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Decadal climate variability of extreme rainfalls in New Zealand

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Abstract

Design rainfalls rely on the assumption that the extremes in storms are independent of each other, and that the expected frequency of high intensity rainfall does not change from year to year. Recent climate studies in New Zealand on rainfall and river flow have shown that persistent climate states, such as the Interdecadal Pacific Oscillation (IPO), can have significant impacts on these variables in the north and northeast of the North Island and the southwest and south of the South Island (McKerchar, 2002). As a consequence, the underlying assumption of stationarity in the high intensity rainfall frequency may be invalid. For a number of locations in New Zealand, this study describes the influence of the IPO on annual maximum rainfall series for 1-, 12- and 24-hour durations over the period 1946-1999, which coincides with the two identified phases of the IPO. At 1-hour the IPO influence appears to be quite small, if present at all, but at 24-hours the influence is stronger with some significant results in the same regions as indicated above. Current rainfall and flood frequency analysis does not conditionally stratify data according to climate state, and this has implications for assessing the risk in the more frequently occurring severe storms.

Introduction

Design rainfalls are required in many applications of hazard mitigation, and storm or wastewater infrastructure development. A design rainfall is a probabilistic (or statistical) estimate that has been derived from a frequency or probability analysis of extreme rainfall data. The quality of

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the rainfall estimate depends on the length and quality of the rainfall records that are collected over the previous decades. Standard underpinning assumptions in the estimation of design rainfalls are firstly, that the annual maxima are independent of each other, and secondly, that the expected frequency of high intensity rainfall does not change from year to year. The presence of persistent climate states may upset the validity of the second assumption. These states are associated with large-scale atmospheric and oceanic patterns over the Pacific Ocean, with two dominant climate oscillations being the interannual El Niño-Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO). Both these phenomena have pronounced signals in the sea surface temperature (SST) of the Pacific Ocean, with the recently identified IPO displaying 'ENSO-like' climate features that operate on decadal to multidecadal time scales (Folland et al., 1999; Power et al., 1999; Salinger et al., 2001).

A time series of the IPO (Figure 1), provided by the Hadley Centre of the United Kingdom Meteorological Office, is derived from the third EOF pattern of 13-year low-pass filtered global SST. The figure shows

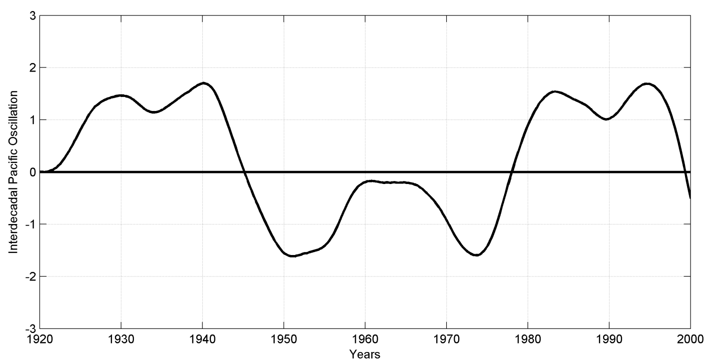

Figure 1. Time series of the Interdecadal Pacific Oscillation from 1920-2000, from data supplied by the Hadley Centre, United Kingdom Meteorological Office. The IPO is derived from the third EOF pattern of 13-year low pass filtered global SST.

three major phases during the 20th century: positive phases in 1920-1944 and 1978-1999, and a negative phase between 1946-1977. These shifts appear to modulate the frequency and intensity of ENSO: during the last positive phase of the IPO there were more El Niño episodes and fewer La Niña ones than during the preceding negative IPO phase. Recent rainfall and flood investigations in the New Zealand region (Salinger and Mullan, 1999; Salinger et al, 2001; McKerchar, 2002; McKerchar and Henderson, 2003) have shown that the most recent phase of the IPO (1978-1999) was consistently drier by up to 8 percent in the north and east of the North Island than the earlier phase (1946-1977). River flows became less variable with fewer floods. Gray (2003, pers. comm.) found that while the frequency of rainfall events remained relatively constant, there were appreciable differences in the frequency of extreme events in each phase of the IPO that contributed to the drier conditions. By contrast, in the south and west of the South Island there were increases of more than 8 percent in both rainfalls and river flows since 1978 when compared to the 1946-1977 period.

