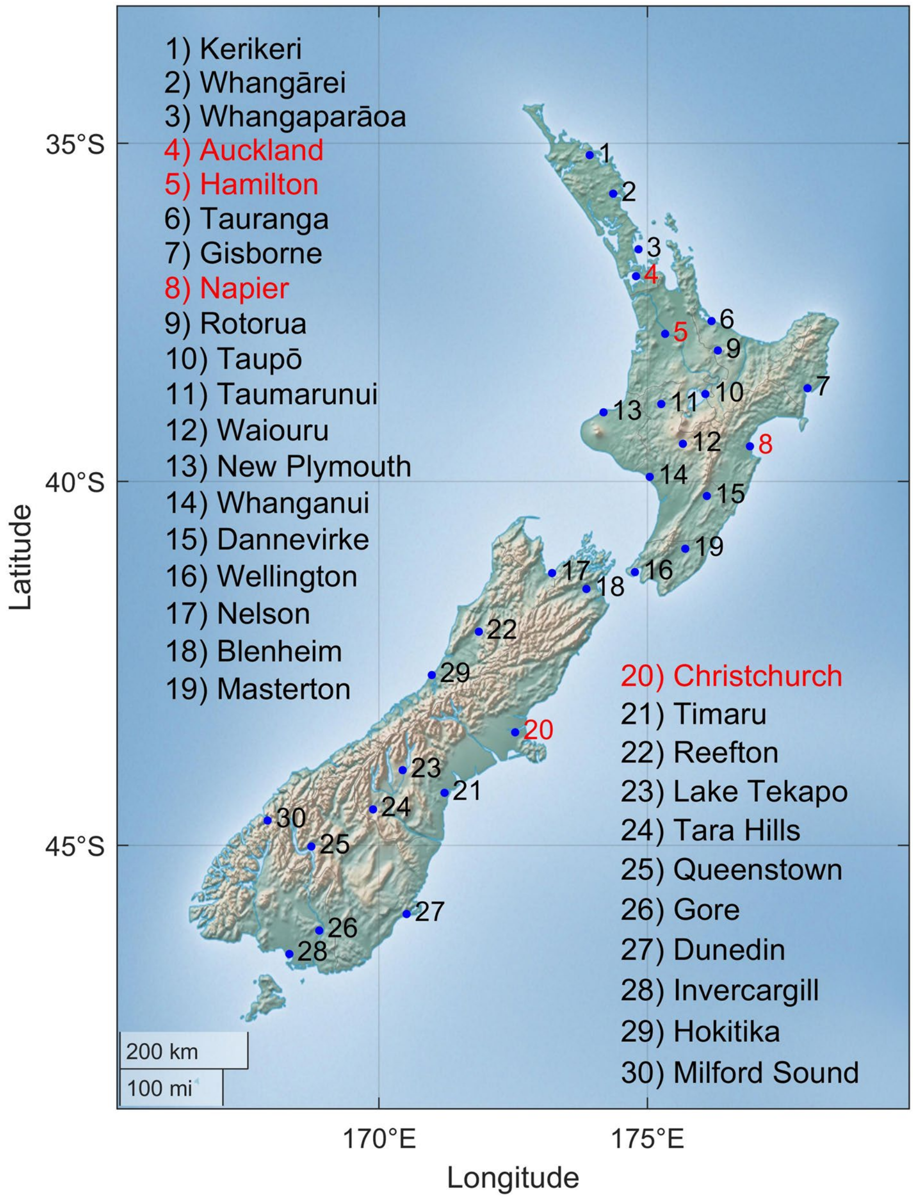

Fig. 1 Map of thirty locations across New Zealand for which weather station data were examined in this analysis. The locations in red text are those highlighted further in Figs. 2 and 7

shows the average number of days per year exceeding temperature thresholds spanning 24 to 31 °C (using data from 1980 to 2019). The green shaded regions illustrate the range between the fourth-hottest (90th percentile) and fourth-coolest year (10th percentile), when each year was considered individually.

