Weather and Climate, **27,** (2006), 3-44

Changes in New Zealand daily rainfall extremes 1930 - 2004

G. M. Griffiths*

National Institute of Water and Atmospheric Research Ltd. (NIWA)

Abstract

Atmospheric circulation has a major impact on mean rainfall in New Zealand due to the large orographic component of rainfall in this country. Since 1930, both New Zealand-average air temperatures and westerly circulation have increased, with the largest increases occurring after 1950. A detailed analysis of New Zealand extreme rainfall for two periods (1930-2004 and 1950-2004) was undertaken, using 11 indices of extremity based on high-quality daily station data. Of interest was whether extremes differed in the later (warmer) period. Regional variation in trends was strongly evident, with a west-east pattern across major mountain ranges showing increased rainfall extremity in the west, but decreased extremity and increased dry spell duration in the east, consistent with increased westerly circulation over New Zealand. This zonal pattern persisted over both periods, even against a background of warming. Index trends showed temporal consistency between the periods, except for a simple intensity measure (rainfall per rain day). Changes in extreme daily rainfalls were strongly related to changes in mean rainfall, although the relationship was weaker in the later (warmer) period. Station 1-day rainfall extremity was highly correlated to westerly circulation (zonal flow) across the country, and to a much lesser extent, meridional flow and New Zealand-averaged temperature anomaly.

1. Introduction

The February 2004 flooding event in Wanganui, Manawatu/Rangitikei, southern Hawkes' Bay and Wairarapa was estimated to have cost at least $NZ 300 million (New Zealand Herald, 24 May 2005), equating to the second largest weather-related cost in New Zealand's history (after inflation adjustment). General media and public speculation followed this event, as to whether significant changes in climate extremes had accompanied climate change – i.e. "was this climate change in action?"

In New Zealand, flooding is our most common natural hazard and floods are our largest source of insurance claims (McKerchar and Pearson, 2001). How-

*email:georgina.weathereye@gmail.com

ever, an examination of relevant literature shows little detailed information about how New Zealand rainfall extremes have changed in the past, and no answer at all to the question of why the changes have occurred.

Salinger and Griffiths (2001) analysed historical daily rainfall data (1951-1998) at 22 rain gauges across New Zealand and calculated annual indices of extremity. Very few statistically significant trends in extreme rainfall intensity were observed, but a clear zonal pattern in extreme rainfall frequency was evident, with decreases in eastern areas of both islands, and increases in the west and south of the South Island. Zonal trends in dry spell duration (defined as the maximum number of consecutive dry days) were observed, with increases at some eastern, coastal sites, but decreases almost universally elsewhere. Changes in extreme rainfall were generally consistent with changes in mean rainfall (e.g. where mean rainfall had increased, extreme rainfall had also increased and vice versa).

Other studies that have analysed historical trends in extreme rainfalls using consistent indices include Manton et al (2001) and Alexander et al (2006). Both of these studies included only a small number of New Zealand rainfall stations, but cover the Asia-Pacific region and the globe, respectively, so that detailed changes in extreme rainfall within New Zealand were not easily evident in the results.

Of note in Alexander et al (2006) was the global tendency towards wetter conditions throughout the 20th century. However, the west/east differences in rainfall trends in the New Zealand results suggested that circulation has had a major impact on our rainfall extremes - even against the background warming seen in this country (the New Zealand-averaged air temperature increased by ~0.9 ºC between 1930 and 2004, with over half of this warming since 1950). This hypothesis is consistent with the fact that New Zealand is surrounded by oceans, the prevailing westerly winds blow almost perpendicularly across significant mountain ranges, and orographic rainfall is estimated to account for up to 90% of precipitation in some areas of the country (Larsen and Gray, 2003).

Circulation in the New Zealand region is known to be significantly influenced by several climate cycles, primarily the the El Niño Southern Oscillation(ENSO), the Interdecadal Pacific Oscillation (IPO), and the Southern Annular Mode (SAM), with corresponding regional impacts on mean rainfall (see below). In addition, climate change modelling (Mullan et al, 2001) predicts increased westerly circulation for New Zealand under enhanced warming.

ENSO is a significant source of seasonal and year-to-year climate variability in New Zealand (Mullan 1995, 1996). In El Niño years, New Zealand tends to experience stronger or more frequent winds from the west or southwest, leading to reduced rainfall in eastern areas and more rain in the west. La Niña enhances northeasterly winds, bringing more moist, rainy conditions to the northeast parts of the North Island.

The decadal IPO climate cycle (Mantua et al, 1997), which exhibits phase reversals about once every 20-30 years, also modulates atmospheric circulation over New Zealand. During the 20th century, three phases of the IPO have been identified (Salinger et al, 2001) - a positive phase (1922–1945) with augmented westerly circulation, a negative phase (1946–1977) with weaker westerlies, and another positive phase (1978–1998). Since 1978, more persistent westerly winds have occurred over central New Zealand, and the frequency of El Niño events has increased. It is also possible that the IPO phase modulates the rainfall-ENSO relationship in New Zealand, such as it does in Australia (Power et al, 1999), although this has not been confirmed by any published research to date. Mean rainfall in New Zealand has responded to the changes since 1978, with the west and south of the South Island becoming about 10 % wetter, and the northeast of New Zealand becoming about 10 % drier (Salinger and Mullan, 1999).

The SAM involves alternating intra-seasonal changes in windiness and storm activity between the mid latitudes (40-50° S), and higher latitudes (50-70° S) (Renwick and Thompson, 2006). In its positive phase, the SAM is associated with relatively light winds and more settled weather over New Zealand latitudes, resulting in lower than normal rainfall throughout western parts of both the North and South Islands. In the opposite (negative) phase, the westerly winds increase over New Zealand, with more unsettled weather, producing above normal rainfall in western areas of New Zealand.

Westerly circulation over central New Zealand (as measured by the Trenberth Z1 index, see the data section) has increased by a small (non-significant) margin over the 1930-2004 period and has increased significantly (at the 10% level) during 1950-2004. This increase in westerly winds may reflect enhanced warming since 1950, as predicted by climate change modelling; the strong IPO westerly phase since 1977; the increased frequency of El Nino events since 1977; or a mixture of all of these considerations. Decadal variation was clearly evident in a smoothed time-series of Z1 (not shown), consistent with IPO phase. The 1940s were a decade of positive Z1 (westerly circulation), while negative Z1 (weaker westerly circulation) dominated the 1950s and 1960s. Positive Z1 prevailed during the 1970s, 1980s and 1990s.

Although the mechanisms behind regional circulation variability are not the foci of this paper, it is important to note that climate variability and/or climate change affect New Zealand regional circulation (and correspondingly alter mean rainfall because of the large orographic component of New Zealand's precipitation). Of primary interest here are the *consequences* of circulation change, and enhanced warming since 1950, on New Zealand rainfall extremes.

Therefore, this paper has two major aims: to provide improved spatial and temporal knowledge of historical changes in New Zealand rainfall extremes by analysing data since the 1930s, at an increased number of high-quality rainfall stations across the country; and to provide a preliminary analysis to link circulation and temperature changes in the New Zealand region (which are known to be influenced, at differing time scales, by various climate cycles and by climate change) to rainfall extremes.

2. Data and homogeneity testing

A search for long-duration, high-quality, single-site daily rainfall records in the National Climate Database (Clidb) was carried out. The stations were selected to maximise geographical 'spread', subject to data quality and availability. In each record, M.A.S.H software (which uses a statistical form of nearest-neighbour comparison) identified any inhomogeneities, discontinuities and outliers (Sventiremy, 2002) which led to manual checking of station metadata, and confirmation of large daily outliers (extremes) by comparison with nearest neighbour data and weather charts where necessary.

Numerous records were rejected because of missing data (> 10 % of annual data missing) or because of probable data inhomogeneities. Known rainfall accumulations (of > 24 hours) were a common problem, and were treated as missing data in all calculations. However, undocumented accumulations probably still remain in some New Zealand rainfall records as a source of error. Inhomogeneities in climate records can result from changes to the station or its operation, i.e. changes in site location, observation practice, exposure, or instrumentation, and can affect both the mean and extremes of a climatic distribution (Trewin and Trevitt, 1996). Adjustment of daily data is known to be an extremely complex task (Aguilar et al, 2003) and so rainfall records where a likely inhomogeneity existed were simply rejected. Overall, 17 daily rainfall records for the period 1930-2004 and 30 daily rainfall records for 1950-2004 (including 2 outlying, oceanic sites at Raoul Island and Campbell Island) were deemed to be of an appropriate quality for analysis (Figure 1). Despite these efforts, undetected inhomogeneities may remain potentially resulting in spurious results. The period 1930-2004 was chosen simply to maximise the number of stations over a common data period, whilst retaining the longest record possible.

Selected monthly indices of New Zealand regional climate were calculated, in order to investigate relationships between circulation, temperature and daily rainfall extremity. Trenberth (1976) defined a number of circulation indices for the New Zealand region, reflecting the strength of local zonal and meridional flow. Updated Trenberth indices (Table 1) were calculated from monthly mean

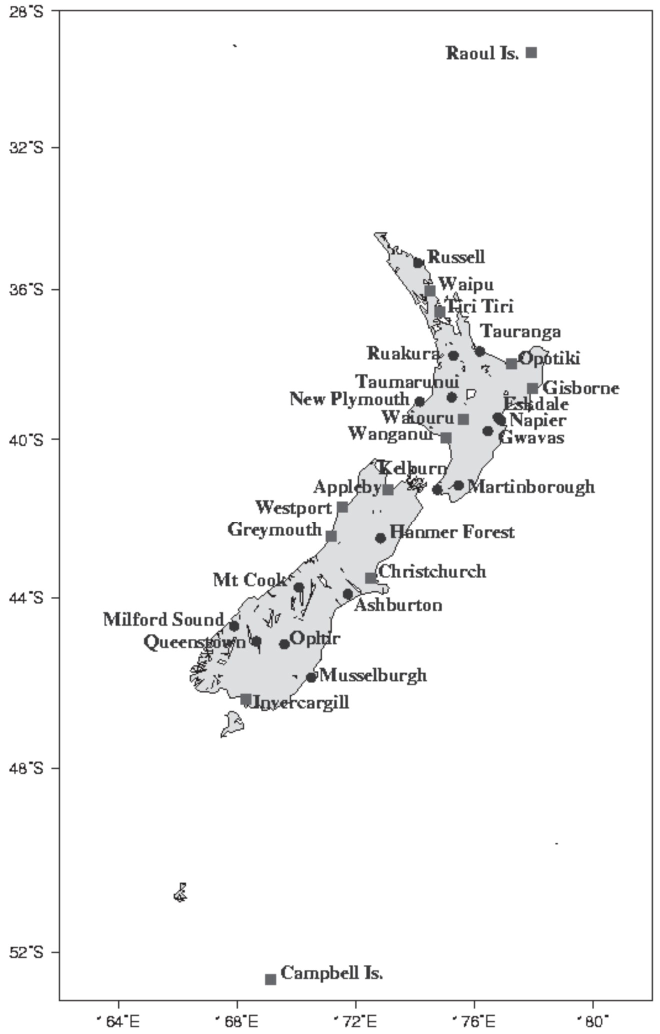


Figure 1: Rainfall stations used in both 1930-2004 and 1950-2004 analyses (dots); stations used only in the 1950-2004 analysis (squares).

station sea level pressure differences (deviations from the 1971-2000 monthly normal). Kidson (2000) derived 12 New Zealand daily weather types (Table 2, Figure 2), broadly falling into 3 regimes (troughs, zonal flow, blocking highs).

Index	Pressure difference	Wind anomaly (± index)
Z1	Auckland – Christchurch	West/East (central New Zealand)
Z2	Christchurch – Campbell Is.	West/East (south of New Zealand)
M1	Hobart – Chatham Is.	South/North
M2	Hokitika – Chatham Is.	South/North (east of New Zealand)

Table 1: Definition of selected monthly Trenberth circulation indices and corresponding airflow anomalies over New Zealand.

Monthly frequencies (%) of the Kidson weather types and a corrected monthly New Zealand-averaged temperature anomaly series (Salinger, 1980) were also updated. The common period 1958-2004 was used in a correlation analysis for all Trenberth, Kidson and New Zealand temperature data, even when earlier data were available, because the Kidson weather types were calculated from NCEP/NCAR reanalysis data, which at the time of original analysis started in 1958.

3. Analysis methodology

RClimdex software (Zhang and Yang, 2004) was developed by the Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI). ETCCDMI initiated the international development of a suite of climate change indices (http://cccma.seos.uvic.ca/ETCCDMI/index.shtml) that primarily focus on extremes. By setting exact formula and software for each index, consistent calculation of extreme indices and direct comparison of results across the globe can occur.

