Trend analysis on frequency of New Zealand climate extremes

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Abstract

NIWA publishes monthly climate summaries which report on the occurrence of extreme climate and weather events. These summaries provide context to present-day observations with respect to the historical record at stations located throughout New Zealand. In the last decade, NIWA has reported many record-setting high temperature extremes in the climate summaries, with comparatively few record-setting low temperature extremes. In this study, we have generated ranked temperature and rainfall data iteratively from 1951 to 2020 and assessed if the trend of occurrences of these extremes (high & low) in New Zealand is changing. To do this, we calculated an extremeness ratio, which is derived by normalising the observed extremes with an expected probability of an extreme based on no long-term warming. We found that, in the last decade, on average, high monthly mean temperature extremes in New Zealand are increasing 4-5 times larger than expected in a climate with no long term warming. We also examined New Zealand's homogenised seven-station temperature series and found a similar trend for mean temperature extremes. In addition, we calculated the mean temperature extremes taking the climate warming trend (~ 1° C per century) into account and found that the rate of increase in extremes is faster than the rate of increase in mean temperature. We also find a positive trend in both high and low rainfall extremes with the low rainfall trend most prominent in eastern New Zealand.

1. Introduction

1.1 Background and context

Many National Meteorological and Hydrological Services issue monthly bulletins containing data from a selection of stations within the country and which may include monthly averages, extremes, and other statistical data (WMO, 2018). These bulletins provide useful information on climate and its variability (WMO, 2018) and often give historic context to contemporary climate observations.

Starting in 2008, New Zealand's National Institute of Water and Atmospheric Research Ltd. (NIWA) has routinely produced monthly, seasonal, and annual climate summaries, and these are primarily disseminated to end users via online publication (NIWA, 2021a). These summaries describe observed temperature and rainfall throughout representative geographical regions of New Zealand, and they highlight any extreme weather and climate events that have occurred. There is an extensive network of climate stations operating throughout New Zealand (data available at cliflo.niwa.co.nz) and data from these stations are used to inform the climate summaries.

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NIWA provides historic context to contemporary observations of climate data by generating rankings for its monthly climate summaries. Specifically, climate data for a given month at a given climate station will be compared with relevant contemporary and historical data for that location to obtain a ranking. A convention has been adopted that if the present ranking is among either the top-four or bottom-four, then the data and associated ranking are presented in the climate summaries. This criterion is arbitrary, but allows NIWA to highlight climate stations where the observed climate for a given period has been particularly notable. We follow this convention, and refer to data values with a top-four or bottom-four ranking as an extreme.

NIWA presents monthly rankings for temperature, rainfall and wind. In the past, rankings of total hours of sunshine were also presented by NIWA. However, this was discontinued in recent years, due to the complexity associated with the comparison of historic sunshine totals measured by manual instruments with contemporary totals from electronic sensors (Legg, 2014; Srinivasan et al., 2019).

The global climate has changed, and human activities are estimated to have caused approximately 1.09°C of global warming above pre-industrial levels (IPCC, 2021). According to the record of global land and ocean temperatures spanning 1880-2020, the seven warmest years have all occurred since 2014, while the 10 warmest years have occurred since 2005 (NOAA, 2021). As a result of such climatic change, the probability of establishing new warm monthly temperature records worldwide has increased, on average five times larger than expected in a climate with no long-term warming (Coumou et al., 2013). Studies in the United States of America and Australia have assessed the changes in occurrence of record high and low daily temperatures (Meehl et al., 2009; Trewin and Vermont, 2010), showing that high temperature extremes have become increasingly more common than low temperature extremes in both countries.

New Zealand's climate has also changed, with the nationwide average temperature rising by a rate of 1.04 ± 0.25°C per century over 1909-2020 (NIWA, 2021b). Since 1998, nine years (1998, 1999, 2005, 2013, 2016, 2017, 2018, 2019 and 2020) have ranked among New Zealand's ten hottest on record (the remaining top-10 hottest year being 1971), with the highest nationwide average temperature of 13.45°C observed in 2016 (NIWA, 2021b). In light of such regularly high nationwide temperatures in recent times, it is reasonable to expect that individual locations throughout New Zealand will have also observed record or near-record high temperatures.

Indeed, for regular users of NIWA's climate summaries, a contemporary imbalance in the number of record or near-record temperature observations is readily apparent. Specifically, there have been many more occurrences of record or near-record high monthly temperatures relative to record or near-record low monthly temperatures. This imbalance was highlighted by Macara and Srinivasan (2018), who showed that from August 2012 to October 2018, there were 1271 instances of record or near-record high monthly mean temperatures at New Zealand locations, compared to just 105 instances of record or near-record low monthly mean temperatures. Whilst this is a stark difference, it is notable that the time period assessed (6 years) is relatively short, and hence the imbalance over longer time scales cannot be assessed. Furthermore, the number of station groupings (Section 2.1.1) examined were not static over the assessed period.

1.2 Study aims

The aim of this study is to provide additional context to climate records published in NIWA's monthly climate summaries, particularly with respect to changing frequencies and trends of occcurrence of extremes. How do the frequencies of these published extremes differ from those of a stationary climate (Section 3.1, Section 3.2) for a static set of station groupings, and are the trends in temperature extremes consistent with New Zealand's observed warming (Section 3.4)? By quantifying the changing frequency of record or near-record climate observations in the context of climate summaries in New Zealand, we will determine if the trends are significant and also whether discrepancies between high and low occurences are apparent.