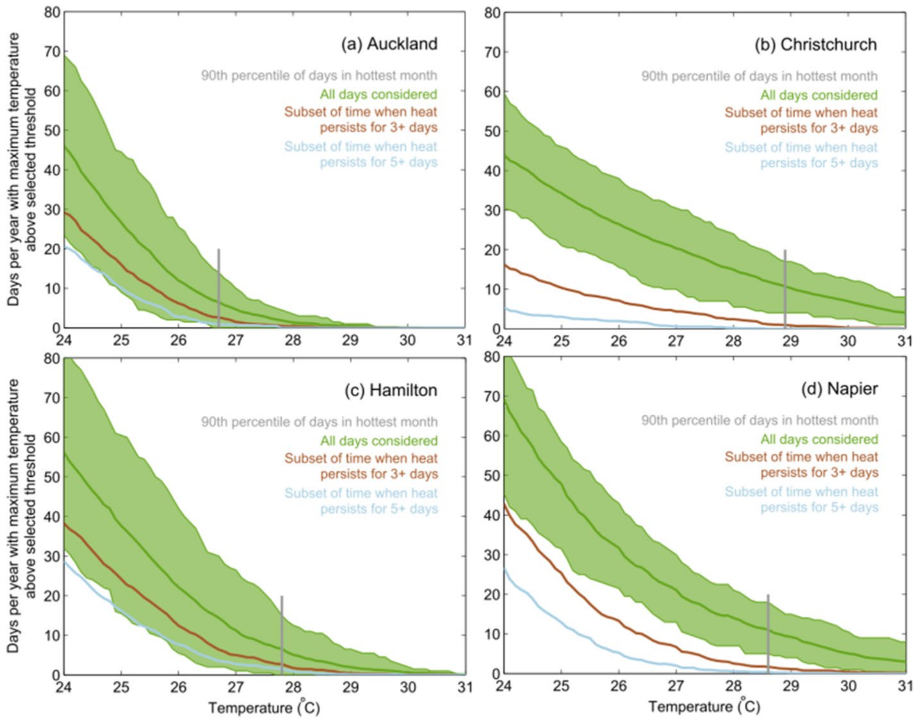

Fig. 2 Frequency of time spent exceeding daily maximum temperature thresholds over 24 °C, for four selected stations: **a**, **b**, **c**, and **d**. Data is extracted from all days across the forty years spanning 1980–2019. The thick green line denotes the average number of days per year in exceedance of the specified daily maximum temperature threshold. Of these individual days above a given threshold, the brown and light blue lines respectively show how many of these hot days are associated with hot spells which persist for at least three and 5 days, also expressed as an average frequency of exceedance per year. The green shading shows the 10^{th}–90^{th} percentile range of exceedances for each temperature threshold, when considering each of the 40 years individually. For reference, the grey vertical line denotes the climatological $90.^{th}$ percentile of daily maximum temperatures across all February days (the hottest month of the year)

While all four locations experience a comparable number of days per year hotter than 25 °C on average, clear differences can be seen in the shape of the temperature distribution and with respect to interannual variability around these mean results. For example, the eastern stations of Christchurch and Napier both tend to have a long distribution tail, with 29 °C being exceeded some 10 days per year on average. But they also exhibit lower levels of variability around these numbers, with differences in the number of extreme hot days between the coolest and hottest years varying by no more than 20 days. By contrast, both the northern stations of Auckland and Hamilton show fewer occurrences of extreme hot days but also higher levels of year-to-year variability. Indeed, the hottest 10% of years in Hamilton see a threshold of 26 °C exceeded on at least 40 occasions while the hottest 10% of years in Christchurch exceed the same threshold only 36 or more times—this despite the fact that an average Christchurch summer sees 25 exceedances and Hamilton only 21.

As well as resolving regional differences in the statistical properties of extreme heat at daily timescales, Fig. 2 (and Figures S1-S30) also offers insights relating to the temporal persistence of extreme hot spells for the four case study locations. Specifically, we calculated the proportion of all individual days above a temperature threshold which belonged to a hot spell in which that same threshold was exceeded for at least 3 (or 5) consecutive days in total. The corresponding results are presented (for an average year only) as the brown and sky blue lines in Fig. 2.

Comparing across locations, it becomes clear that the majority of extreme hot days seen in Christchurch occur as 1- or 2-day hot spells only, with a remarkably small fraction of days belonging to hot spells lasting 3 days or more. Such a result is consistent with our understanding of the meteorological drivers of extreme heat over the east coast of the South Island: strong north-westerly winds are needed to advect warm, moist air over the Southern Alps, before air temperatures rapidly warm from a combination of the föhn effect and sensible heat flux over the Canterbury Plains (Macara 2016). However, these weather systems are associated with inherently unstable flow regimes and therefore rarely persist over one region for a long period (Macara 2016). By contrast, most locations in the upper North Island (as exemplified by Hamilton and Auckland in Fig. 2) experience more than half of their hot days in the form of protracted hot spells lasting at least 5 days.

3 Defining local heatwaves using historical data

To improve the management of heat-related health and economic risks, as well as to assist the preparation of climate change adaptation plans, localised definitions of heatwaves have become commonplace in communities around the world (Matthies et al. 2008; Perkins and Alexander 2013). Here, we re-examine the temperature data presented in Section 2 to develop a transparent method of defining local heatwave thresholds across New Zealand.