Given that the climate states persist on decadal time scales, McKerchar (2002), McKerchar and Henderson (2003), and Franks and Kuczera (2002) question whether the assumptions underpinning frequency analysis remain valid. If the data can no longer be automatically assumed to be "statistically stationary", they need to be stratified according to the dominant climate state. The aim of this study therefore is to assemble time series of extreme rainfall covering one complete IPO cycle to investigate the extent of the influence of the IPO on high intensity rainfall over New Zealand. Annual maxima are extracted and robust non-parametric statistical tests are applied to identify which regions of New Zealand appear to have coherent and pronounced changes in extreme rainfall.

Data and Methodology

Rainfall records from NIWA's Climate Database and Water Resources Archive were used in this study. Annual maximum rainfall series for durations of 1-hour, 12-hours and 24-hours were extracted from monthly maxima. These three durations were chosen to reflect the dominant atmospheric processes and scales of motion associated with the rainfall identified by Houze (1981): at 1-hour convective/mesoscale precipitation systems; at 24-hour stratiform precipitation and synoptic scale weather patterns; and at 12-hour either a transition from, or a combination of both convective and stratiform processes.

Annual maximum rainfall series for 27 locations throughout New Zealand (see Figure 2) were chosen, largely on the basis of record

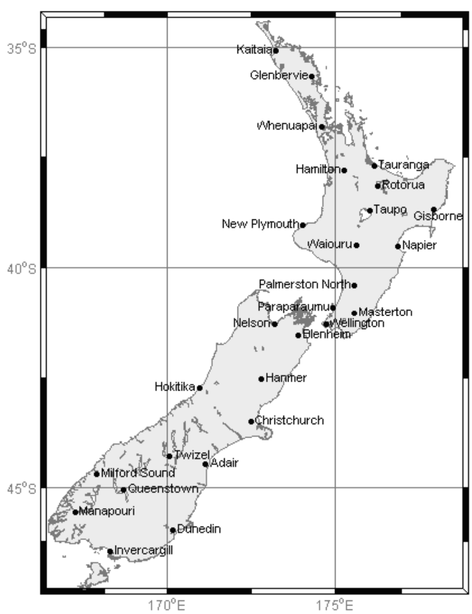

Figure 2. Location of sites used in study. Details of each station's data record are given in Table 1.

Table 1. Locations used in this study identifying which sites have composite records from one or more nearby sites. The Wilcoxon Ranksum Test for homogeneity assessment of composite records shows which locations are significant to at least the 0.1 level, and for what duration.

Site	Composite Record	Record Length 24h	Record Length 1 & 12h	Wilcoxon Ranksum Test
Kaitaia	Yes	1946-1999	1950-1999	1h: p=0.08
Glenbervie	Yes	1946-1999	1967-1999	12h: p=0.07
Whenuapai	Yes	1946-1999	1946-1999	
Hamilton	Yes	1946-1999	1969-1995	24h: p=0.04
Tauranga	No	1946-1999	1962-1994	
Rotorua	Yes	1946-1999	1967-1996	
Taupo	Yes	1946-1999	1950-1999	
Waiouru	Yes	1946-1999	1967-1996	
New Plymouth	No	1946-1999	1949-1996	
Gisborne	Yes	1948-1999	1948-1990	
Napier	No	1946-1999	No data	
Masterton	No	1946-1999	No data	
Palmerston North	No	1946-1999	1948-1998	
Paraparaumu	No	1953-1999	1955-1999	
Wellington	No	1946-1999	1946-1999	
Nelson	Yes	1946-1999	1946-1992	
Hokitika	Yes	1946-1999	1968-1999	
Milford Sound	No	1946-1999	1967-1999	
Blenheim	No	1946-1999	1967-1984	
Hanmer	No	1946-1999	No data	
Christchurch	No	1946-1999	1955-1993	
Adair	Yes	1946-1999	1967-1998	
Twizel	Yes	1953-1996	No data	24h: p=0.04
Queenstown	No	1946-1999	1969-1999	
Dunedin	No	1946-1999	1968-1996	
Manapouri, West Arm	No	1946-1999	No data	
Invercargill	No	1946-1999	1946-1999	