Climate summaries published in New Zealand typically use regional groupings of non-homogenised station records to portray or represent the climate of areas of interest, such as population centres or homogeneous geographic regions. These groupings are further described below. To assess the validity of presenting extremes based on groupings, we will compare the non-homogenised station grouping mean temperature extremes against those derived from NIWA's seven-station homogenised dataset (Mullan et al., 2010) in Section 3.3. Finally, we also compare the frequency of mean temperature extremes from the seven-station series to the background climate warming trend in Section 3.4. By taking the positive trend of mean temperatures into account, we aim to test whether or not the occurrence of extremes is consistent with what might be expected due to a warming climate.

2. Methodology

2.1 Climate extremes calculation process

2.1.1 Station groupings

Over time, New Zealand's climate monitoring network has changed, with new stations opening, stations closing, instrumentation changes, station location changes, and potential station exposure changes. This poses a challenge to providing un-biased historic context for contemporary observations for New Zealand locations. For example, if a station has been operational for only five years, then it is not particularly notable for that station to observe its highest monthly mean temperature on record.

To account for the dynamic nature of the climate monitoring network in New Zealand, 190 station groupings have been established. These groupings encompass open climate stations (i.e. operational) and additional closed climate stations (i.e. no longer operational) for cities, towns and other rural or isolated areas of the country where climate data are available. The stations comprising each grouping have been carefully selected to ensure their overall climate characteristics are comparable, and representative of the climate at the grouping location. As such, there is more than one grouping at several of New Zealand's main centres. An example of this is Wellington city, where there are two groupings. One is based on stations at Kelburn, a hillside suburb to the northwest of the central business district (CBD), whilst the other is based on stations at the Airport, a low-elevation coastal location to the southeast of the CBD. Separate groupings are necessary here because the difference in elevation and exposure to prevailing winds means that the site clusters have a different rainfall and temperature climatology.

NIWA uses these station groupings when generating location-based rankings listed in its Climate Summaries. The current climate value is compared against all values from all stations within the group, without any regard for homogeneity between one station's record and another. This approach is used due to the practical limitations of performing homogeneity checks in real-time, as well as the complexity associated with developing homogenous historic records.

Data homogeneity is a major issue in the assessment of changes in observed climate (e.g. Trewin and Vermont, 2010). In order to address this, NIWA's seven station series was also used in this study as an independent benchmark of the temperature trend. This series comprises a homogenous temperature record for seven New Zealand locations dating back to 1909 (Mullan et al., 2010). When data from these locations are combined, they form New Zealand's nationwide reference temperature time series, which is regularly updated in NIWA's Climate Summary reports.

2.1.2 Method of calculation

For this study, extremes have been calculated so as to emulate the existing procedure which is part of NIWA's National Climate Database automated monthly statistical processing. This processing includes quality control checks and standard statistical calculations such as monthly means. For the indices described in Table 1, the rank of the current month's value is calculated for each station grouping. If the value is ranked in the top four it is classified as extreme and stored in the database along with its anomaly with respect to the 1981-2010 climate normal value. In the case where the value of an extreme is same as a previous extreme, an 'equal' rank is assigned.

To be eligible for an extreme ranking, the station grouping must have a record length of at least 20 years. The automated ranking process has been operational only since the year 2008. However, for this study rankings have been calculated retrospectively back to 1951 for only those station groupings with records starting at or before 1931. Precalculation of the initial 4th ranked extreme value prior to the year 1951 for each station grouping was done separately and the ranking calculation process was run from 1951-2020 to archive all the monthly extremes that were observed during this period. Querying this archived record enabled us to construct the timeseries of frequency of extremes that occurred from 1951 to 2020.

2.2 Extremeness ratio

As discussed in the previous section, extremes are ranked based on the historical record and any value that exceeds a previous historical threshold becomes a new extreme. This means that the threshold for a new extreme changes over time. In the case of high extremes the threshold increases and for low extremes the threshold decreases with every new extreme event. As a result, an extreme that occurs later in a timeseries carries more weight, i.e. is more unusual, than an extreme that occurred prior. This behaviour is depicted schematically in Figure 1, which shows the probability of a high extreme event decreasing

Table 1: Climate indices assessed in this study. The equivalent ETSCI index abbreviation is included where relevant (https://climpact-sci.org/indices).

Climate Index	ETSCI code	Description
Mean air temperature	TMm	Monthly average air temperature, calculated as the average of the monthly mean of daily maximum and minimum temperatures.
Mean max air temperature	TXm	Monthly average daily maximum air temperature.
Mean min air temperature	TNm	Monthly average daily minimum air temperature.
Extreme max temperature	TXx	Monthly highest daily maximum air temperature.
Lowest max temperature	TXn	Monthly lowest daily maximum air temperature.
Extreme min temperature	TNn	Monthly lowest daily minimum air temperature
Highest min temperature	TNx	Monthly highest daily minimum air temperature.
Total monthly rain	N/A	Monthly sum of daily rainfall totals.
Highest 1-day rain	Rx1day	Monthly maximum daily rainfall total.