3.1 Selecting heatwave thresholds on the basis of relative rarity

First, temperature data are re-analysed to identify all discrete heat events for which different integer thresholds of daily maximum temperature were consecutively exceeded for a variety of *N*-day timescales, with *N* spanning from 1 to 10 days. Further details are provided in Table 1 for an example station (Christchurch), with results for all stations presented in the Supplementary Information.

Next, we applied two expert judgements: the first was choosing to primarily focus on relatively extreme 3-day hot spells (brown lines in Fig. 2; pink shaded row in Table 1), broadly following the recommendations of Perkins (2015). Second, we chose to select an integer temperature threshold (29 °C for Christchurch) to define heatwave events at each station, such that approximately ten unique events (hereafter "heatwaves") had occurred there over the last 40 years, each of which lasting 3 or more days. Because only integer temperature thresholds were considered, the subsequent heatwave count did end up varying for different locations, ranging between 7 and 17 events (see Tables S2-S31). For the Christchurch example presented in Table 1, there were 29 separate occasions where daily maximum temperatures exceeded 28 °C for 3 or more consecutive days (too frequent), while only four of those events saw 3 consecutive days above 30 °C (too rare). Thus, we opted to define a heatwave in Christchurch as *any period of (at least) 3 consecutive days when maximum temperatures exceeds 29 °C*, a criteria met eleven times between 1980 and 2019.

Table 1 Absolute frequency of extreme hot spells in Christchurch for the 40-year period spanning 1980–2019. The top row shows the number of individual days during which daily maximum temperatures equalled or exceeded each of the specified integer temperature thresholds. For example, if the daily maximum temperature on 1 day was recorded as 27.3 degrees, this would be recorded as an additional day in all columns up to and including the "27 °C" threshold. The other rows of the table show the number of discrete occasions where exceedances of the specified temperature threshold occurred as part of a hot spell persisting for *at least* the specified number of days, with the third row (pink) used to select heatwave temperature thresholds (light blue). For example, the fifth row aligning with the 26 °C column contains 15 counts: this means that there were 15 separate occasions throughout the 40-year record which were associated with hot spells equal to or longer than 5 days, and where daily maximum temperatures were equal to or above 26 °C for each of these individual days. If an individual hot spell lasted seven rather than 5 days, that would be recorded as one additional count in each of the rows up to and including the seventh row, rather than up to and including the fifth row

		Daily maximum temperature threshold (°C)								
		23	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Number of consecutive	**1**	1180	1049	868	706	569	440	320	230	144
	2	531	409	314	223	169	117	77	45	17
	3	244	173	112	77	50	29	11	3	1
	4	116	71	48	36	18	8	1	0	0
	5	63	39	23	15	4	2	0	0	0
	6	33	12	5	3	2	0	0	0	0
	7	16	5	2	0	0	0	0	0	0
	8	7	1	0	0	0	0	0	0	0
	9	4	1	0	0	0	0	0	0	0
	10	3	0	0	0	0	0	0	0	0

3.2 Variations in the intensity of local heatwaves

As seen in Fig. 3a, applying this framework for all stations yields local heatwave thresholds ranging from 23 to 30 °C across the country. Most of the northern half of the North Island has thresholds of 27 °C or 28 °C, while values of 28 °C or above are commonplace along the eastern coast of the country, including those Central Otago stations (23–25 in Fig. 1) immediately leeward of the Southern Alps. Stations along the west and southwest of the North Island, and in the southeast of the South Island, typically exhibit heatwave thresholds of 25 °C, while even cooler thresholds are found along the South Island's west coast.

It is important to acknowledge that these thresholds have been determined solely on the basis of daytime maximum temperatures persisting for consecutive days. While the severity of daily maximum temperatures indeed represents the primary determinant of adverse health outcomes from extreme heat (Hajat et al. 2010; Mayrhuber et al. 2018; Ebi et al. 2021), minimum overnight temperatures also play an important role when contextualizing the overall risks associated with a heatwave. For example, if temperatures cool significantly overnight, this can help to offset the accumulation of risk otherwise associated with extended periods of extreme daily maximum temperatures (Scalley et al. 2015).

In this context, Fig. 3b reveals the most common daily minimum temperatures recorded at each station, when averaging across all recorded heatwave days. While most locations in the North Island experience overnight temperatures averaging over 16 °C during heatwave periods, there are distinctly cooler regions found in the South Island.