Following data homogeneity testing, the RClimdex software was used to calculate 11 rainfall indices (Table 3) recommended by the ETCCDMI. These rainfall indices were selected as relevant to New Zealand's climate, and refer to

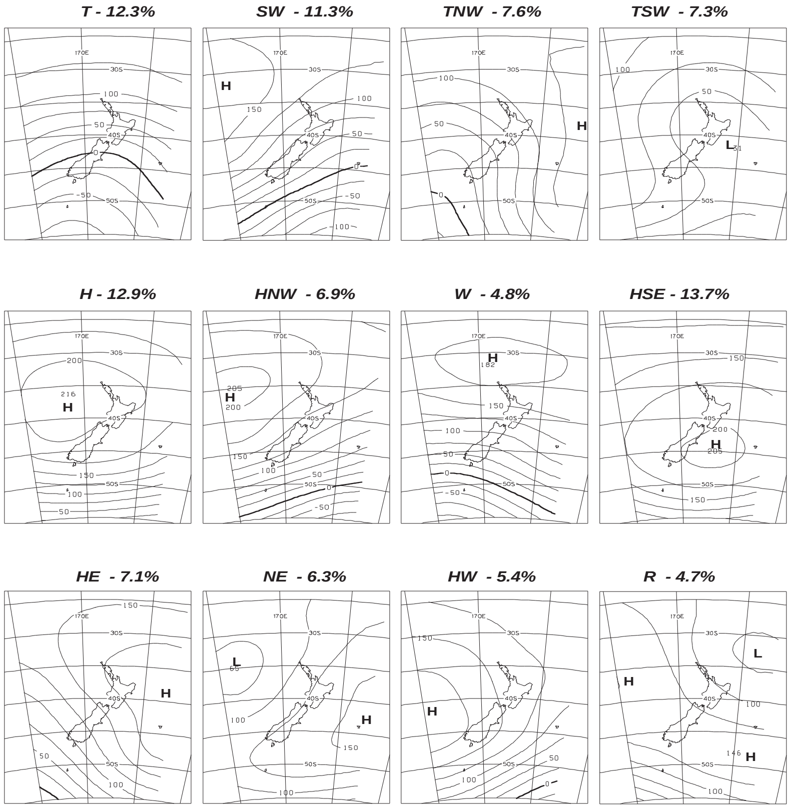
Following data homogeneity testing, the RClimdex software was used to calculate 11 rainfall indices (Table 3) recommended by the ETCCDMI. These rainfall indices were selected as relevant to New Zealand's climate, and refer to

wet extremes with a modest return period (of <= 1 year). This ensures that the number of events is sufficiently large to allow for meaningful trend analysis over the New Zealand record i.e. of length 50 - 75 years.

Index	Synoptic Type	Description
TSW	Trough/southwesterly	Trough in southwest flow crossing New Zealand
T	Trough	Trough in westerly flow crossing New Zealand
SW	Southwesterly	Southwesterly flows
NE	Northeasterly	Northeasterly flows
R	Ridge	Ridge – light winds over the south, easterlies over the north
HW	High to southwest	High to west of the South Island with light south – southwesterly flows
HE	High to east	High to the east with developing northwesterly flow
W	Westerly	Westerly flow
HNW	High to northwest	High west of the North Island with southwesterly flow
TNW	Trough in northwest	Trough to the west preceded by northwesterly flow
HSE	High to southeast	High east of the South Island with easterly flow for the North Island and light winds elsewhere
H	High	Light winds – North Island Westerly flow – far south

Table 2: Description of Kidson weather types.

The indices were analysed over two periods – 1930-2004 and 1950-2004. As explained earlier, 1930-2004 was chosen as the longest-possible common data period. A decision was made not to split the index analyses into the three IPO related phases (1922–1944, 1945–1977, 1978–1998) for a number of reasons. Firstly, the rainfall common data period did not extend back to 1922. Secondly,



T - 12.3% *SW - 11.3%* *TNW - 7.6%* *TSW - 7.3%*

H - 12.9% *HNW - 6.9%* *W - 4.8%* *HSE - 13.7%*

HE - 7.1% *NE - 6.3%* *HW - 5.4%* *R - 4.7%*

Figure 2: Composite patterns of 1000 hPa height and frequency of occurrence for the 12 clusters obtained from twice-daily NCEP/NCAR reanalyses from January 1958 to July 1997 (directly from Kidson 2000). Percentage values represent the average annual frequency of each type over the period studied. Winds flow along the contours shown, with speed inversely proportional to the contour spacing.

because of the large increase in New Zealand-averaged temperatures around 1950, there was interest as to whether extremes after 1950 behaved differently -to those prior to 1950. Thirdly, it appeared that the period since about 2000 had been anomalously ‘extreme’, with frequent and significant flooding events across New Zealand – and it was desirable to capture this in any indices of extremity. Lastly, and most importantly, each of the three IPO periods was considered too short for calculating robust trends within. Therefore, two analysis periods were chosen, reflecting data constraints, and the reasons above.

The period 1961-1990 was chosen as the base period for the indices that represent counts of days crossing climatological percentile thresholds at a station. A non-parametric Kendall’s tau based slope estimator was calculated to compute trends and test for trend significance, since this method does not assume a distribution for the residuals and is robust to the effects of outliers in the series (Alexander et al, 2006). Trends with p-values <= 0.05 (<= 0.10) are deemed significant (weakly significant) in the text. Trends were then plotted spatially using GMT software (Wessel and Smith, 2001).

All 11 extremity indices were derived from daily rainfall data, and calculated into annual (calendar year) indices. For ‘spell duration’ indicators (e.g. consecutive dry days), a spell is able to continue into the next calendar year and is counted against the year in which the spell ends. Annual index values were not calculated if there were more than 15 days of missing data in a year.

A wet day is defined as a day with rainfall >=1 mm. This relatively high ‘wet day’ threshold was chosen by the ETCCDMI to reduce the risk of significant biases in the indices (particularly CDD and CWD) due to under-reporting of small rainfall amounts (or inclusion of small amounts in the subsequent rainfall total). Previous international studies have found that lower wet day thresholds (such as 0.2 mm) can be sensitive to under-reporting, and to problems such as changes in the units of measurement (e.g. Hennessy et al, 1999, Zhang et al, 2001). Although there is no evidence of historical under-reporting of small rainfall amounts at high-quality climate stations in New Zealand (Stuart Burgess, pers. Comm.), to the author's knowledge no thorough investigation of this issue has been undertaken in New Zealand, and further investigation of

Index	**Name used in text**	**Brief definition**	**Unit**
Rx1day	Maximum 1-day rainfall amount	Annual maximum 1-day precipitation	mm
Rx5day	Maximum 5-day rainfall amount	Annual maximum consecutive 5-day precipitation	mm
SDII	Simple daily intensity index	Annual total wet-day precipitation divided by the annual number of wet days (rainfall >=1 mm)	mm/day
R10	Number of days above 10 mm	Annual count of days when rainfall >=10 mm	days
R20	Number of days above 20 mm	Annual count of days when rainfall >=20 mm	days
R25	Number of days above 25 mm	Annual count of days when rainfall >=25 mm	days
CDD	Consecutive dry days	Maximum number of consecutive days with rainfall <1 mm	days
CWD	Consecutive wet days	Maximum no. of consecutive days with rainfall >=1 mm	days
R95p	Very wet day magnitude	Annual rainfall total when rainfall > reference period 95th percentile* (magnitude of ~16 wettest events per year)	mm
R99p	Extreme wet day magnitude	Annual rainfall total when rainfall > reference period 99th percentile* (magnitude of ~4 wettest events per year)	mm
PRCPTOT	Annual total wet-day precipitation	Annual total rainfall on wet days (rainfall >=1 mm)	mm

Table 3: Brief description of rainfall indices. The 1961-1990 reference period was used to determine percentile values

whether rainfall under-reporting has influenced these results would be warranted in future work.

The annual (calendar) maximum 1-day and maximum consecutive 5-day rainfall amounts were calculated in the Rx1day and Rx5day indices, respectively. Several ‘annual count’ indices were also included: for example, the number of days with rainfall above 10 mm (R10), 20 mm (R20) and 25 mm (R25).

Two ‘spell duration’ indices were analysed, namely the maximum number of consecutive dry days (CDD) and consecutive wet days (CWD). In a global sense, New Zealand rainfall is spread relatively evenly throughout the year (i.e. there is no pronounced dry season), with the implication that the CDD index in this country is a meaningful measure of unusually dry conditions and a proxy ‘drought’ indicator. Of detriment, however, is the fact that the CDD and CWD indices are very sensitive to missing data, especially if a single day’s record were enough to terminate a CDD or CWD period. In both the CDD and CWD calculations, missing data are handled conservatively, in that a missing value breaks both CDD and CWD periods.

The annual number of wet days was calculated for use in two indices (but are not shown directly). Annual total ‘wet-day’ precipitation (PRCPTOT) represents the total rainfall occurring only on wet days (>= 1 mm) – it is therefore not the same as the traditional “total annual rainfall” which sums all recorded rainfall – for reasons explained above. The annual simple daily intensity index (SDII) is the average rainfall amount occurring on a wet day (defined as PRCPTOT divided by number of wet days).

Lastly, two ‘percentile’ indices were calculated – the very wet day (R95p) and extremely wet day (R99p) indices. Both use the 1961-1990 reference period to calculate a long-term 95th (99th) percentile rainfall value based on rainfall during wet days only. Then, annual rainfall is tallied, whenever daily (wet day) rainfall exceeds the reference period percentile value. To illustrate, the R95p index is calculated as follows: Let RR_{wj} be the daily precipitation amount on a wet day *w* (rainfall>=1mm) in period *j* (j = calendar year) and $RR_{wn}95$ let be the 95th percentile of precipitation on wet days in the 1961-1990 period. If *W* represents the number of wet days in the period, then:

$$R95p_j = \sum_{w=1}^{W} RR_{wj} \text{ where } RR_{wj} > RR_{wn}95$$

Percentage changes in annual Rx1day, Rx5day and PRCPTOT indices were compared over the periods 1930-2004 and 1950-2004. The percentage change was calculated from the RClimdex annual trend (as derived from the regression slope), multiplied by the number of years in the period, and then divided by the average index value of all data in the relevant period. This analysis was undertaken in order to compare the relative sizes of shifts in total wet-day rainfall versus extreme 1-day rainfall.

Additionally, the Rx1day index was calculated monthly and seasonally. Monthly index values were not calculated if there were more than 2 days of missing data in a month. The monthly Rx1day index was correlated with indices of local circulation, weather type and temperature over the period 1958-2004, as flooding in New Zealand is typically due to either synoptic features or convective, localised rainfall, both with durations in the order of 1 day or less. Because seasonal trends in the Rx1day index are of interest in their own right, they are also tabled and discussed separately.

4. Results

4.1 Spatial pattern

Figures 3-10 spatially display trends in selected rainfall indices over both analysis periods, with the trend significance depicted by symbol size (i.e. proportional to p-value). Table 4 and Table 5 quantify trend magnitude (trend per decade) and significance for all 11 rainfall indices.

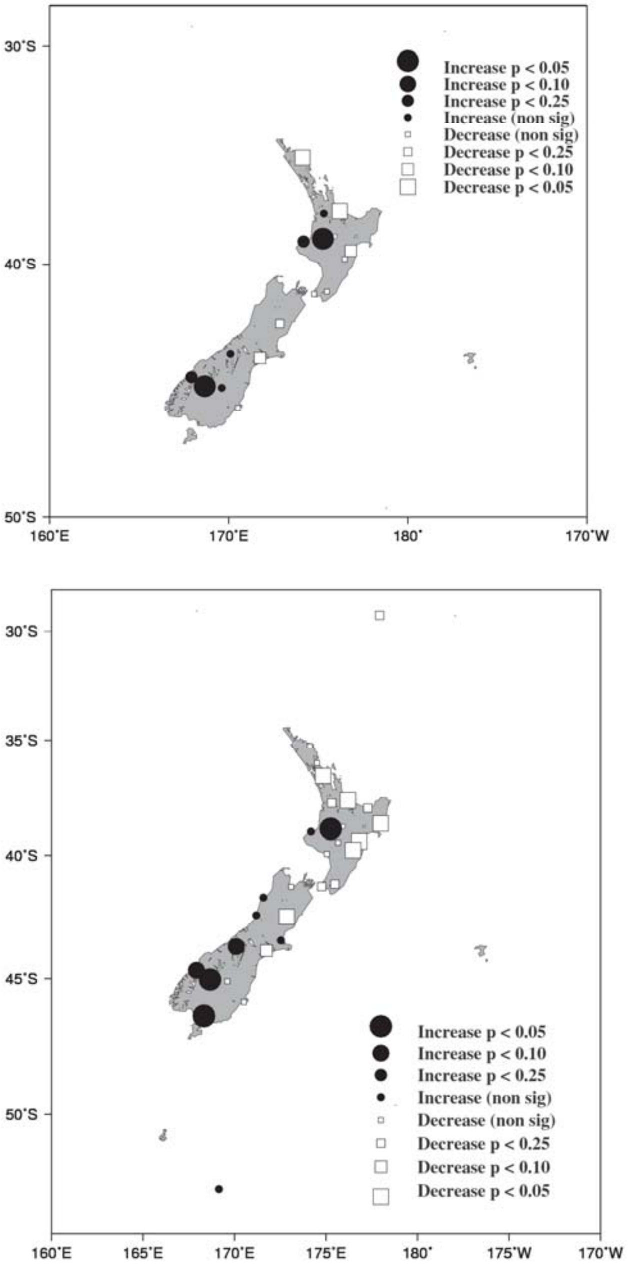


Figure 3: Trends in PRCPTOT (annual total wet-day precipitation): top panel 1930-2004; lower panel 1950-2004.