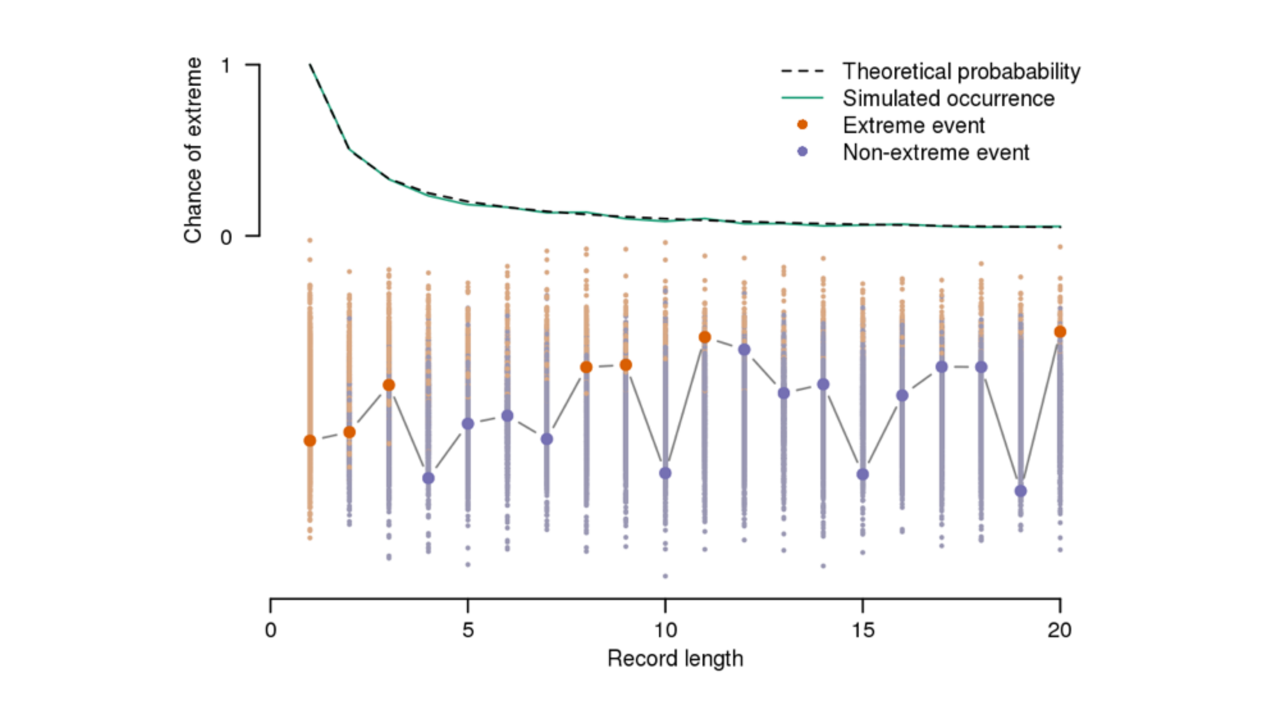

Figure 1: Simulation of extremes occurrence based on a stationary Gaussian distribution. The large orange and purple dots show record and non-record events from a single random time-series, while the smaller dots show events from 999 other realisations. By definition, the first year of all simulations is 'extreme'. The green line shows the proportion of simulated extreme events at each time step, while the black dashed line is 1/N, where N is the record length.

over time. In order to assess whether a particular climate index is producing more or less extremes than would be expected based on record length, we have used an 'extremeness ratio', *R*. This is the average of the ratio of observed extreme, *O(ext)*, against expected probability of an extreme, *P(ext)*, across all months in a year *(m)* and station groupings *(s)*:

$$R = \frac{1}{s \times m} \sum_{i=1}^{s} \sum_{j=1}^{m} \frac{O_{i,j}(ext)}{P_i(\text{ext})} \tag{1}$$

Assuming the climate is stationary, the expected probability of a new record is $1/N$ where N is the length of the record for the particular station grouping and ranking. To account for the inclusion of the top four ranked values, we have used the following equation as the expected probability of an extreme:

$$P(ext) = {}^{4}/_{N} \tag{2}$$

Observed extremes have been assigned a binary value of O=0 in case of no extreme observed for a given month and group and O=1, if there was any 1-4 ranking value observed. If the final R value for a given year is greater than 1, it implies that there were more extremes observed than would be expected based on the record lengths of the station groupings at that point. After calculating an annual series of R for each variable in Table 1, a linear trend was fitted to each series with respect to year. This was done to assess the statistical relationship of R with respect to year thereby testing the existence of any underlying trend.

3. Results

As described above, a linear model with respect to year was fitted to the annual series of R to test the null hypothesis that there is no relationship between R and year (i.e. no positive or negative trend). Using the p-value from each model we can assess whether the trend is significantly different from zero. Based on this analysis, for all high temperature extremes, we found a positive trend with high statistical significance (Table 2). We also found significant positive trends for all rainfall extremes, with low total rain extremes having the highest significance. No statistically significant trend was found for low temperature extremes except for the extreme min and lowest max temperature. Further details of the results are discussed in the following sections, where we also describe tests performed to ensure the results are not dependent on timeseries length, number of groupings or number of extremes per month.

3.1 Temperature-related trend

To show the effect of the normalisation process, Figure 2 compares the mean occurrence of unnormalised extremes against the extremeness ratio for monthly mean high temperature extremes. The mean number of unnormalised extremes was derived without applying any correction factor for the length of the record. So, if there was any top-4 ranked record, it was counted as 1 for each month and grouping, and then averaged across all groupings for the whole year. As illustrated in Figure 2, the mean occurrence of unnormalised high temperature extremes is relatively constant through this period except for last decade. Conversely, the trend in the extremeness ratio becomes increasingly positive as the record length increases, leading to an increased difference between the two trend lines going forward in time.