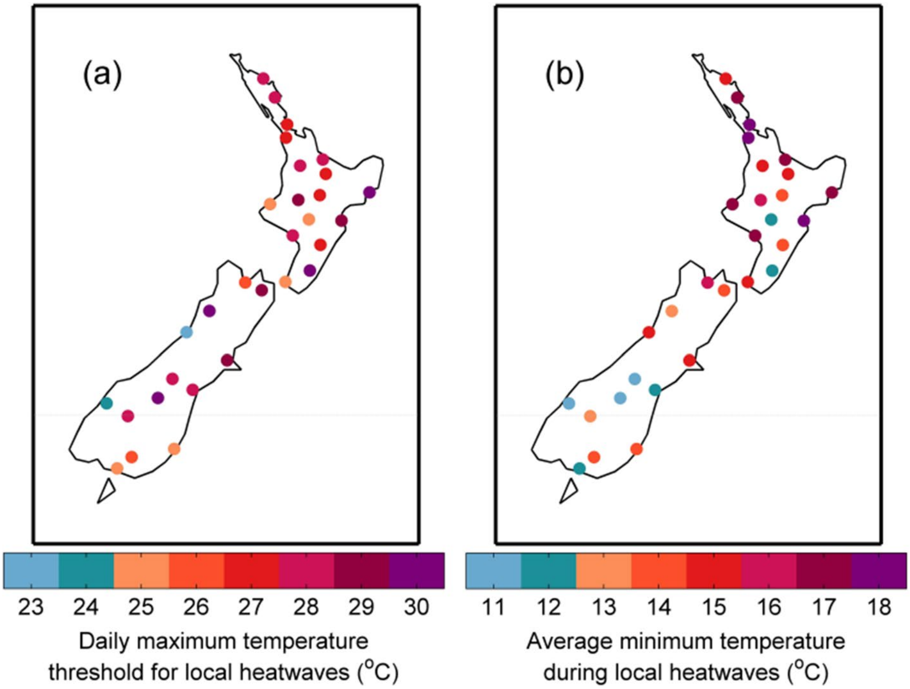

Fig. 3 The left-hand panel presents the daily maximum temperature threshold (**a**) used to define local heatwaves for each of the thirty stations considered in this study. This integer threshold is designed such that each station experienced exceedances for continuous 3-day periods approximately ten times (varying between 7 and 17 depending on location) over the 40-year period considered (1980–2019). The right-hand panel (**b**) shows the average daily minimum temperature experienced across all heatwave days (rounded to the nearest integer)

Selected stations in Central Otago, particularly Lake Tekapo and Tara Hills, exhibit overnight temperatures averaging only 11 °C during local heatwaves, suggesting that relative risks in these regions could be less pronounced, despite temperatures regularly exceeding 30 °C during the day in heatwave conditions.

When further considering the full distribution of daily maximum and minimum temperatures in Fig. 4, a clearer understanding of the diversity in temperature extremes seen during locally-defined heatwaves emerges. As is perhaps expected, given that all heatwave days have been defined with a prescribed lower bound for maximum temperatures, variations in heatwave severity during the hottest time of day are largely small: most stations have an interquartile range of less than 2 °C when considering maximum temperatures from all heatwave days. By contrast, this range is nearer 3–5 °C for corresponding overnight temperatures. Combined, the full statistics of Fig. 4 show the limited potential to discriminate heat-related risks during heatwaves on the basis of exceptionally cool overnight temperatures: arguably, only those stations at higher elevations in the North Island (Waiouru) and the aforementioned Central Otago stations show significant departures from overnight temperatures also seen elsewhere.

Finally, to consider the potential of alternative proxies for extreme local heat, Fig. 4 further includes grey bars to denote the 90th percentile of daily maximum temperatures across all February days (FQ90)—a metric which is clearly less rigorous than the heatwave