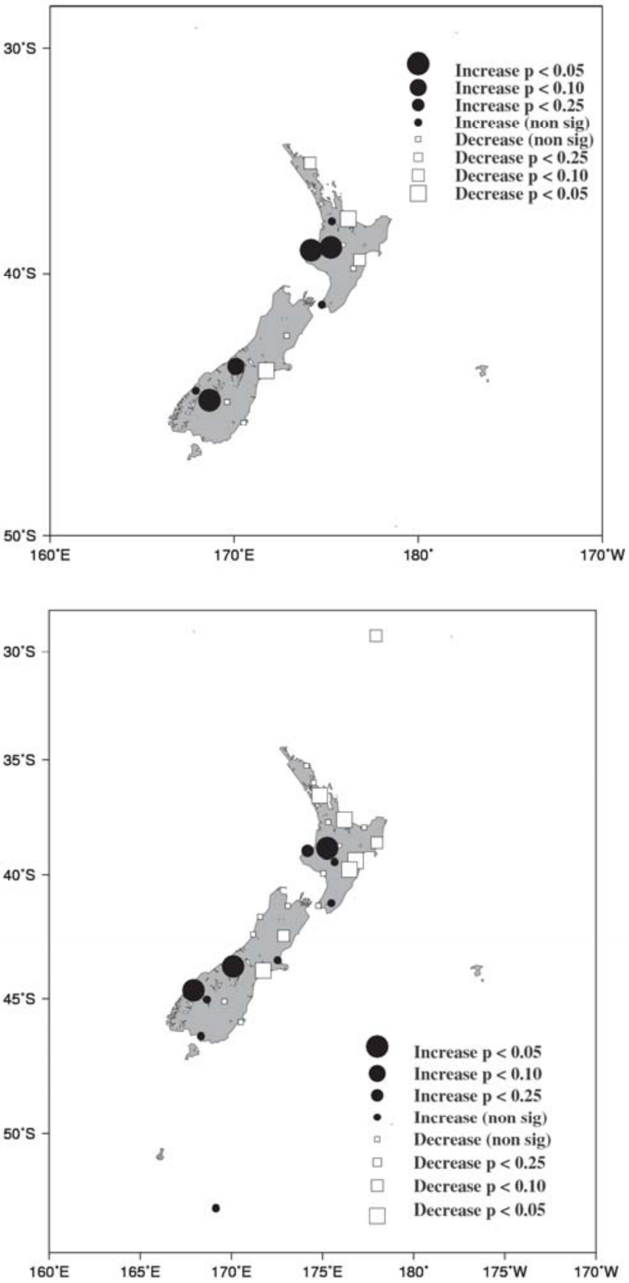


Figure 4: Trends in R25 (number of days with rainfall above 25 mm): top panel 1930-2004; lower panel 1950-2004.

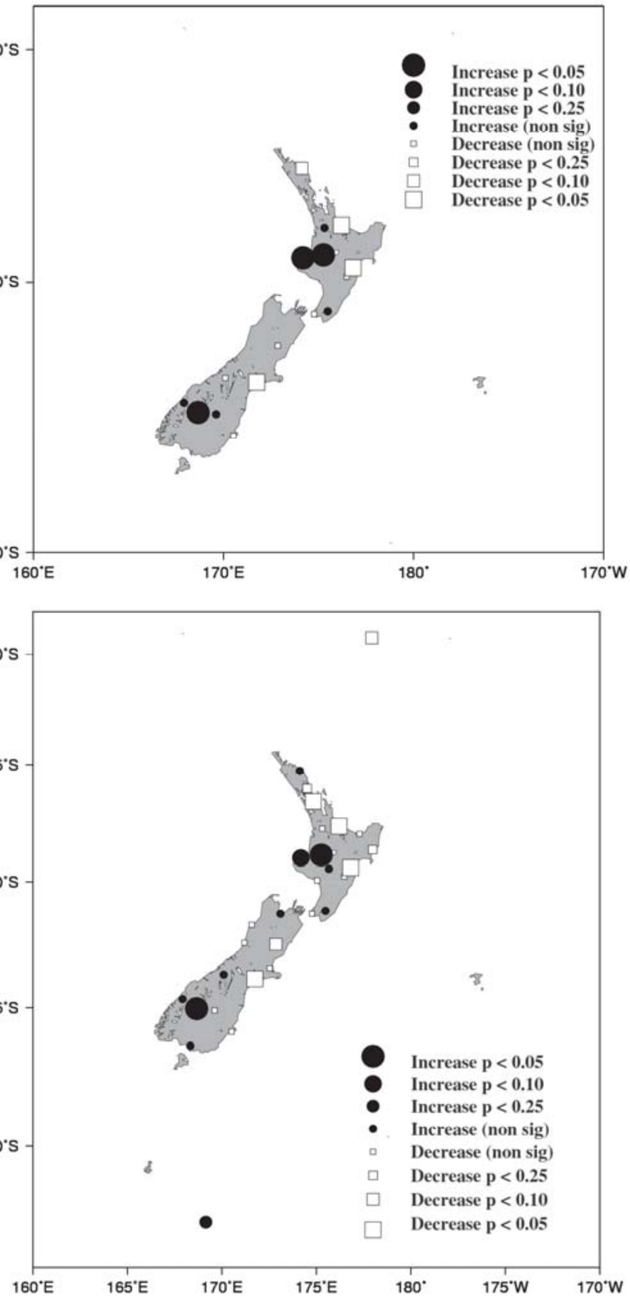


Figure 5: Trends in R95p (very wet day magnitude): top panel 1930-2004; lower panel 1950-2004.

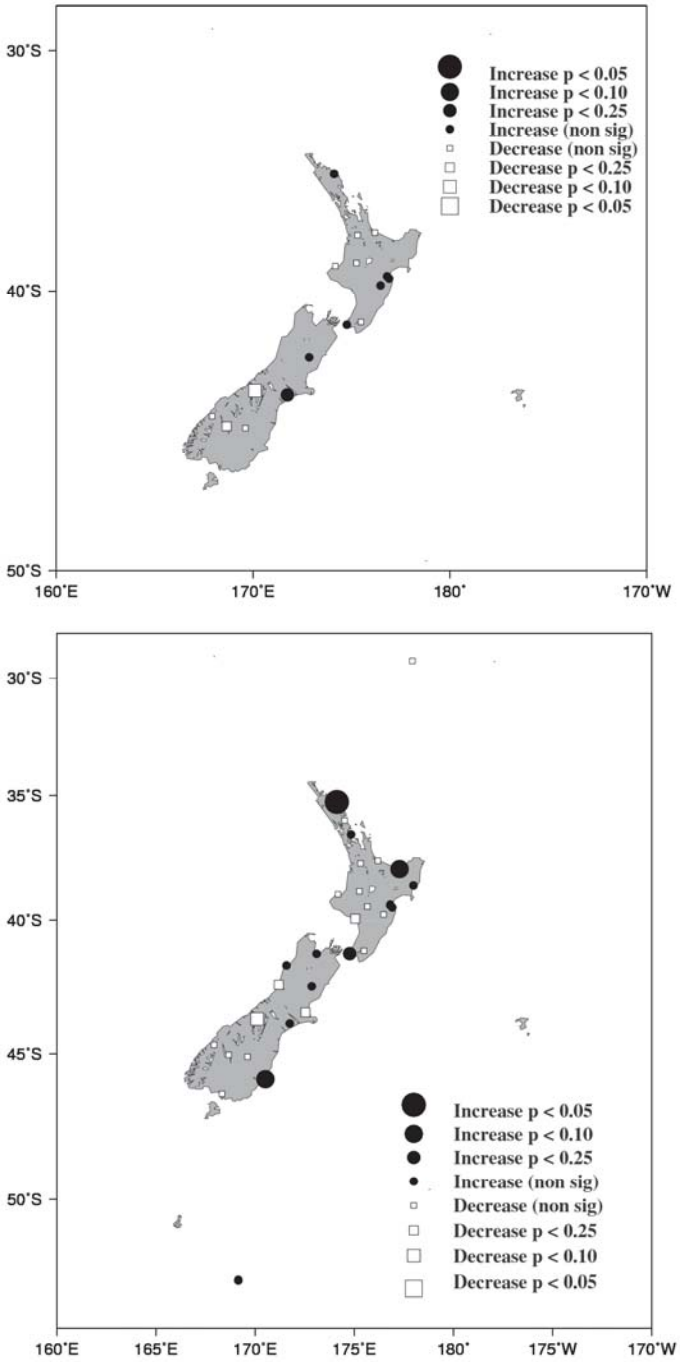


Figure 6: Trends in CDD (consecutive dry days): top panel 1930-2004; lower panel 1950-2004.

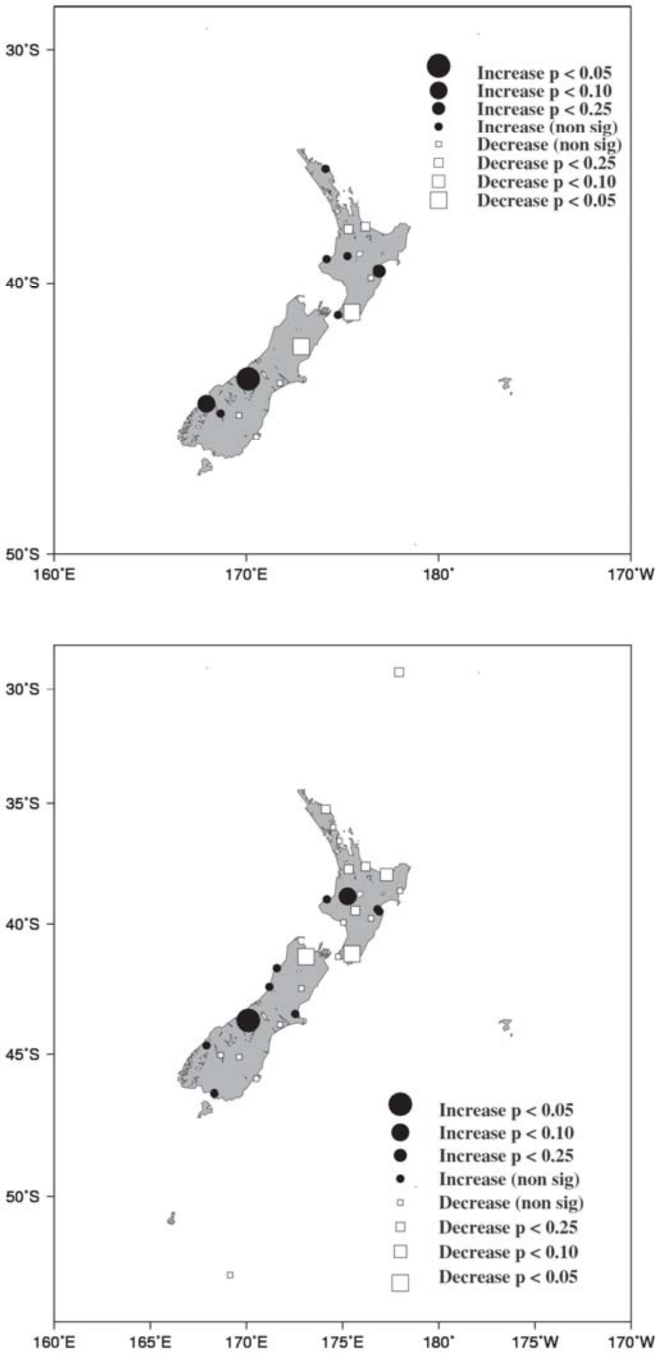


Figure 7: Trends in CWD (consecutive wet days): top panel 1930-2004; lower panel 1950-2004.