To ensure that our use of the top-4 extremes (normalising by $4/N$) does not impact on the validity of the results, we compared the equivalent extremeness ratio based on only the top extreme normalised by $1/N$ (Figure 2, blue line). As can be seen, both the $1/N$ and $4/N$ time-series give consistent results and therefore we have used the top four ranked extremes with an expected probability of $4/N$ for our trend analysis as this increases the sample size, improving the significance of the results.

The main trend analysis is performed from 1951 to 2020 and as a result, the number of station groupings were limited due to availability of observations from at least 1931 (as described in Section 2.1.2). This was to ensure there were at least 20 years of observation as of 1951

Table 2: Observed trend in occurrence of extremes, 1951-2020.

Climate Index	Extreme type	Estimate per year (increase in R per year)	p-value - confidence
Mean air temperature	High	0.040	>99.9%
Mean max air temperature	High	0.0411	>99.9%
Mean min air temperature	High	0.028	>99.9%
Extreme max temperature	High	0.025	>99.9%
Highest min temperature	High	0.023	>99.9%
Total monthly rain	High	0.009	>99%
Highest 1-day rain	High	0.011	>99.9%
Mean air temperature	Low	-0.002	No significance
Mean max air temperature	Low	-0.001	No significance
Mean min air temperature	Low	0.001	No significance
Extreme min temperature	Low	0.007	>95%
Lowest max temperature	Low	0.011	>99%
Total monthly rain	Low	0.011	>99.9%

and also to prevent new station groupings being added in the latter part of the timeseries. Approximately 46 temperature groups met these conditions and in order to test that these groups represent the overall trend, we compared the mean temperature trend output of these 46 groups with a set of 85 groups that met the same set of conditions from 1971 onwards. The comparison showed that the trend was similar and robust even for this shorter time period with the additional groups available post-1971 (Figure 2, black line). This comparison also highlights that the extremeness ratio is producing comparable results regardless of length of record between the groups starting from 1951 vs 1971. The groupings from 1951 were distributed evenly throughout the country except a gap in coverage from Auckland to Whangarei.

Figure 3 plots the extremeness ratio for all temperature variables (both high/low) with respect to year. As can be seen, the temperature-related variables have a strong positive trend for high extremes (Figure 3a, b, and Table 2). Mean temperature, max and min temperature variables show no trend in case of low extremes (Figure 3c and Table 2), indicating the high temperature extremes are now occurring much more frequently than low temperature extremes. Extreme daily min temperature and lowest daily max temperature have minor positive trends and show high variability around the expected value of 1. We also analysed if there were any differences in temperature related trend between east coast vs west coast and both showed similar trends for both high and low extremes in mean temperature.

3.2 *Rainfall-related trend*

For the rainfall analysis, 78 groups were used which had data available satisfying the 20 year observations condition from 1951. The results of the trend analysis are summarised in Table 2 above. Similar to temperature, we performed an analysis of mean unnormalised extremes with respect to extremeness ratio for low rainfall extremes