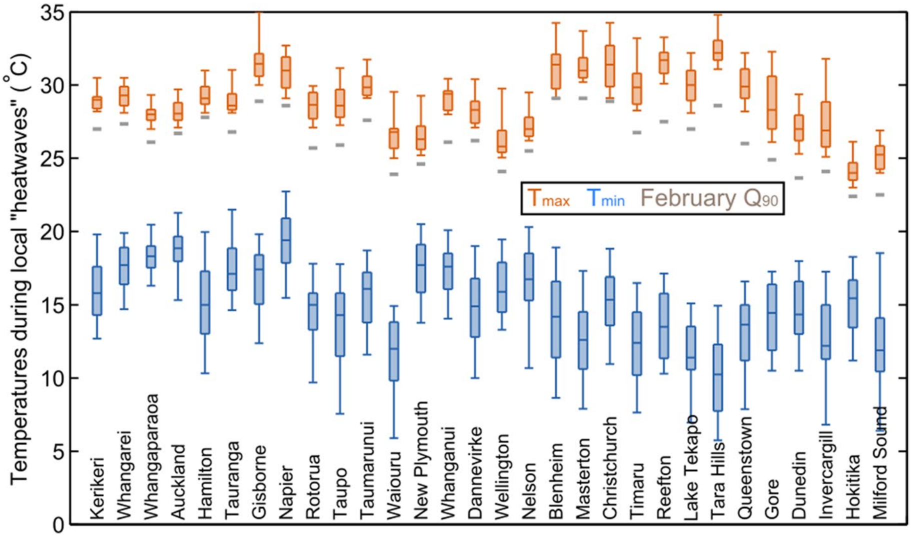

Fig. 4 Box-and-whisker plots showing the distribution of daily temperature maxima (orange) and minima (blue) during all local heatwave days, for each of the thirty stations. The boxes show the interquartile range of the distribution; the whiskers show the 5th and 95th percentile of all heatwave days. The grey bars further denote the climatological 90th percentile of daily maximum temperatures across all February days (the hottest month of the year) for each station

thresholds introduced in Section 3.1, but nevertheless offers value by being simple to understand. We find that FQ90 happens to approximate the more complex heatwave thresholds in a few locations, like Auckland and Christchurch. More generally though, stations tend to exhibit an FQ90 value one or two degrees cooler than their corresponding heatwave threshold (the lower bound of the orange distributions).

4 Historical changes in mean and extreme temperatures across New Zealand

In the context of worsening anthropogenic climate change, it is important to also understand how extreme summer temperatures have changed in New Zealand over recent decades. Examining these changes is particularly important given that New Zealand was one of the few regions for which the confidence of attributable increases in the frequency of hot extremes was judged to be low by Working Group 1 of the Intergovernmental Panel on Climate Change in their Sixth Assessment Report, owing to a lack of supporting evidence in the peer-reviewed literature (Seneviratne et al. 2021).

4.1 Recent changes in the intensity of summertime heat

Figure 5 shows time-series of daily temperature maxima (T_{max}) averaged over all January and February days for each station, with anomalies presented with respect to a 1981–2000 baseline. As an example, each purple marker in the middle figure panel shows the median T_{max} anomaly based on all January and February days for that year and the nine previous

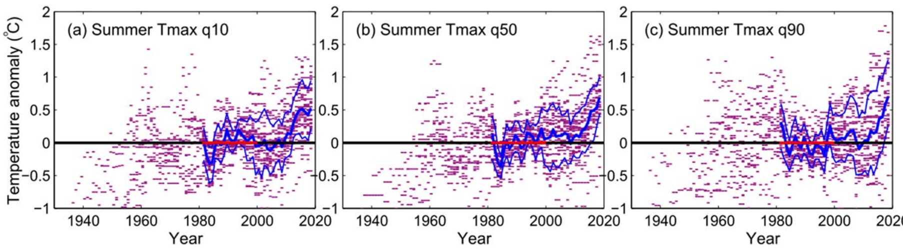

Fig. 5 Time-series of average daily maximum temperature anomalies during the months of January and February, across all thirty stations. Each purple marker denotes, for a single station, the Nth percentile of daily maximum temperatures across all days in January and February, for the 10-year period ending on the year with the data point marked, where N is 10, 50, and 90 for panels **a**, **b,** and **c.** All available data across all thirty stations are presented on each panel, as an anomaly with respect to a local 1981–2000 baseline period (red horizontal line). All stations have data post-1972, while some stations have data dating back to the 1920s: the thick and thin blue lines in each figure show the median and 16th–84th percentile range of anomalies for the time period where data exists for all stations

years (10-year running periods help to reduce sampling uncertainty), separately for each of the thirty stations.

As an illustrative exercise, we also consider each year for which 10-year running anomalies could be calculated for all thirty stations and highlight the mean anomaly for each year from these thirty data points (thick blue line), along with the corresponding 16th-84th percentile range (approximating a one standard deviation range; thin blue lines). Since temperature data were available at all stations from only 1972, the first such end year with blue lines presented is 1981 (which considers data over the 1972–1981 period).

Results show a range of decadal fluctuations pre-1980, none of which are robust across all stations (not shown), followed by a clear increase in the magnitude of summertime temperatures over the last 20 years. Specifically, the 10 years spanning 2010–2019 is more than 0.5 °C warmer than the baseline period for the median station, with consistent increases in the 10-year running mean temperatures seen year-on-year since 2000–09. This trend of rising temperatures is robust across all stations and whether considering the 10th, 50th, or 90th percentile of summertime temperatures, thereby offering confidence that a signal of summertime warming has in fact emerged from internal variability (Hawkins et al. 2020), even when using a relatively recent baseline period of 1981–2000 (Hawkins and Sutton 2015). Furthermore, the lack of any discernible differences between Figs. 5a and c suggests that these increasing maximum temperature anomalies are mostly emerging through a uniform shift of the distribution mean, rather than through a combination of changes in both the mean and shape of the distribution.