length, although at 13 locations composite rainfall series were developed from one or more close or nearby sites. Table 1 provides details of the rainfall records used. Most of these sites had 24-hour data spanning at least the two phases of the IPO from 1946-1999 while for the shorter durations there are just three sites that have data for the entire 54-year period. The homogeneity of the composite series was assessed with the non-parametric Wilcoxon Ranksum test (Robson et al., 2000). This metric, also known as the Mann-Whitney test, is a powerful rank-based test that makes no assumptions about the statistical distribution of the data, and assesses whether the median values in each constituent sample are similar. If a significant difference exists between the two samples, most of the lower ranks will be occupied by values from one sample, with the higher ranked data mostly in the other sample. No overall adjustments for site changes were made to any of the composite records even though at four sites (Kaitaia, Glenbervie, Hamilton, and Twizel) the test indicated heterogeneity in their time series. While methods exist for removing or reducing inhomogeneities in monthly and annual climate records, the adjustment of very short duration data is fraught with difficulties when the random and sporadic nature of rainfall is considered.

A straight-forward method to investigate changes in extreme rainfall regimes due to multi-decadal climate shifts is to stratify the rainfall record into two or more non-overlapping samples and test for differences between the samples (Franks and Kuczera, 2002). The strength of this approach to resolve differences between the different samples depends on how the data are stratified. Independent climate information, here the polarity of the IPO (Figure 1), is used to stratify the annual maximum rainfall series. Using independent climate information as the basis of sample splitting provides robust results (Franks and Kuczera, 2002) when testing whether the two samples belong to the same stochastic distribution, or are samples from different distributions. The non-parametric Wilcoxon Ranksum test, described earlier, is used to test for significant differences between annual maximum rainfalls stratified by the IPO.

Results and Discussion

The effect of stratifying a rainfall series by the IPO can be seen in Figure 3 for Milford Sound, in the southwest of the South Island, where

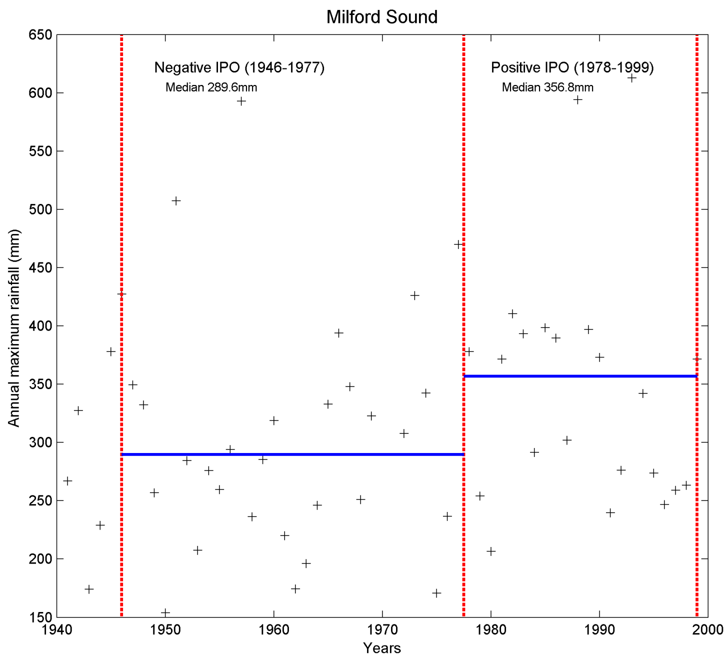

Figure 3. 24-hour annual maximum rainfalls measured at Milford Sound for the period 1940 to 1999. The vertical lines delineate the two recent phases of the IPO: a negative phase from 1946-1977 and a positive phase from 1978-1999. The horizontal lines are the median values of the annual maximum rainfall during each phase.