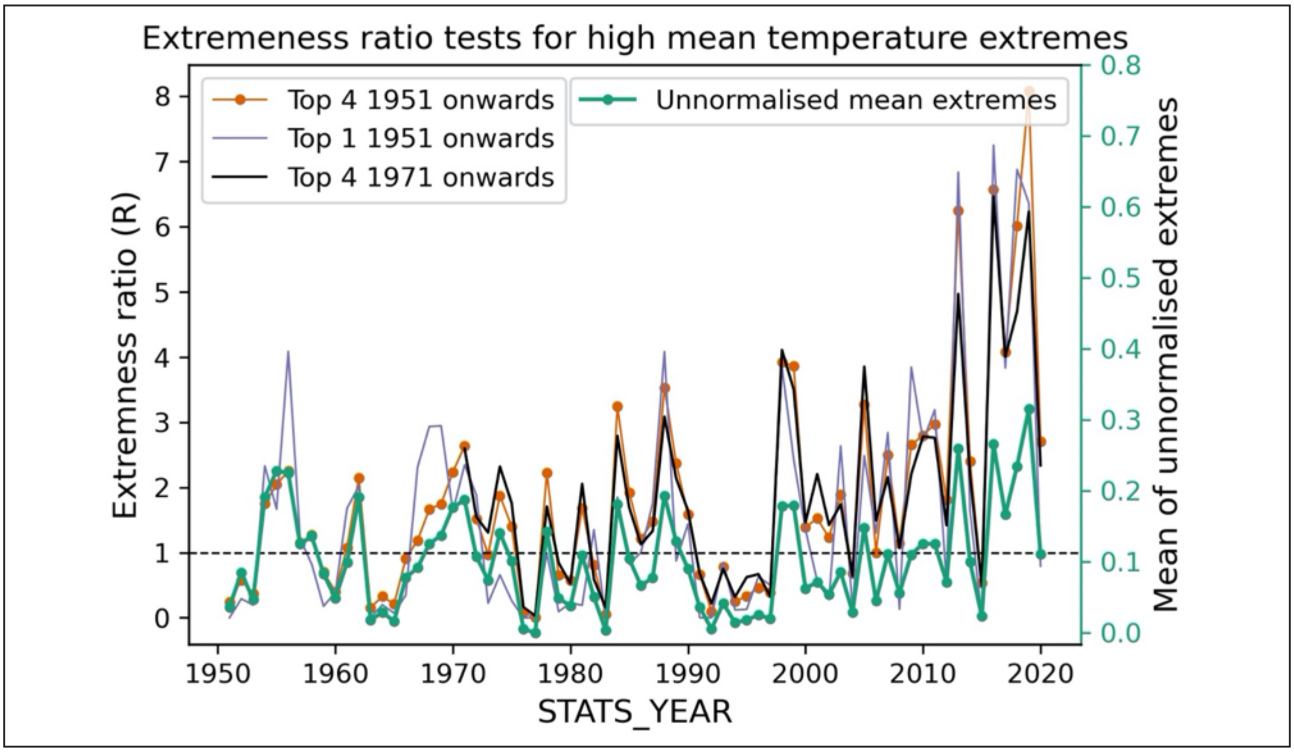

Figure 2: The annual time series of mean unnormalised extremes (green) compared with normalised extremes (orange). Also included is a time-series of normalised extremes based only on the top-most extreme (purple). Finally, the black solid line is the top-4 extremes from 1971 with additional groups following a very similar trend with top-4 extremes from 1951. The black dotted line indicates expected extremes in a stationary climate.

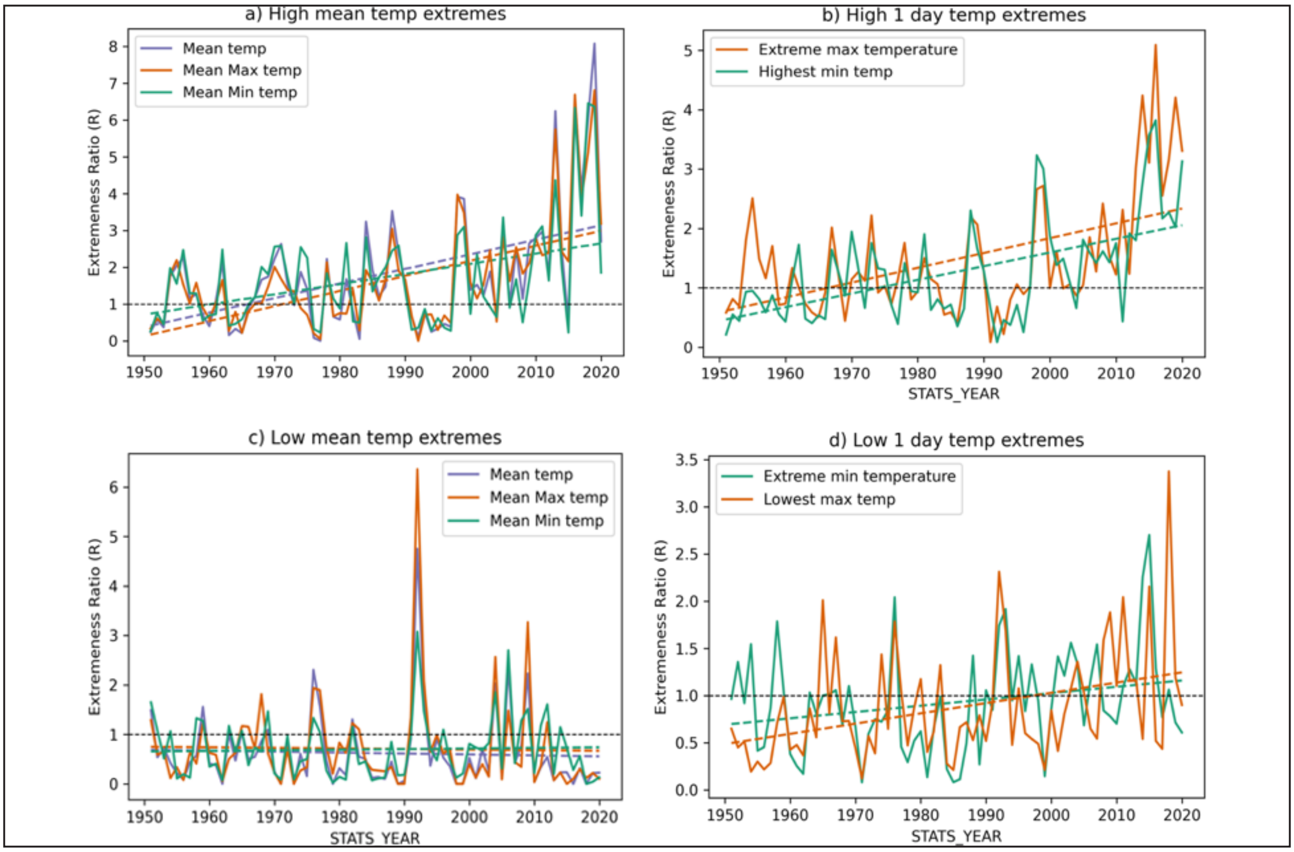

Figure 3: Results for all temperature extremes: a) high mean temperature (top-left), b) high 1-day temperature extremes (top-right), c) low mean temperature extremes (bottom-left), and d) low 1-day temperature extremes (bottom-right). Dotted lines in all panels are the fitted linear trend line corresponding to each variable.

(Figure 4a). Here we do not investigate the Top1/Top4 or post 1971 versions for rainfall extremes.