4.2 Recent changes in the frequency of extreme summer heat

Figure 6 similarly considers historical changes in summertime heat across all stations, this time examining changes in the frequency of extreme heat by looking at exceedances of the 90th, 95th, and 99th percentile of T_{max} across all January and February days (again relative to a 1981–2000 baseline period). While recognising that a running "change in probability" metric necessarily centres on unity for the baseline period, these results nevertheless show negligible changes earlier in the twentieth century, before a signal of more frequent hot

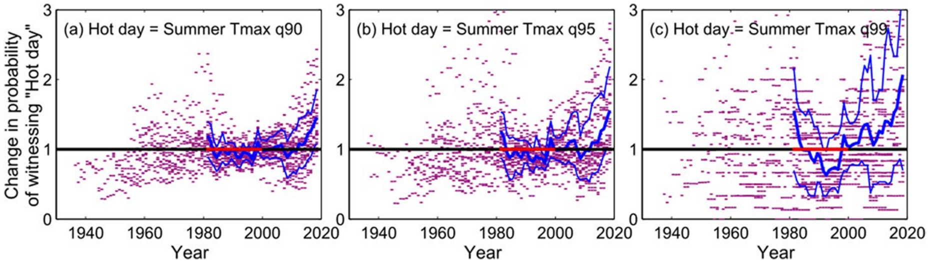

Fig. 6 Same as Fig. 5, but showing running 10-year average changes in the probability of experiencing locally defined hot days across all thirty stations, where a hot day is defined in each panel as respectively exceeding the local 90th (**a**), 95th (**b**), or 99th (**c**) percentile of daily maximum temperatures over all January and February days between 1981 and 2000

days begins to again emerge over the last twenty years. Such patterns of change are robust even when considering alternative baseline periods (Figure S31).

The variability between stations becomes more pronounced when considering increasingly higher percentile thresholds, which is an expected outcome of reducing the sample size from which to draw conclusions. Despite this, the time-evolution of changes in hot day probability for the median station remains robust across the three hot day definitions, increasing by at least 50% when comparing the most recent 10-year period with the late-twentieth century baseline.

5 Understanding the emergence of future changes in extreme heat

Understanding how further increases in global temperatures will propagate to affect local extreme heat risks is another critical step for local and national decision-makers in New Zealand, particularly to ensure appropriate and proportional response measures can be developed.

To do so, Figs. 7a and c show the distribution of all daily maximum temperatures observed in Christchurch and Auckland between 1980 and 2019 during the hottest months of January and February (≈2360 days). Using these distributions, five categories of "hot day" are considered for each location: the lower bounds of each category correspond to the 80th, 90th, 95th, 99th, and 99.9th percentiles, while the upper bound of each category is the lower bound of the next one (except for the unbounded hottest category). This means that the first "hot day" category corresponds to days with temperature maxima falling between the 80th and 90th percentile of the baseline distribution, while the fraction of days falling within each of these categories is also fixed at increasingly small values (see bars on farthest left of panels b and d). Consistent with the uniform changes seen in Fig. 5, we then apply a uniform shift to each of the temperature distributions by increments of + 1 °C, + 2 °C, and + 3 °C as a simple proxy for twenty-first-century changes in local temperatures, before considering how the frequency of days falling within each of the fixed hot day categories evolve. While previous studies have found average temperatures across the New Zealand domain tend to increase at a near 1:1 ratio with corresponding changes in global mean warming (Seneviratne et al. 2021), it is important to emphasise that these prescribed shifts in the distribution of *local maximum* temperatures should not be misconstrued as being equivalent to future changes in global warming levels.