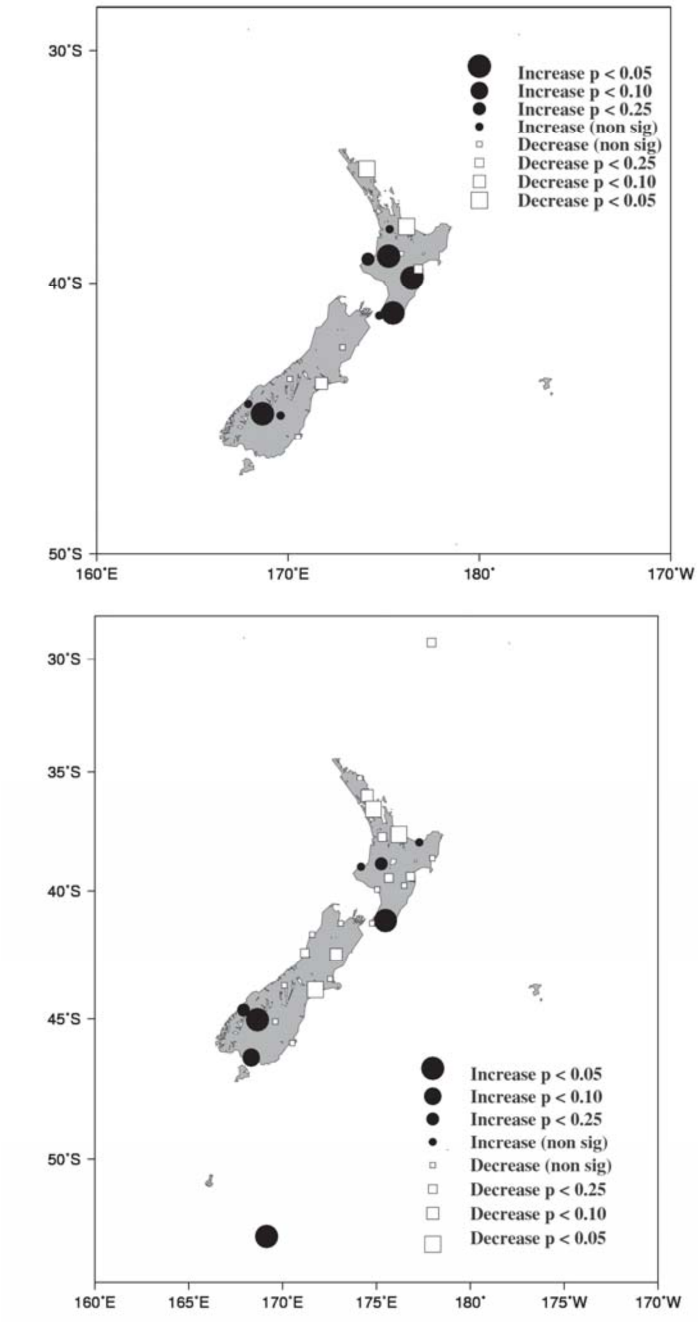


Figure 8: Trends in SDII (simple daily intensity index): top panel 1930-2004; lower panel 1950-2004.

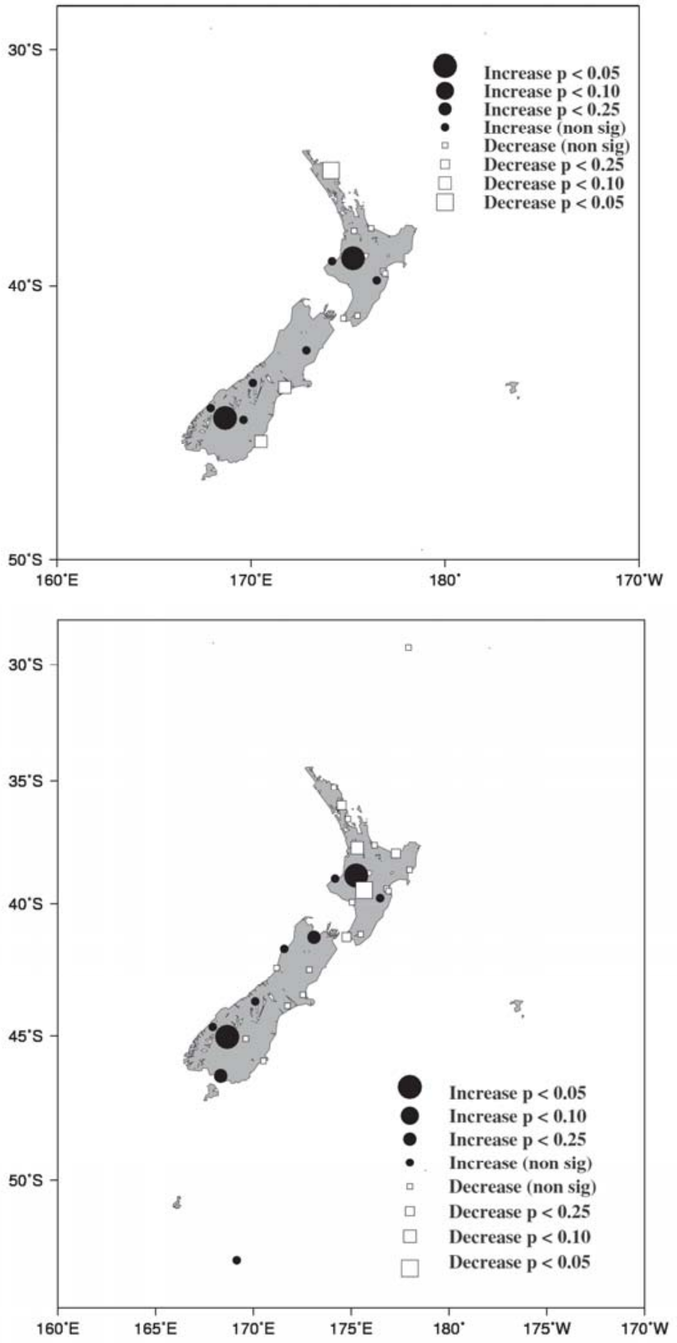
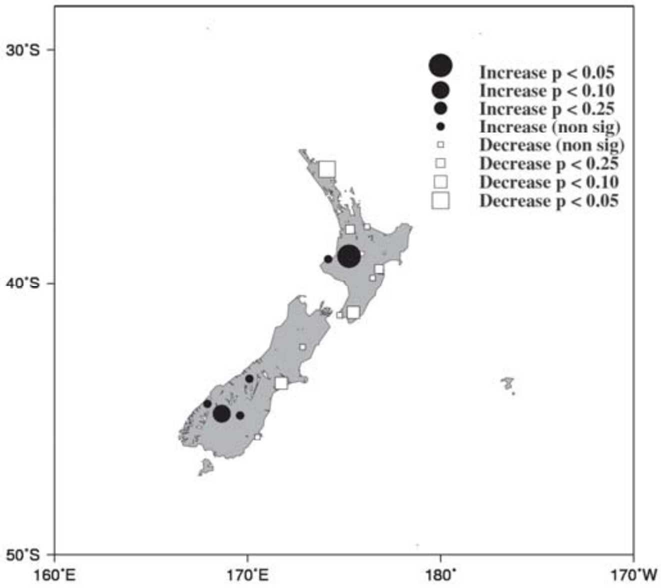


Figure 9: Trends in Rx1day (maximum 1-day rainfall amount): top panel 1930-2004; lower panel 1950-2004.



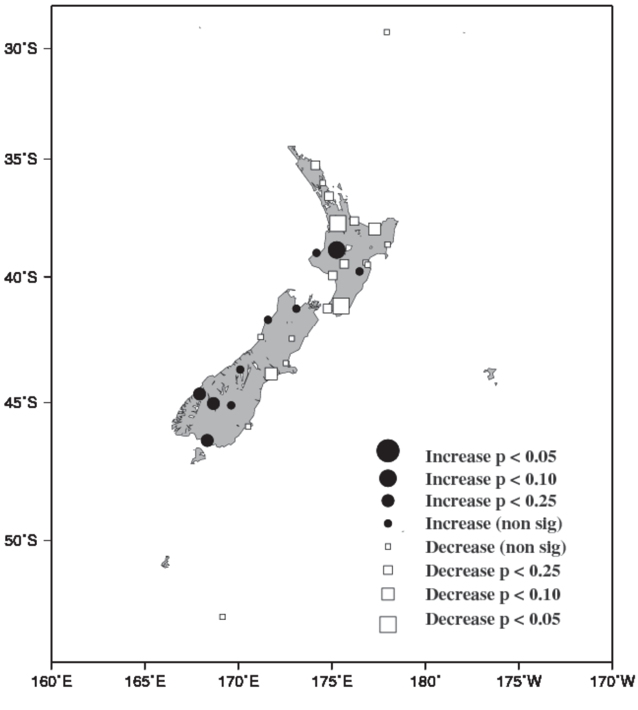


Figure 10: Trends in Rx5day (maximum 5-day rainfall amount): top panel 1930-2004; lower panel 1950-2004,

Similarly to results found by Salinger and Griffiths (2001), a zonal (west/east) pattern in rainfall trends is evident across the main axial mountains of both islands – and notably, this zonal pattern is consistent over both periods. For example, increases in 1950-2004 mean rainfall (Figure 3) and extreme rainfall (e.g. Figures 4, 5) are generally seen to the west of a line from Westport to Invercargill, to the west of a line Kelburn to Waiouru to Ruakura, and at Campbell Island. Decreasing mean and extreme rainfall and increasing CDD is generally seen elsewhere (e.g. in the north and east of both islands) and at Raoul Island. This generalised pattern translates across all of the indices, but there can be subtle differences for stations near these nominal boundaries.

Exceptions to this generalised pattern tend to occur at Christchurch, Greymouth, Appleby, Martinborough, Wanganui, Waiouru, Gwavas, or Russell, almost always when trends are effectively zero at these sites (e.g. non-significant). For example, the R25 1950-2004 trend pattern (Figure 4) is subtly different to the generalised pattern at Christchurch, Greymouth, Westport, Wanganui, Waiouru and Martinborough (with non-significant trends at all six sites), as is the R95p 1950-2004 trend pattern at Greymouth, Westport, Appleby, Martinborough, Wanganui, Waiouru and Russell (Figure 5), again with trends at these sites effectively zero.

4.2 Index significance and consistency between indices.

Some indices (e.g. Rx1day, R95p, R99p) were quite ‘noisy’, as measured by their coefficient of variation (CV), the ratio of standard deviation to mean. For the stations analysed here, typical CV values (not shown) for PRCPTOT, SDII and R10 were between 10% and 20%, while CV values ranged between ~25-30% for the R20, CDD and CWD indices, and greater (or much greater) than 40% for the remaining indices, which capture more extreme events by definition. It would be expected that ‘noisy’ indices, such as R99p, showed fewer significant trends than, say, PRCPTOT or SDII. Notably, the CDD and CWD indices (Table 4 and 5) showed very few significant trends over either period,

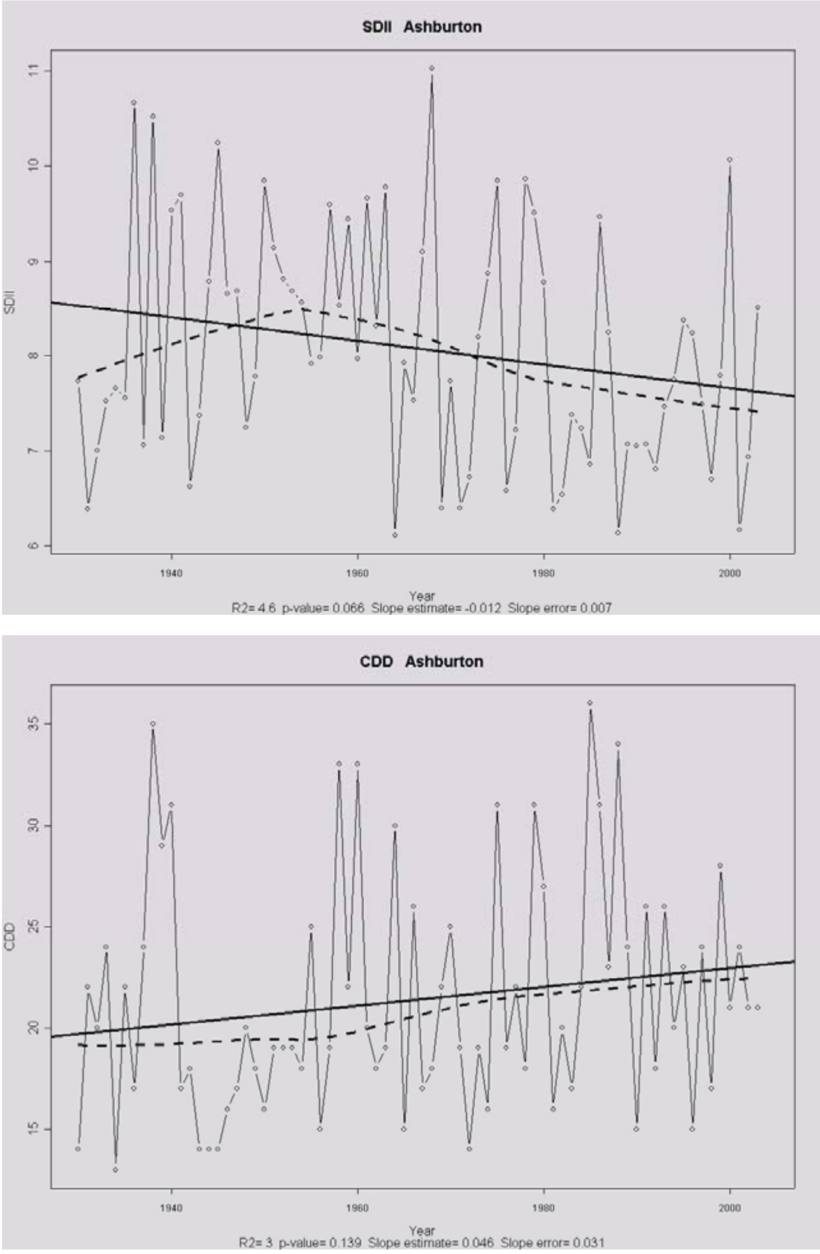


Figure 11: Time series 1930-2004 at Ashburton of (a) SDII and (b) CDD as generated by RClimdex. Annual series (thin line), trends computed by linear least square (thick solid line) and locally weighted linear regression (thick dashed line).

even though CDD and CWD CV values were ranked around the middle of the 11 indices. This may reflect the sensitivity of these indices to missing values, or be a real reflection of no change in these measures of dry or wet spells. To illustrate, Figure 11 depicts the difference in 'noisiness' at Ashburton between the SDII index (which varies between 6 and 11, showing an increase until about 1950, and thereafter a weakly significant decrease) and the CDD index (which varies from 13 to 36 days, and shows no statistically significant trend). At Ashburton, the SDII CV was 15% and the CDD CV was 27%

.