In this case, unlike temperature, the trend of mean unnormalised low rain extremes was negative and the process of normalisation to this mean raw low rain extremes adjusts the trend in the positive direction. This positive trend is in line with the overall drying trend that is represented by the total monthly potential evapotranspiration deficit (PED[1]) averaged across all the stations as can be seen in Figure 4a. We observe a statistically significant (99.9% confidence) linear relationship between PED and low rain extremes resulting in a 0.005 increase in R per mm increase in PED. In addition, Figure 4b plots the high monthly rainfall extremes trend along with high 1-day rainfall trend, both of which show a small but significant positive trend. Although small, both high and low rainfall extremes demonstrate a positive trend (Table 2) and this might be an indication of increasing variability in overall rainfall patterns.

To investigate the rainfall trends in more detail, the station groupings were separated into an 'east coast' and 'west coast' set based on the regional classification[2] system used in the climate database. The south of South Island and Northland regions were not included in either the west or east coast grouping. Figure 5 contains the extremeness ratio separated into east and west coast for both high and low rainfall extremes. The annual low extremes have similar variability in R between the east and west coasts except during the 1970s and 80s. This disagreement could be related to the changing phase of the Inter-decadal Pacific Oscillation (IPO) shown on Figure 5 with a thick

[1] https://niwa.co.nz/climate/information-and-resources/drought/charts
[2] https://docs.niwa.co.nz/library/public/NZMSmp110(1985).pdf

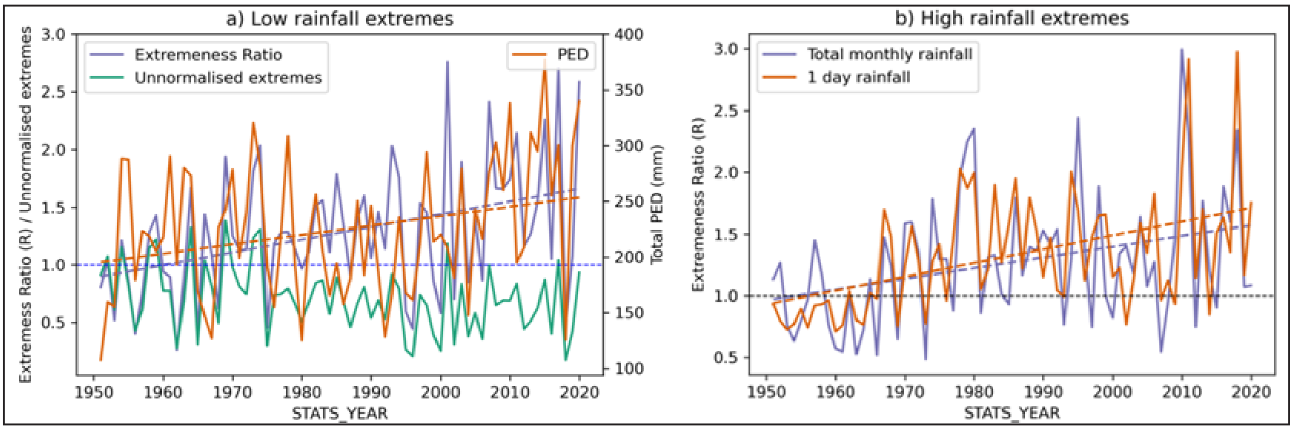

Figure 4: a) Low rain trend compared with extremes without normalisation and PED. Note: A scaling factor of 10 was applied to the unnormalised extremes so they could be included with the extremeness ratio on a single axis. b) High rain extremes (1-day rain and total monthly rain). Dotted lines in all panels are the fitted linear trend line corresponding to each variable.

green line depicting the negative phase. For high rainfall extremes, the difference between the west and east coast overall trends is small. For low rainfall extremes, an overall stronger positive trend (99.9% confidence) is observed for the east coast when compared with the west coast where very little trend (no statistical significance) is observed. This trend in the east coast is consistent with the projections of increased westerly winds in New Zealand, especially during winter and spring, thereby causing drier conditions in the east (MFE, 2018).

3.3 Comparison with seven-station homogenised series

To examine the impact of using data from station groupings that were not homogenised, extremes in NIWA's seven-station mean temperature series (Mullan et al., 2010) were also assessed using the methodology described in Section 2. We calculated the Extremeness Ratio from the seven-station series dataset and compared it against the equivalent ratio from the station groupings. As illustrated in Figure 6, the extremeness ratios of both the station groupings and seven-station series show a