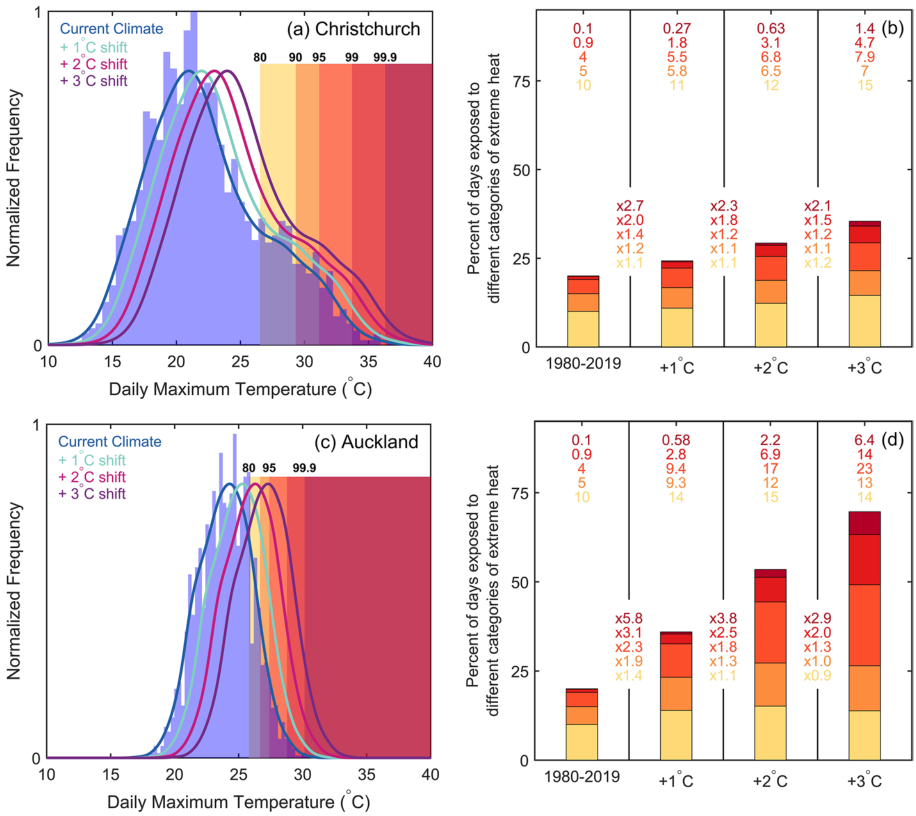

Fig. 7 Schematic representation of changes in the frequency of hot day experiences under hypothetical warming scenarios. Forty years (spanning 1980–2019) of daily maximum temperature data for the months of January and February are presented as blue histograms for Christchurch (**a**) and Auckland (**c**), alongside synthetic probability distribution functions where all temperatures are systematically shifted by + 1 °C, + 2 °C, and + 3 °C. Panels **b** and **d** illustrate the probability of experiencing different categories of extreme heat, with categories partitioned on the basis of percentiles in the current climate (with these percentiles labelled in the left-hand panels). The numbers above the bars denote the frequency of each of the hot day categories (as a percentage of all days); the numbers between the bars denote the factor by which the frequency of occurrence has increased with each successive increment of warming

Several robust patterns emerge when considering these synthetic changes in summertime heat. For example, the first increment of warming always generates larger relative changes in the frequency of all categories of extreme heat when compared with subsequent increments of change: as seen in Fig. 7d, Auckland experiences a 5.8-fold increase in the most extreme heat category after the first degree of warming but only a 2.9-fold increase in response to the third degree of warming.

Second, it is always the most extreme heat thresholds which exhibit the fastest increases in recurrence frequency with further warming. Across both stations, the number of days falling within the yellow hot day category increase from 10 to 14–15% after 3 °C of uniform warming (an increase of 50%), while the number of days falling within the most extreme hot day category rise from 0.1 to between 1.4% (Christchurch) and 6.4% (Auckland) in response to the same signal of change (an increase of 1400% and 6400%, respectively). This pattern of the most extreme temperatures increasing in frequency fastest is consistent with previous research (Kharin et al. 2018) and can be partly explained by the fact that the upper bounds of change in recurrence frequency are driven by the baseline rarity of that event: a rarer event means larger relative increases in frequency can occur in the future (Harrington and Otto 2018).

However, the clearest result of Fig. 7 is the contrasting speed with which extreme heat is changing in Auckland versus Christchurch. In Auckland, lower levels of temperature variability mean that 70% of all summer days will fall within one of the 5 hot day categories after a 3 °C rise in average temperatures: by contrast, an equivalent level of warming only results in half as many days (36%) falling into one of the hot day categories in Christchurch, due to its inherently more variable summertime climate. Similar differences exist when looking at any of the individual hot day categories and are most pronounced for the most extreme categories. In short, locations that exhibit low levels of temperature variability—as is the case for much of the northern half of the North Island—will always experience the emergence of extreme heat-related risks much faster with additional warming (Frame et al. 2017; Harrington 2021a).

6 Discussion

Lastly, to synthesize our understanding of extreme heat for each station in this analysis, Table 2 presents expert judgements of the combined, relative risks of extreme heat for vulnerable communities in each location, using a qualitative numerical scale (1 is very low risk, 5 is very high). To offer further clarity as to how we make a qualitative designation for each station (Harrington et al. 2021), additional columns are presented relating to the relative severity of daytime temperatures, overnight temperatures, and the likelihood of extreme heat persisting across multi-day timescales (stations with lower day-to-day temperature variability, as with Section 5, also experience much longer heatwaves). Its emphasis that this framework is used to disaggregate relative heat risks for different locations only within New Zealand: even stations in the highest risk categories of Table 2 will likely

Table 2 Expert judgement of the relative risks associated with extreme heat for different regions in New Zealand