Trend	Rx1day	Rx5day	SDII	R10	R20	R25	CDD	CWD	R95p	R99p	PRCPTOT
per decade	mm	Mm	mm/day	days	days	days	days	days	mm	mm	mm
Ruakura	-1.1	-2.1	0.1	0.1	0.1	0.2	-0.2	-0.2	3.8	-3.7	0.5
Taumarunui	**2.4**	**4.3**	**0.1**	0.8	**1**	**0.8**	-0.1	0.2	23.3	9.5	35.4
New Plymouth	0.5	2.3	0.1	0.7	0.4	**0.4**	0	0	**14.4**	2.5	13.9
Kelburn	-1.1	-0.2	0.1	0.2	0.2	0.2	0.3	0	-0.7	-3.8	-0.7
Russell	**-6**	**-9.4**	**-0.5**	**-1.1**	**-0.9**	-0.6	0.3	0.1	-34.9	**-26.5**	**-48**
Tauranga	-1.7	-2.8	**-0.2**	-0.7	**-0.5**	**-0.6**	-0.3	-0.1	**-22.6**	-6.9	-37.5
Eskdale	-2.4	-5.1	-0.1	-0.1	-0.3	-0.3	0.1	0.1	**-28.2**	-12.6	-24.2
Napier	-1.1	-2.2	-0.1	0	-0.1	0	0	0.1	-5.6	-5.1	-7.6
Gwavas	0.3	-0.7	**0.2**	-0.1	-0.1	0	0	-0.1	-4.3	3	-9.9
Martinborough	-0.5	-2.7	**0.2**	0.3	0.1	0	-0.1	**-0.3**	1	-2.2	-1.8
Mt Cook	0.6	2.9	-0.3	1.1	1.2	1.1	-0.4	0.3	-1.3	-24.9	52.8
Milford Sound	2.7	4.1	0.1	0.5	0.6	0.6	-0.1	0.4	37.2	5.7	65.2
Queenstown	**2.3**	2.9	**0.2**	**0.8**	**0.5**	**0.3**	-0.4	0	**16.9**	**9.6**	**24**
Hanmer Forest	0	-0.8	-0.1	-0.3	-0.3	-0.2	0.2	**-0.2**	-3.5	-6.2	-15.6
Ashburton	-1.7	-3.5	-0.1	-0.4	-0.2	**-0.3**	0.5	-0.1	**-11.6**	-3.4	**-16.7**
Ophir	0.1	0.5	0	0.1	0.1	0	-0.1	0	1.2	-0.9	1.9
Musselburgh	-1.9	-1.8	0	-0.2	0	-0.1	0	0	-2.3	-3.1	-4.7

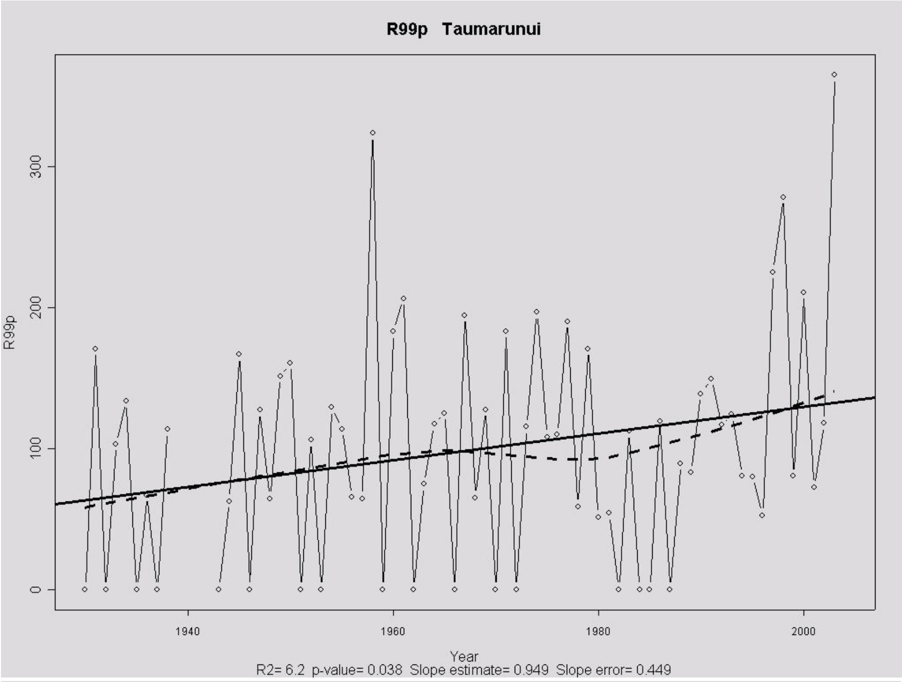
Table 4: Trends and significance in annual rainfall indices 1930 – 2004. Grey shading denotes p-value <= 0.10. Grey shading with bolding denotes p-value <=0.05. Additional stippling demarks negative trends from positive trends.

Indeed, the number of sites with significant trends did vary across the indices (Tables 4 and 5). Only one of 17 stations (Mt. Cook) displays a significant or weakly significant CDD trend over 1930-2004, compared with 7 sites for SDII, R25, R95p and 6 sites for R20 and PRCPTOT. Similarly, 12 sites out of 30 display significant or weakly significant trends in PRCPTOT for the period 1950-2004, compared with 11 sites for R20 and R25, and 9 sites for SDII and R95p. Overall, the indices that most often show statistical significance are PRCPTOT, R20, R25, R95p and SDII, which reflects index 'noisiness' to a large degree – the exception being the R95p index, which is a relatively noisy index showing a high number of statistically significant changes. The New Zealand results are consistent with the Alexander et al (2006) study, which found significant increases over 1951-2003 in global averages of PRCPTOT, R10, R20, R95p and SDII (although trends computed on gridded data showed little significance).

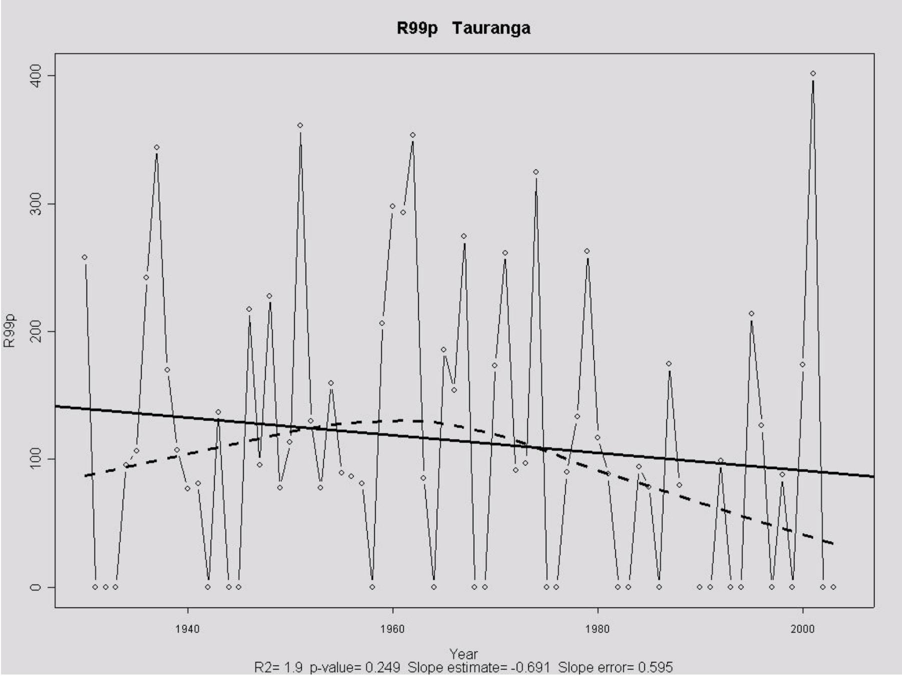
Trend per decade	Rx1day mm	Rx5day mm	SDII mm/day	R10 days	R20 days	R25 days	CDD days	CWD days	R95p mm	R99p mm	PRCPTOT mm
Raoul Is.	-4.3	-1.7	-0.2	-0.4	-0.6	-0.8	-0.3	-0.2	-42.1	-20.4	-47.5
Ruakura	-3.1	**-6.4**	-0.1	-0.9	-0.5	-0.2	-0.1	-0.3	-4.8	-11.3	-22.1
Taumarunui	**3.6**	**4.7**	0.1	0.8	**0.9**	**1.1**	-0.2	0.4	**23.1**	9.3	**38.6**
New Plymouth	0.6	2.2	0.0	0.7	0.3	0.5	-0.1	0.2	21.7	2.6	18.5
Waiouru	**-3.7**	-3.4	-0.1	-0.3	0.2	0.1	-0.1	-0.3	3.8	-2.5	-4.1
Wanganui	-1.4	-3.2	0.0	0.3	0.1	0.0	-0.6	-0.1	-1.7	-1.7	-0.6
Kelburn	-2.0	-3.8	-0.1	-0.5	-0.3	-0.3	0.5	-0.2	-11.8	-3.7	-26.5
Russell	-2.5	-6.1	0.0	-1.1	-0.7	-0.2	**0.9**	-0.3	5.4	5.7	-17.7
Waipu	-3.4	-3.0	-0.2	-0.2	-0.5	-0.1	-0.3	-0.1	-19.9	-10.5	-20.3
Tiri Tiri	-2.5	-4.5	**-0.2**	-0.9	**-0.8**	**-0.7**	0.2	-0.2	**-35.1**	**-16.1**	**-40.7**
Tauranga	-2.6	-7.6	**-0.3**	-1.2	**-0.8**	**-0.7**	-0.2	-0.3	**-46.8**	**-19.2**	**-66.3**
Opotiki	-5.1	-10.0	0.1	-1.1	-0.7	-0.3	1.1	-0.3	-3.0	-14.8	-42.9
Gisborne	-1.3	-0.9	-0.1	-0.6	-0.5	-0.5	0.8	-0.1	-20.8	-15.2	**-40.8**
Eskdale	-3.3	-2.9	-0.2	-1.0	**-0.9**	**-0.9**	0.4	0.2	**-33.6**	-11.2	**-52.9**
Napier	-2.3	-2.3	-0.1	0.0	-0.2	-0.1	0.0	0.1	-0.2	-1.8	-10.8
Gwavas	1.0	0.2	-0.1	**-1.0**	**-0.7**	-0.6	-0.3	0.0	-13.1	3.3	**-35.2**
Martinborough	-1.3	**-5.6**	**0.2**	-0.2	0.0	0.0	-0.2	**-0.4**	1.5	-2.8	-16.8
Westport	0.5	0.2	-0.1	0.9	0.0	-0.4	0.2	0.3	-12.6	-7.1	10.5
Greymouth	0.0	-0.1	-0.1	0.9	-0.5	0.0	-0.3	0.1	-8.5	-4.1	9.7
Mt Cook	3.7	4.1	0.0	1.1	**2.2**	**2.0**	-0.7	**0.6**	51.4	21.2	143.1
Milford Sound	5.4	19.2	0.5	2.0	2.0	**2.0**	-0.1	0.4	62.5	-3.8	159.1
Queenstown	**3.9**	4.3	**0.3**	0.9	0.6	0.2	-0.1	0.0	**23.0**	**13.1**	**30.0**
Invercargill	1.3	2.4	0.1	**1.2**	0.4	0.1	-0.1	0.0	8.5	-0.1	**27.5**
Appleby	2.7	3.4	0.0	-0.2	-0.6	-0.3	0.0	**-0.4**	4.6	7.1	-8.9
Hanmer Forest	-0.7	-5.2	-0.2	**-1.3**	**-1.0**	-0.8	0.5	-0.1	-26.4	-8.5	**-44.5**
Christchurch	-1.2	-1.1	0.0	0.5	-0.1	0.1	-0.8	0.1	-0.1	-1.3	0.3
Ashburton	-1.0	**-5.0**	**-0.3**	-0.6	**-0.6**	**-0.7**	0.5	0.0	**-20.3**	1.6	-21.8
Ophir	-0.8	0.7	0.0	0.1	0.0	0.0	-0.7	0.0	-1.5	-1.3	-0.3
Musselburgh	-0.9	-0.4	-0.1	-0.2	-0.2	-0.2	0.9	-0.1	-6.6	-3.3	-9.3
Campbell Is.	0.9	-1.2	**0.1**	0.7	0.1	0.1	0.1	-0.4	10.7	-0.1	5.2
No. sig trends 1930-2004 (not now)	3	2	3	3	1	1	0	2	1	3	1
No. sig trends 1950-2004 (not previously)	0	0	1	3	6	4	2	1	1	1	4

Table 5. Trends and significance in annual rainfall indices 1950 – 2004. Grey shading denotes p-value <= 0.10. Grey shading with bolding denotes p-value <=0.05. Additional stippling demarks negative trends from positive trends. For 17 stations with data over both analysis periods, underlining denotes non-significant trends over 1950-2004 that were previously weakly significant or significant over 1930-2004; boxing indicates weakly significant or significant trends over 1950-2004 that were non-significant over 1930-2004.