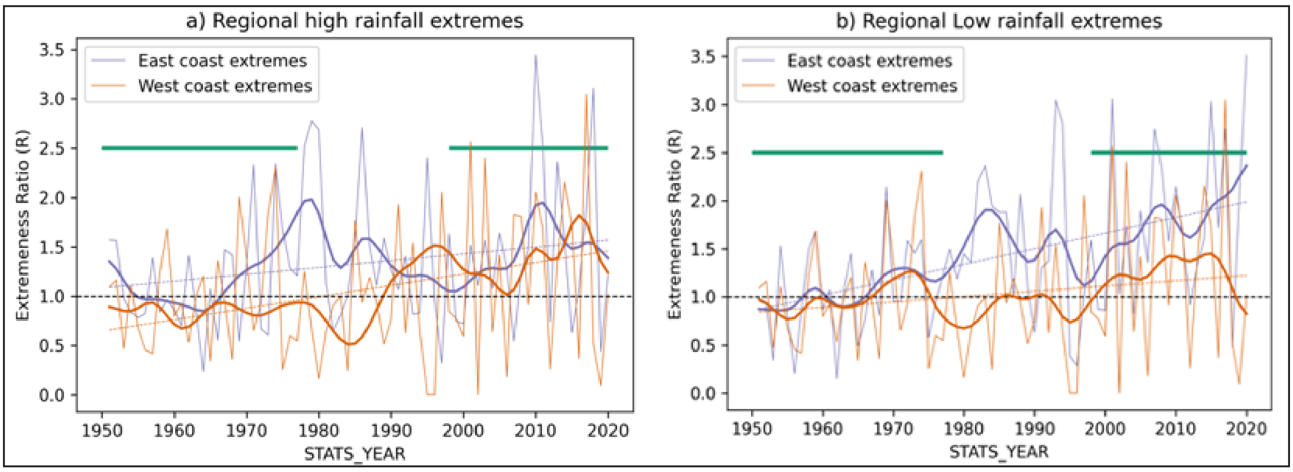

Figure 5: Occurrence of rainfall extremes, partitioned by east and west coast region. Smoothing is done using 1d Gaussian filter (sigma=2). Dotted lines in all panels are the fitted linear trend line corresponding to each region. Thick green line in the plot represents the period of Gaussian smoothened (sigma=2) IPO negative phase and the disagreement between west and east coast high/low extremes in 1970s and 1980s might be related to the changing phase of IPO.

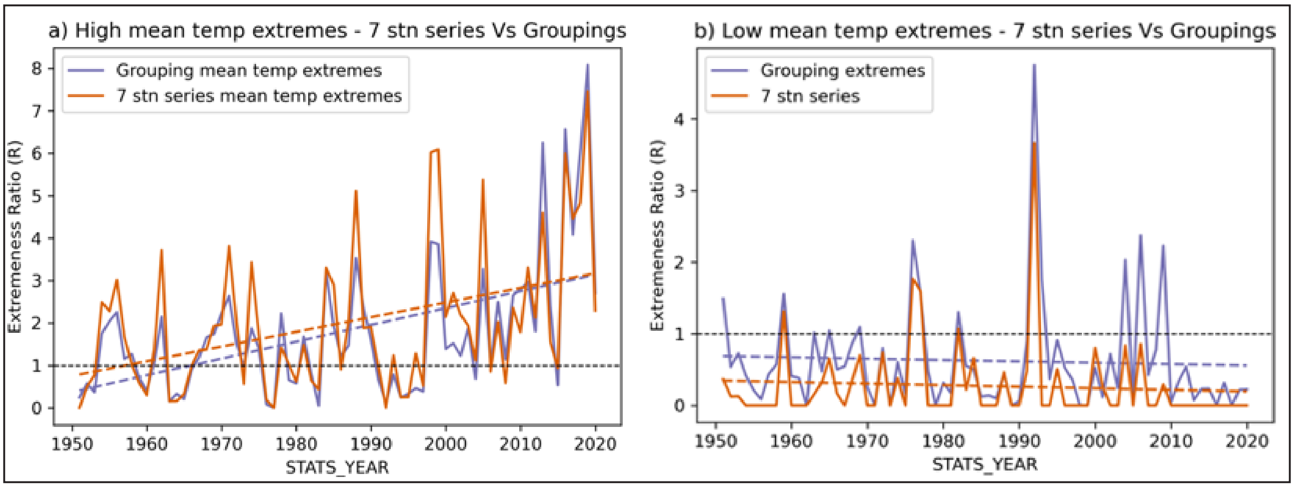

Figure 6: Seven-station series extremes vs station grouping extremes. Dotted lines in all panels are the fitted linear trend line corresponding to groupings and 7 station series mean temperature extremes.

consistent strong upward trend for mean temperature high extremes and no trend for low temperature extremes. There was a high correlation coefficient of 0.9 for high mean temperature extremes and 0.86 for low mean temp extremes between the seven-station series and the station grouping data. This highlighted that the station groupings were capturing the overall trend and variability in extremes that was observed in the homogenised dataset.

3.4 Comparison of stationary and trend-corrected extremeness ratio

As described in Section 2, we calculated our extremeness ratio assuming a stationary climate. In other words, we estimated our expected probability of an extreme based on $1/N$ law giving equal chance of an extreme based on the length of the record. Coumou et al., (2013) performed a study of mean monthly temperature extremes comparing the extremes on a stationary climate against a climate with a long-term warming trend. They calculated the extremeness ratio with expected probability of an extreme using $1/N$ (for stationary climate) and compared with an expected probability of $1/N$ + trend (for warming climate). We performed a similar comparison on the seven-station series dataset to test if the extremes were changing at the same rate as the mean temperature.

For a warming climate, we used the following expected probabilty (Franke et al., 2010; Coumou, et al., 2013):

$$P(N) \approx 4\left(\frac{1}{N} + \alpha(N)\frac{\mu}{\sigma}\right) \quad \text{and} \quad \alpha(N) = \frac{2\sqrt{\pi}}{e^2}\sqrt{\ln\left(\frac{N^2}{8\pi}\right)} \qquad (3)$$

where μ is the long-term linear trend for each station and month and σ is the short-term variability for each station and month. A multiple of 4 was included to account for the use of the top-4 extremes.

After deriving the expected probability for each station using the above equation, we derived the Extremeness ratio and compared with the $4/N$ extremeness ratio as shown in Figure 7.

By the end of the 2010s, the mean temperature extremes are on average 4 to 5 times more than expected given a stationary climate, and are 2 to 3 times more than expected given a non-stationary climate. So, after taking into account the long term temperature trend of around 1 degree per century, we are still observing on average 2 to 3 times more extremes than expected, indicating that extreme events are increasing at a faster rate than the mean temperature. This implies that the shape of the temperature distribution is also changing.