Location	Risk category	Criteria		
		Daytime temperature	Overnight temperatures	Persistence across days
Napier, Gisborne	**5 (Very High)**	Very High	High	High
Kerikeri, Whangārei, Whangaparāoa, Auckland, Hamilton, Tauranga, Whakatane, Taumarunui.	**4 (High)**	High	High	High
Lake Tekapo, Tara Hills, Queenstown, Masterton, Reefton, Blenheim.	**3 (Moderate)**	Very High	Low	Moderate-High
Christchurch, Timaru	**3 (Moderate)**	Very High	Moderate	Low
New Plymouth, Nelson, Whanganui, Taupō, Rotorua, Gore.	**2 (Low)**	Moderate	High	High
Hokitika, Milford Sound, Invercargill, Wellington, Waiouru, Dunedin.	**1 (Very Low)**	Low-Moderate	Low-Moderate	Low-Moderate

experience milder impacts relating to extreme heat than many lower latitude and lower income countries around the world (King and Harrington 2018).

As Table 2 shows, both Hawke's Bay (Napier) and the East Cape (Gisborne) are classified as very high risk regions, driven by a combination of exceptionally hot heatwaves which often persist for more than 3 days, along with little respite being offered by high minimum temperatures overnight. Similarly, nearly all stations in the northern half of the North Island have been classified as high risk: these stations have local heatwaves which can last for exceptionally long periods, and with minimal cooling overnight, although the magnitude of daytime temperature maxima tends to be lower than Napier and Gisborne.

Included in the "moderate" risk category are many stations situated in the rain shadows of mountainous regions: they all share the characteristics of having extremely high temperatures during local heatwaves, but any health impacts are likely tempered by each heatwave day being interspersed by much cooler temperatures overnight (averaging 12 °C or below). Christchurch and Timaru have also been classed as moderate-risk locations, but this choice was made primarily because local heatwaves regularly failed to persist for more than 2 days as opposed to temperatures dropping markedly overnight.

All remaining stations are categorised as either low or very low risk. Many of these communities are either coastal, preferentially exposed to cooler weather systems arriving from the south of New Zealand, or situated next to lakes at higher elevations: all of these factors contribute to summertime temperatures remaining cooler than other parts of the country, even during relatively extreme events.

Finally, it is important to acknowledge the absence of any humidity considerations in this study. This is primarily the result of data constraints: high-quality station observations of hourly relative humidity (daily-mean data is insufficient to meaningfully quantify heat stress (Vanos et al. 2020)) are only available for 28 years at some stations, with many stations having even shorter records. Focusing on temperature-only heatwave metrics does offer a more useful benchmark for future climate change studies, since bias-correcting climate model representations of heat stress maxima is more complex when compared with adjusting for temperature maxima alone (Sippel et al. 2016). However, future research should be prioritised to examine the characteristics of recent heatwave events in New Zealand using both humidity-based heat stress metrics and temperature-only approaches.

7 Summary

Increases in the severity and frequency of extreme heatwaves are one of the clearest manifestations of a warming climate (Perkins-Kirkpatrick and Gibson 2017). While initial research has pointed to similar outcomes also emerging over New Zealand (Harrington 2021b), there remains a lack of published research as to how extreme heat events are already affecting individual communities in New Zealand. Of course, local decision-makers and public health practitioners need an understanding of the basic characteristics of extreme heat events in the current climate before they can meaningfully prepare for the worsening effects of a warmer future. This analysis was intended to address these information deficits by offering a comprehensive assessment of the severity, persistence, and frequency of locally extreme heatwaves for thirty locations throughout New Zealand (Sections 2 and 3). Further, we have quantified recently observed changes in extreme heat

(Section 4), as well as offering insights as to how future changes in mean temperature can be understood in terms of influencing the recurrence frequency of extreme hot days (Section 5).

Our synthesis helps to reveal which regions in New Zealand are more (or less) susceptible to the adverse impacts of extreme heat, along with supporting evidence to explain our expert judgements. We have also quantified with unprecedented detail how the statistical characteristics of extreme heat can vary for different parts of the country, and how further changes might emerge in the future. Combined, this information will enable local councils, health providers, and central government to work from a common evidence base, a crucial step in ensuring local communities can successfully adapt to the heatwaves of tomorrow.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-022-03427-7.

Author contribution LJH conceived the study and performed the data analysis. LJH and DF both contributed equally to the writing of the manuscript.

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Data availability All data are publicly available via https://data.mfe.govt.nz/table/105056-daily-temperature-1909-2019/.

Declarations

Ethical approval Not applicable.

Consent to participate and publish LJH and DF all declare their consent.

Competing interests The authors declare no competing interests.

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