Figure 12 shows time series of the R99p index (extreme wet day magnitude) at four selected sites, in order to highlight the contrasts typically seen between western and eastern sites. The western sites of Taumarunui and Queenstown display a quasi-linear and significant increase in R99p over the period 1930-2004. Tauranga shows an overall (non-significant) decrease in R99p extremity (except for an outlier in 2001), but decadal variation is evident – in fact, the locally-weighted regression line shows an increase in R99p until about the mid 1970s, and thereafter a sharp decrease. This decrease is consistent with more prevalent west to southwest flow since 1977 as identified by Salinger and Mullan (1999), as Tauranga lies in the lee of the North Island central plateau during


R99p Taumarunui

R2= 6.2 p-value= 0.038 Slope estimate= 0.949 Slope error= 0.449


R99p Tauranga

R2= 1.9 p-value= 0.249 Slope estimate= -0.691 Slope error= 0.595

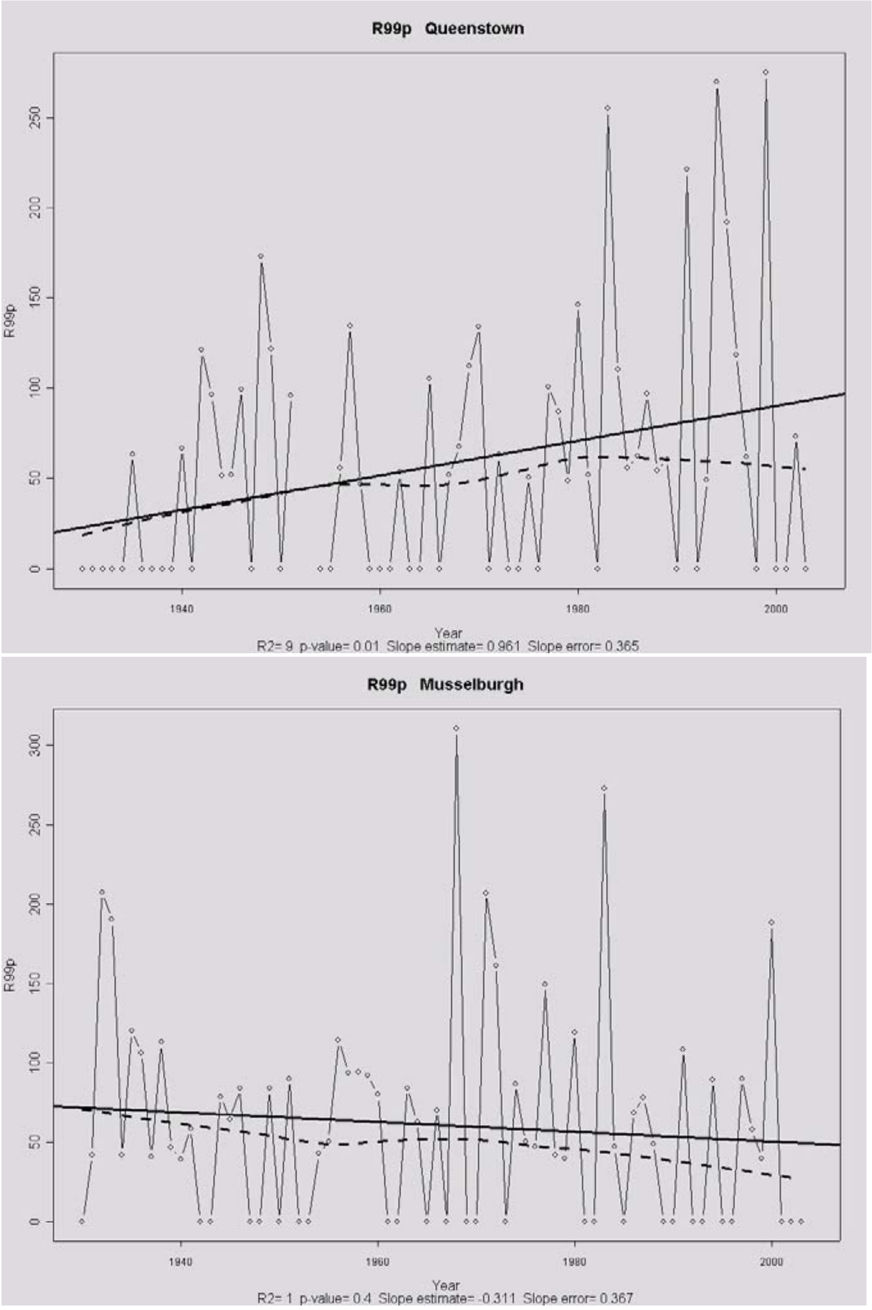


Figure 12: Time series 1930-2004 of R99p (extreme wet day magnitude, mm) at 4 illustrative sites (a) Taumarunui (b) Tauranga (c) Queenstown and (d) Musselburgh: Annual series (thin line), trends computed by linear least square (thick solid line) and locally weighted linear regression (thick dashed line).

southwesterly regimes and receives correspondingly reduced rainfall. Musselburgh displays no overall trend in R99p, but more variability is clearly apparent in the index over the latter half of the series. The significance of both 1930-2004 and 1950-2004 trends is generally largest in the northeast of the North Island (e.g. Tauranga, Gisborne, Napier) and in the southwest of the South Island (e.g. Mt. Cook and Queenstown), followed by Taranaki and the King Country (New Plymouth and Taumarunui). Exceptions are R99p (not shown spatially), with significant 1950-2004 trends only found in the northeast of the North Island and at Queenstown, and CDD (Figure 6), which features very few significant or weakly significant trends at all. Only the Mt. Cook 1930-2004 CDD trend is significant, with Ashburton very close to weak significance, and only four sites - Musselburgh, Opotiki, Mt. Cook and Russell - show significant trends over the period 1950-2004. Another exception is CWD (Figure 7), which shows significant trends at Mt. Cook (both periods) as well as around central New Zealand (Martinborough (both periods), Hanmer Forest (1930-2004) and Appleby (1950-2004)).

The lower North Island clearly shows a region of significant 1930-2004 increases in simple daily intensity (Figure 8) which is not evident over the later period, except at Martinborough. This is the only clear-cut illustration in all 11 indices where 1930-2004 trends are spatially/regionally inconsistent with trends over the later period, when trends are large enough to be significant or weakly significant. The 1950-2004 SDII trends tend to show the generalised west/east pattern, except at Martinborough (which retains a significant increase in SDII), and at Mt. Cook, Greymouth, Westport, Wanganui, Opotiki (which all show non-significant trends).

The patterns seen in Rx1day (Figure 9) and Rx5day (Figure 10) trends are generally consistent between the two indices, between the 1930-2004 and 1950-2004 periods, and with the generalised precipitation trend pattern seen in PRCPTOT, except where trends are effectively zero.

For each station with significant or weakly significant trends (Table 4 and 5), the direction of these significant or weakly significant trends is generally consistent with the direction of that station’s PRCPTOT trend, whether the PRCPTOT trend itself is significant, or not. The two notable exceptions are the SDII trends for Gwavas and Martinborough over 1930-2004, and the SDII trend for Martinborough over 1950-2004. For these east coast North Island sites, total rainfall has decreased (non-significantly), but daily intensity (with more rain per rain day) has increased. This may be due to undetected data discontinuities, be caused by a ‘real’ (but unknown) climate forcing, or reflect a relative sensitivity to the number of rain days versus total wet-day rainfall, since the SDII index is based on both these measures of rainfall

4.3 PRCPTOT and Rx1day relationship, consistency between periods

Figure 13 and Table 6 reflect the general consistency in trend direction and magnitude between indices at each site. Figure 13 illustrates the strong relationship between mean annual (PRCPTOT) and extreme daily (Rx1day) precipitation. The regression slopes for both periods approximate 1 (1.2 for the 1930-2004 period, 0.8 for the 1950-2004 period including Appleby and Waiouru, and 0.9 for the 1950-2004 period without Waiouru or Appleby), implying that extreme daily rainfall (Rx1day) is changing at a similar rate to the annual rainfall (PRCPTOT). This is an important result for two reasons: the relationship between annual rainfall and extreme daily rainfall has been generally consistent over the two periods, and historically, increasing (decreasing) mean rainfalls have corresponded to increasing (decreasing) daily rainfall extremes. Exceptions are located in eastern or northeastern areas of the country, i.e. Hanmer Forest, Gwavas, Appleby, with decreased PRCPTOT but increased Rx1day (although trends are not always significant). The relationship between mean annual and extreme daily rainfall is much stronger (R^2 = 0.71) for the longer period than for the latter period (R^2 = 0.39), for which Appleby and Waiouru seem rather anomalous. Removing these two sites increases the 1950-2004 R^2 value to 0.51. As metadata show station changes at both of these sites post 1980 (although homogeneity checks did not flag these as statistically significant), there may be valid reasons to remove these data. However, the relationship between mean and extreme rainfall remains weaker over the warmer 1950-2004 period, even with these stations removed.

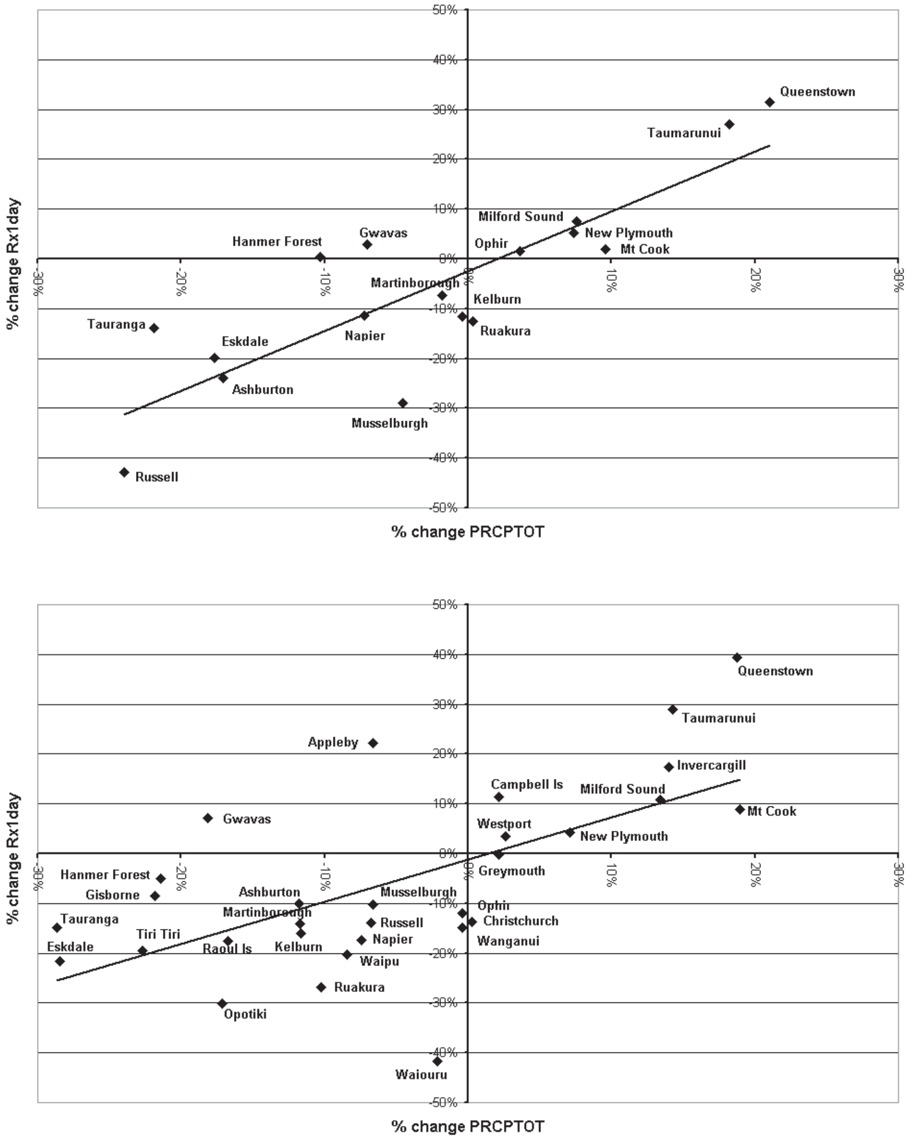


Figure 13: Percentage change in Rx1day versus PRCPTOT. Top panel: 1930-2004 data (R^2 = 0.71, slope = 1.2). Lower panel: 1950-2004 data (R^2 = 0.39, slope = 0.8)