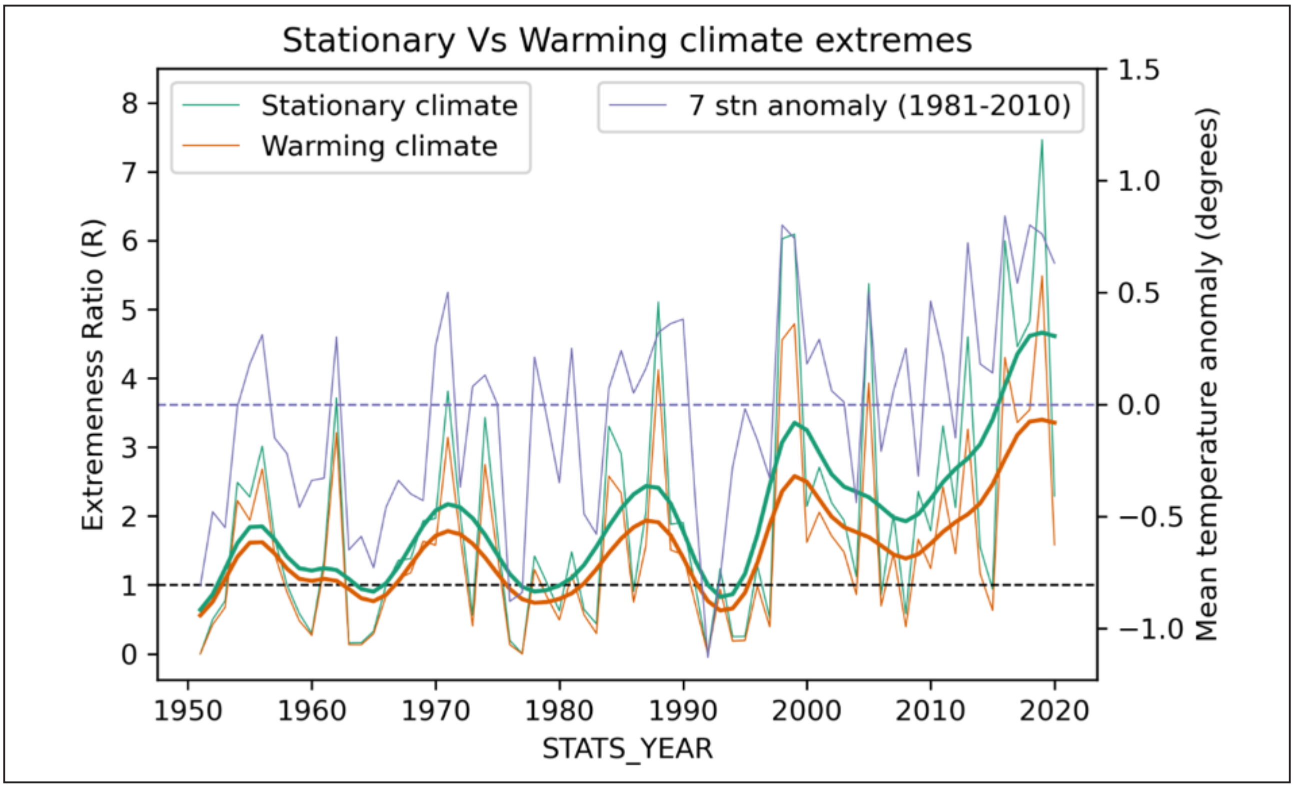

Figure 7: Blue is the mean temperature anomaly for the seven-station series (1981-2010 normal) using the right-side axis. Green is the extremes normalised assuming an expected probability due to a stationary climate. Red is the extremes adjusted using the warming climate trend estimated from the seven-station series which should follow the y=1 line, if the increase in extremes is consistent with the mean temperature trend. Smoothing is done using 1D Gaussian filter (sigma=2).

4. Conclusion and future work

In this study we derived an extremeness ratio assuming a stationary climate to represent frequencies of extremes for different temperature- and rainfall-related variables in New Zealand, from 1951-2020. We performed trend analyses and found a strong positive trend for all high temperature extremes, with extremes increasing around 4-5-fold on average in the last couple of decades in New Zealand. We could also determine from the trend that high temperature extremes occur more frequently than low temperature extremes. A positive trend for both high and low total rainfall extremes is observed, with low rain extremes mainly increasing in the east coast of New Zealand. We have also compared non-homogenised mean temperature extremes with the seven-station series and found that the station groupings were capturing the overall trend reasonably consistently in comparison with a homogenised dataset. This provides confidence that we can derive a more comprehensive New Zealand-wide picture and include variables not captured by the seven-station series. Finally, we derived mean temperature extremes after taking into account the mean warming trend and found that the rate of high temperature extremes is increasing faster than the mean temperature increase.

The result from this study provides confidence and additional context to NIWA's method of presenting climate records in the Climate Summaries, and in particular addressing scientific and public interest in how the frequency in climate extremes may be changing with long term climate change. As a next step, the extremeness ratio calculation can be operationalised and included in the monthly climate summaries to provide additional context to reported extremes. Also, the calculation of temperature extremes from the homogenised seven-station series can also be operationalised and used as a reference for temperature extremes. In future, we also intend to perform additional analyses on low rainfall extremes and its relationship with the New Zealand Drought Index (NZDI) (Mol et al., 2017) and the climate indices (Thomson., 2006). This would enable a more comprehensive comparison of drought with low rainfall extremes.

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