% change	**Rx1day**	**Rx5day**	**PRCPTOT**
Ruakura	-13%	-15%	0%
Taumarunui	27%	27%	18%
New Plymouth	5%	13%	7%
Kelburn	-12%	-1%	0%
Russell	-43%	-42%	-24%
Tauranga	-14%	-14%	-22%
Eskdale	-20%	-25%	-18%
Napier	-11%	-13%	-7%
Gwavas	3%	-4%	-7%
Martinborough	-7%	-25%	-2%
Mt Cook	2%	5%	10%
Milford Sound	8%	6%	8%
Queenstown	31%	24%	21%
Hanmer Forest	0%	-5%	-10%
Ashburton	-24%	-28%	-17%
Ophir	2%	7%	4%
Musselburgh	-29%	-16%	-5%
Raoul Is.	-17%	-5%	-17%
Ruakura	-27%	-34%	-10%
Taumarunui	29%	21%	14%
New Plymouth	4%	9%	7%
Waiouru	-42%	-22%	-2%
Wanganui	-15%	-21%	0%
Kelburn	-16%	-18%	-12%
Russell	-14%	-21%	-7%
Waipu	-20%	-11%	-8%
Tiri Tiri	-19%	-23%	-23%
Tauranga	-15%	-28%	-29%
Opotiki	-30%	-38%	-17%
Gisborne	-9%	-4%	-22%
Eskdale	-22%	-11%	-28%
Napier	-17%	-11%	-7%
Gwavas	7%	1%	-18%
Martinborough	-14%	-38%	-12%
Westport	3%	1%	3%
Greymouth	0%	0%	2%
Mt Cook	9%	6%	19%
Milford Sound	11%	20%	13%
Queenstown	39%	26%	19%
Invercargill	17%	16%	14%
Appleby	22%	16%	-7%
Hanmer Forest	-5%	-21%	-21%
Christchurch	-14%	-7%	0%
Ashburton	-10%	-30%	-12%
Ophir	-12%	7%	0%
Musselburgh	-10%	-3%	-7%
Campbell Is.	11%	-8%	2%

Table 6: Percentage change in Rx1day index, Rx5day index and PRCPTOT index. Top table: 1930-2004 data. Lower table: 1950-2004 data

A temporal comparison of significant or weakly significant trends in the 17 stations with data covering both analysis periods (Table 5) reveals that the significance of trends has increased in the later period for the PRCPTOT, R20, R25 and CDD indices. Russell, Taumarunui and Queenstown are notable cases where trend significance in the later period has decreased. Although the 1950-2004 trends are all in the same direction as for the 1930-2004 period at these 3 sites, the level of significance has reduced for the R99p, Rx1day, Rx5day, SDII and R10 indices. However, analysis of p-values for the 1950-2004 period for these 3 stations (not shown) reveals that the p-values are often < 0.15 and usually < 0.25 for these indices at these 3 sites. Overall, the temporal consistency in trend direction between 1930-2004 and 1950-2004 is strong when trends are significant or approaching significance.

4.4 Seasonal Rx1day trends

Seasonal trends in Rx1day are displayed in Table 7 for 16 sites for the period 1930-2004 (Ophir was removed due to missing data at the monthly scale). For sites loosely labelled ‘eastern North Island’ extreme 1-day rainfalls have generally decreased in summer (consistent with mean rainfall changes since 1977 seen in Salinger and Mullan, 1999) but increased in spring. For eastern South Island sites, extreme 1-day rainfalls have generally, decreased in both spring and summer. The ‘western North Island’ stations show mixed trends. Extreme 1-day rainfall has generally increased in winter (again consistent with mean rainfall changes seen in Salinger and Mullan, (1999) and spring for the sites loosely labelled ‘western South Island’. Note that these conclusions are generalised in nature, with many of the trends not significant.

4.5 Monthly Rx1day correlations with circulation and temperature data

Lastly, a simple correlation analysis using monthly data over the period 1958-2004 was undertaken for 17 sites between Rx1day, weather type indices, New Zealand-averaged temperature anomaly and circulation indices (Table 8), with

		DJF	MAM	JJA	SON	ANN
Western North Is.	Ruakura	-0.1	0.9	-0.1	-1.2	-1.1
Mixed trends.	Taumarunui	**3.8**	1.2	1.9	1.1	**2.4**
	New Plymouth	-1.7	1.9	0	1.3	0.5
	Kelburn	-1.4	-1	0.8	0.2	-1.1
	Average	0.2	0.8	0.7	0.4	0.2
Eastern North Is.	Russell	**-7.3**	-3.7	-3.3	0.1	**-6**
Less extreme summer rain,	Tauranga	-0.9	0.2	**-3.9**	-1.5	-1.7
More extreme spring rain.	Eskdale	-1.8	-1.8	-0.9	1.3	-2.4
	Napier	-1.8	-1.3	-0.9	1.6	-1.1
	Gwavas	-1	0.9	0.7	2.8	0.3
	Martinborough	0.2	-0.4	-0.1	1.3	-0.5
	Average	-2.1	-1	-1.4	0.9	-1.9
Western South Is.	Mt. Cook	4.2	-3.5	3.7	2.2	0.6
More extreme winter rain,	Milford Sound	-0.5	-2.9	**6.3**	0.4	2.7
More extreme spring rain.	Queenstown	1.1	0.2	**2.6**	1.6	**2.3**
	Average	1.6	-2.1	4.2	1.4	1.9
Eastern South Is.	Hanmer Forest	-1.4	-1.6	1	0	0
Less extreme summer rain,	Ashburton	**-2.3**	0.3	0.2	-0.7	-1.7
Less extreme spring rain.	Musselburgh	-0.5	-1.2	0.1	-1.1	-1.9
	Average	-1.4	-0.8	0.4	-0.6	-1.2

Table 7: Seasonal trends in the Rx1day index (mm/decade) over the period 1930-2004. Grey shading denotes p-value <= 0.10. Grey shading with bolding denotes p-value <=0.05. Additional stippling demarks negative trends from positive trends. (NB: Ophir data removed due to missing monthly data).

p-values adjusted for multiple correlations (i.e. false positive tests arrived at simply by chance) using the Bonferroni correction (Miller, 1981) and the SYSTAT statistical package. Those variables which remained significantly correlated to the Rx1day index, after the Bonferroni correction, were found to be meteorologically plausible.

Table 8 quantifies trends in annual Trenberth and Kidson indices over the period 1958-2004. The frequency of both the TSW (trough in southwest flow) and NE (northeasterly) weather types has significantly decreased since 1958, while the Z1 (westerly winds over central New Zealand) and M1 (southerly winds over the Tasman Sea and New Zealand) indices have weakly increased/ strongly increased, respectively. The New Zealand temperature anomaly has also weakly increased over the period analysed Significant correlations between weather types and the Rx1day index appear to be localised, and relatively infrequent. Of the 12 weather type frequency indices (Figure 2), only 3 types (TSW, NE, R) were related to daily rainfall extremity at a number of rainfall sites, while 3 types (related to blocking highs) were correlated with only 1 or 2 specific sites. However, the significant relationships between daily rainfall extremes and weather type frequencies that were identified were consistent with an analogous weather map, and made meteorological ‘sense’.

	TSW	T	SW	NE	R	HW	HE	W	HNW
Ruakura	0.12	-0.01	-0.07	**0.18**	-0.04	0.00	0.02	-0.05	-0.12
Taumarunui	0.07	0.15	0.00	0.08	-0.04	-0.06	0.03	0.03	-0.07
New Plymouth	0.02	0.00	-0.10	0.09	-0.02	0.03	0.11	-0.03	-0.13
Kelburn	0.11	0.05	-0.05	0.01	0.01	-0.06	0.09	-0.02	-0.06
Russell	0.11	-0.09	-0.15	**0.20**	0.02	0.01	0.01	-0.11	-0.10
Tauranga	0.10	-0.11	-0.11	0.19	0.02	0.02	0.06	-0.13	-0.12
Eskdale	0.16	-0.03	-0.14	0.11	**0.26**	0.03	-0.01	-0.08	-0.14
Napier	**0.18**	-0.02	-0.08	0.05	**0.20**	0.05	-0.04	-0.09	-0.13
Gwavas	0.14	-0.01	-0.14	**0.17**	**0.25**	0.09	-0.02	-0.10	**-0.18**
Martinborough	0.13	0.05	-0.07	0.07	0.10	-0.05	0.02	-0.03	-0.08
Mt Cook	-0.12	0.11	0.01	-0.07	-0.07	0.00	0.11	0.19	-0.01
Milford Sound	**-0.17**	0.05	0.02	-0.06	-0.12	-0.06	0.07	0.23	0.08
Queenstown	-0.13	0.09	0.09	-0.11	-0.15	-0.12	0.08	0.36	0.11
Hanmer Forest	**0.27**	0.02	-0.10	0.05	0.11	-0.07	0.00	-0.12	-0.15
Ashburton	**0.25**	0.00	-0.05	0.10	**0.19**	0.03	-0.06	-0.18	-0.14
Ophir	0.02	-0.08	-0.03	0.13	0.10	0.03	0.03	0.02	-0.04
Musselburgh	0.12	0.03	-0.01	0.10	0.08	-0.05	-0.05	-0.03	-0.10
Annual trend	**-0.054**	-0.014	0.039	**-0.052**	0.011	0.008	0.007	0.017	0.022

	TNW	HSE	H	Z1	Z2	M1	M2	NZT
Ruakura	0.07	0.04	-0.09	-0.03	-0.11	0.03	-0.14	0.03
Taumarunui	0.10	-0.10	-0.12	0.11	-0.04	0.09	-0.12	0.07
New Plymouth	0.12	0.08	-0.12	-0.01	-0.15	-0.01	**-0.19**	0.12
Kelburn	0.12	-0.04	-0.09	-0.03	**-0.19**	0.08	-0.14	-0.02
Russell	0.05	0.11	-0.04	**-0.21**	-0.13	0.02	**-0.27**	0.12
Tauranga	0.12	0.09	-0.08	**-0.19**	-0.14	-0.03	**-0.21**	0.08
Eskdale	0.05	0.06	-0.15	**-0.26**	-0.13	-0.03	-0.15	0.01
Napier	0.04	0.03	-0.12	**-0.23**	-0.15	0.03	-0.08	-0.03
Gwavas	0.09	0.05	**-0.19**	**-0.25**	**-0.21**	0.14	-0.15	-0.02
Martinborough	0.08	-0.01	-0.12	-0.07	**-0.16**	0.08	-0.11	-0.01
Mt Cook	0.02	-0.05	-0.06	0.34	**0.19**	-0.07	-0.07	**0.18**
Milford Sound	-0.07	0.00	0.02	0.35	**0.27**	-0.08	0.04	**0.22**
Queenstown	0.00	**-0.16**	0.02	**0.36**	**0.18**	-0.04	-0.03	**0.17**
Hanmer Forest	0.08	0.03	-0.10	**-0.23**	**-0.33**	0.05	-0.13	-0.09
Ashburton	0.07	0.02	-0.16	**-0.21**	**-0.29**	0.13	-0.06	-0.16
Ophir	0.05	-0.01	-0.08	0.05	-0.07	0.01	-0.10	0.10
Musselburgh	0.08	-0.01	-0.11	0.05	**-0.23**	0.06	-0.03	-0.03
Annual trend	-0.010	-0.009	0.036	0.181	0.026	**0.541**	-0.044	0.008

Table 8: Correlations of monthly Rx1day (mm) with monthly frequency indices of Kidson weather type (% of time) and Trenberth circulation indices and New Zealand temperature(NZT) anomaly (C), based on monthly data over the period 1958-2004 inclusive. Trends and significance in annual Trenberth and Kidson indices (1958-2004) are also shown at the bottom of each table. Grey shading denotes p-value <= 0.10. Grey shading with bolding denotes p-value <=0.05. (P-values adjusted for multiple testing using Bonferroni corrections). Additional stippling demarks negative correlations from positive correlations.

In contrast, the zonal circulation indices Z1 and Z2 were highly correlated to extreme 1-day rainfall magnitude at numerous stations (Table 8), with positive correlations in western sites of the South Island (Mt. Cook and Milford Sound), and numerous negative correlations in eastern sites of both islands. This is consistent with relationships between annual rainfall and mean circulation changes (Salinger and Mullan, 1999), the increasing strength and frequency of extreme daily westerly flow (daily Z2) to the south of New Zealand since the 1960s (Salinger et al, 2005), and the increasing trend in the annual Z1 index (westerly winds over central New Zealand) during 1958-2004 (Table 8).

The meridional index M2 (southerly flow between Hokitika and the Chatham Islands) was negatively correlated with sites sheltered (exposed) from rainfall in southerly (northerly) flows (Tauranga, Russell, New Plymouth), which is consistent with orographic sheltering/exposure. Mean rainfall in these regions is known to be extremely sensitive to the absence or presence of northerly winds. However, the significant increase in the annual M1 index (southerly flow between Tasmania and the Chatham Islands) over the 1958-2004 period did not yield any significant monthly correlations between station extreme daily rainfall and M1 circulation strength.

Several sites showed significant links to New Zealand temperature anomaly over the period 1958-2004. Daily rainfall extremity is positively correlated to temperature anomaly at Queenstown, Mt. Cook and Milford Sound, but negatively correlated at Ashburton (with increased Rx1day linked to below average temperatures). The latter case is consistent with cooler, southeasterly flows over the southeast of the South Island, as produced by the TSW pattern, which was also highly correlated to extreme daily rainfall at Ashburton.

Overall, Table 8 showed numerous significant relationships between indices of westerly circulation and extreme daily rainfall, and several significant correlations between New Zealand temperature and daily rainfall extremity. In addition, at several sites, multiple significant correlations between extreme 1-day rainfall magnitude and circulation indices or weather types existed - the *combination* of which are plausible and consistent with orographic or synoptic rainfall patterns in New Zealand. For example, Russell has shown a general decrease in Rx1day (extreme daily rainfall) since the 1930s (Figure 9), but also since

1958 (not shown). The decrease in daily rainfall extremity at this site since 1958 coincides with a decrease in the frequency of northeasterly flows (NE weather type), which can climatologically yield heavy rainfall events in the northeast of New Zealand, and an increase in westerly circulation over central New Zealand (Z1), which climatologically yields reduced-intensity precipitation (e.g. showers versus prolonged rainfall events) in eastern areas.

5. Discussion and conclusions

Atmospheric circulation is known to have a major impact on regional mean rainfall in New Zealand because of the large orographic component of rainfall in this country. New Zealand-region circulation is significantly influenced by well-known climate cycles such as ENSO, the IPO, and the SAM; and climate change modelling predicts altered (increased) westerly circulation for New Zealand under enhanced warming. Although global studies on rainfall extremes often show a tendency towards wetter conditions throughout the 20th century, previous New Zealand research (of a somewhat limited scope) showed that trends in daily rainfall extremes exhibited clear west/east differences across the major axial mountain ranges, suggesting that circulation had had a major impact on New Zealand rainfall extremes.

New Zealand-average air temperatures increased by approximately 0.9 ºC between 1930 and 2004 (with over half this warming observed since 1950). Westerly circulation over central New Zealand, although subject to decadal variation consistent with IPO phase, has increased by a small margin over the 1930-2004 period, and significantly increased (at the 10% level) during 1950-2004. This increase in westerly circulation is consistent with the enhanced warming since 1950, as predicted by climate change modelling; the strong IPO westerly phase since 1977; the increased frequency of El Nino events since 1977; or a mixture of all of these considerations.

This research aimed to investigate the relationship between circulation, and warming, and New Zealand daily rainfall extremes, using high-quality, station data analysed over two analysis periods: 1930-2004 and 1950-2004. Of considerable interest was whether the trends for the later (warmer) period differed from those for the earlier period. Eleven annual indices of daily rainfall extremity were calculated, consistent with global methodology.

Similarly to previous studies, a zonal (west/east) pattern in extreme rainfall trends was evident across the main axial mountains of both islands, with increases in mean and extreme daily rainfall generally seen to the west of a line from Westport to Invercargill, to the west of a line Kelburn to Waiouru to Ruakura, and at Campbell Island. Decreasing mean and extreme rainfall, and increasing dry spell duration, was generally seen in the north and east of both islands and at Raoul Island. This zonal pattern was consistent over both the 1930-2004 and 1950-2004 periods.

The strong consistency of trends (spatially, temporally, and between indices) is notable and adds robustness to the indices methodology employed here.

The strong regional nature of trends (e.g. similar trends within the northeast of the North Island) adds weight to the results - even though trends at many sites did not reach statistical significance - and reassures us that data inhomogeneities have probably been minimised as much as is practicable. Although many trends were not statistically significant, trend significance for both analysis periods was generally largest in the northeast of the North Island, the southwest of the South Island, followed by Taranaki and the King Country. The indices that showed most statistical significance were PRCPTOT, SDII, R20, R25, and R95p - which reflects lower index ‘noisiness’ to a large degree – the exception being the R95p index.

Temporal consistency in trends between the two periods is notable - given the temperature difference between the two periods - and implies that (increased westerly) circulation is a major influence on extreme rainfall in New Zealand. One exception was SDII, a simple intensity measure (rainfall per rain day) which showed differences at several sites between the two periods. However, the SDII may be sensitive to the number of rain days observed.

The trend consistency between indices (especially PRCPTOT, R10, R20 and R25) lends further robustness to the index approach. Trends in all 11 indices of rainfall extremity over both periods generally exhibit ‘internal’ consistency at a station – that is, at a station with significant or weakly significant trends in rainfall extremity, the direction of these trends is consistent with changes in PRCPTOT e.g. at stations where mean rainfall has increased (decreased), daily rainfall extremity has also increased (decreased).

In fact, the relationship between daily rainfall extremity (Rx1day) and mean rainfall change (PRCPTOT) is so strong that the regression slope between observed percentage change in PRCPTOT versus the observed percentage change in Rx1day is close to 1, over both 1930-2004 and 1950-2004 periods. However, the relationship was weaker (with more scatter) in the warmer 1950-2004 period, and at a few eastern, coastal sites.

A more detailed analysis of Rx1day over the period 1958-2004 was then undertaken, given that flooding in New Zealand is typically due to synoptic features or convective rainfall, both with durations of 1 day or less. A seasonal analysis implied reduced summer extreme daily rainfall magnitude for eastern areas of both islands, and increased extremity in winter and spring in the western South Island, although very few of the observed trends were significant. Significant correlations between weather types and the monthly Rx1day index were localised and relatively infrequent (although they were meteorologically plausible and consistent with an analogous weather map). In contrast, both the zonal (westerly) circulation indices Z1 and Z2 were highly correlated with extreme 1-day rainfall magnitude at numerous stations (at about half the sites for both Z1 and Z2), with positive correlations in western areas of the South Island, and negative correlations at eastern sites of both islands. Four of the 17 sites showed significant links to New Zealand-averaged temperature anomaly over the period 1958-2004, with 3 sites (Mt. Cook, Milford Sound, Queenstown) in the western South Island showing increased daily rainfall extremity with increased temperatures.

In conclusion, this analysis has extended the knowledge of historical trends in New Zealand rainfall extremes since the 1930s, and made preliminary links to mechanisms behind the observed changes. Trends in extreme daily rainfalls in New Zealand showed spatial and temporal consistency, even against a background of warming. Regional variation in observed trends of extreme daily rainfall indices was strongly evident, consistent with increases in westerly circulation over New Zealand. Changes in extreme daily rainfalls were strongly related to changes in mean rainfall, although the relationship was weaker in the later (warmer) period. Station 1-day rainfall extremity was highly correlated to zonal flow across the country, and to a much lesser extent, to meridional flow and New Zealand-averaged temperature anomaly. It is hoped that the results found here will prove helpful for studies predicting future changes in extreme rainfalls in New Zealand under altered circulation regimes or enhanced greenhouse conditions.

Acknowledgements

This research was supported by the New Zealand Foundation for Research, Science and Technology, contract No. C01X0202. Thanks to Drs Brett Mullan and Jim Renwick, NIWA, for help with methodology, manuscript review, and calculation of updated Trenberth circulation and Kidson weather type data. Additional thanks to two anonymous reviewers for their useful contributions.

References

Aguilar, E., Auer, I., Brunet, M., Peterson, T. C. and Wieringa, J., 2003. *Guidelines on Climate Metadata and Homogenization, WCDMP* **53**, WMO-TD 1186, 55 pp., World Meteorol. Org., Geneva, Switzerland.

Alexander, L. V., X. Zhang, T. C. Peterson, J. Caesar, B. Gleason, A. Klein Tank, M. Haylock, D. Collins, B. Trewin, F. Rahimzadeh, A. Tagipour, K. Rupa Kumar, J. Revadekar, G. Griffiths, L. Vincent, D. Stephensonh, J. Burnh, E. Aguilar, M. Brunet, M. Taylor, M. New, P. Zhai, M. Rusticucci, and J. L. Vazquez-Aguirre, 2006. Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res*, **111**, D05109, doi:10.1029/2005JD006290.

Hennessy K.J., Suppiah R., Page C.M., 1999. Australian rainfall changes, 1910–1995. *Australian Meteorological Magazine* **48**, 1–13.

Kidson, J.W., 2000. An analysis of New Zealand synoptic types and their use in defining weather regimes. *Int. J. Climatol.,* **20**, 299-316.

Larsen, H. and Gray, W. 2003. Estimating the effect of Global Climate Change on orographic precipitation. *Proceedings from the 7th International conference on Southern Hemisphere Meteorology and Oceanography, Wellington,* 24-28 March 2003, pages 54-55

Manton, M.J., Della-Marta, P.M., Haylock, M.R., Hennessy, K.J., Nicholls, N., Chambers, L.E., Collins, D.A., Daw, G., Finet, A., Gunawan, D., Inape, K., Isobe, H., Kestin, T.S., Lefale, P., Leyu, C.H., Lwin, T., Maitrepierre, L., Ouprasitwong, N., Page, C.M., Pahalad, J., Plummer, N., Salinger, M.J., Suppiah, R., Tran, V.L., Trewin, B., Tibig, I., Yee, D., 2001. Trends in extreme daily rainfall and temperature in southeast Asia and the South Pacific: 1916-1998. *Int. J. Climatol.,* **21**, 269-284.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteor. Soc.,* ***78**,* 1069–1079.

McKerchar, A. I. and Pearson, C. P., 2001. Factors causing flooding to be New Zealand's number one hazard. *Tephra*, February 2001. Vol **18**, 9-15.

Miller, R.G., 1981. *Simultaneous Statistical Inference,* 2nd edn. Springer Verlag.

Mullan, A.B. 1995. On the linearity and stability of Southern Oscillation–climate relationships for New Zealand, *Int. J. Climatol., **15**,* 1365–1386.

Mullan, B., 1996. Effects of ENSO on New Zealand and the South Pacific. In: Braddock, D. (ed.) *Prospects and needs for climate forecasting*. Miscellaneous Series 34, pp. 23–27. Royal Society of New Zealand, Wellington.

Mullan, A.B., Wratt, D.S., and Renwick, J.A., 2001. Transient model scenarios of climate changes for New Zealand. *Weather and Climate*, **21**, 3-34.

Power, S., Casey, T., Folland, C.K., Colman, A and V. Mehta, 1999. Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics*, **15**, 319-323.

Renwick, J. and Thompson, D. 2006. The Southern Annular Mode and New Zealand climate. *Water & Atmosphere* **14**(2), 24-25.

Salinger, M.J. 1980. The New Zealand temperature series, *Clim. Mon*., **9**, 112-118.

Salinger, M.J. and Mullan, A.B. 1999. New Zealand climate: Temperature and precipitation variations and their links with atmospheric circulation 1930-1994. *Int. J. Climatol.,* **19**, 1049 -1071.

Salinger, M.J. and Griffiths, G.M. 2001. Trends in New Zealand daily temperature and rainfall extremes. *Int. J. Climatol.,* **21**, 1437-1452.

Salinger M.J., Griffiths, G.M., and Gosai, A. 2005. Extreme pressure differences at 0900 NZST and winds across New Zealand. *Int. J. Climatol.,* **25**, 1203-1222.

Salinger, M.J., Renwick, J.A., and Mullan, A.B., 2001. Interdecadal Pacific Oscillation and South Pacific climate. *Int. J. Climatol., **21***, 1705-1721.

Szentimrey, T., 2002. *Multiple Analysis of Series for Homogenization (MASH v2.03): Program user's guide.*

Trenberth, K.E., 1976. Fluctuations and trends in indices of the Southern Hemisphere circulation. *Quart. J. Royal Meteor. Soc*., **102**, 65-75.

Trewin B.C. and Trevitt A.C.F., 1996. The development of composite temperature records. *Int. J. Climatol.,* **16**, 1227-1242.

Wessel, P. and Smith, W.H.F., 2001. *The Generic Mapping Tools GMT Version 3.4 – Technical Reference and Cookbook*, downloaded from http://gmt.soest.hawaii.edu/ in January 2004.

Zhang, X., Vincent, L. A., Hogg, W. D. and Niitsoo, A. 2001. Temperature and precipitation trends in Canada during the 20th century, *Atmos. Ocean*, **38**, 395–429.

Zhang X. and Yang. F., 2004. *RClimdex (1.0) User Manual*, downloaded from cccma.seos.uvic.ca/ETCCDMI in October 2004.

Submitted to Weather and Climate December 2005, revised November 2006.