the influence of the IPO is known to be strong (Salinger et al., 2001).
The 24-hour median annual maximum rainfall (or equivalently a 2-year average recurrence interval (ARI) event) is plotted in the figure for the two most recent phases of the IPO. During the positive phase of the IPO (1978-1999), the median annual maximum rainfall has increased

by 23 percent over the earlier phase. However, the mean of the annual maximum rainfall series increased by just 13 percent, and is in line with the 14 percent increase in annual mean river flows for the nearby Clutha River found by McKerchar (2002). For 1-hour and 12-hours, where there were just 8 samples available in the negative phase of the IPO, the median value increased by 19 and 4 percent respectively. The disparate sample sizes used could compromise the power of statistical testing (Franks and Kuczera, 2002) when looking at the significance of any differences in the rainfall.

Another way of comparing the effect of stratifying extreme rainfalls by the IPO is to perform separate frequency analyses. Such an analysis makes use of an extreme value statistical distribution: here a type 1 extreme value (EV1) statistical distribution was fitted using probability-weighted moments (Hosking et al., 1985). An EV1 distribution is used in preference to the more flexible generalized extreme value (GEV) distribution. [Note: The EVI distribution is a special case of the GEV with shape parameter set to zero]. There is a possibility of over-fitting with the GEV from using the small, negative phase IPO, datasets at many sites in this study. With larger amounts of data, for example a complete phase of the IPO, it becomes reasonable to use a GEV distribution for parameter and confidence limit estimation. Figure 4 presents the results from a frequency analysis for the two IPO phases at Milford Sound for the 1- and 24-hour durations. The 90 percent confidence limits associated with the high intensity rainfall estimates are also shown on the figure. Confidence limits take account of the sample size, and a larger uncertainty is displayed in the figure, arising from a short 1-hour record in the negative IPO phase. The plots show increases in rainfalls in the post 1977 period, when compared to the earlier IPO phase. At 24-hours, and for a storm with a 50-year ARI, the rainfall increased from 580 mm to 615 mm, a 6 percent increase. A rainfall extreme associated with a 50-year ARI in the negative IPO

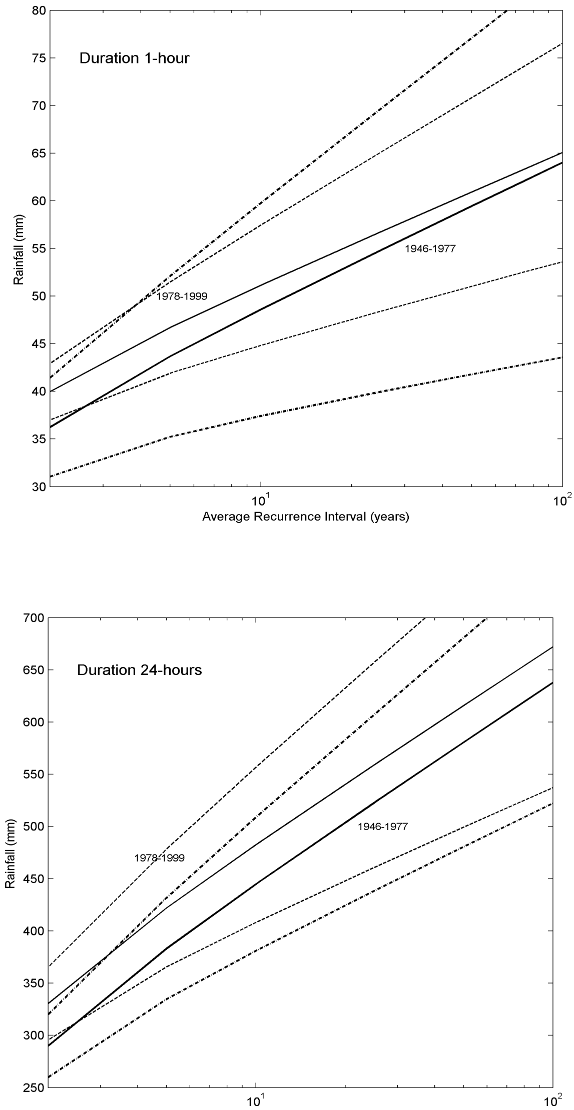

Figure 4. Frequency analysis of extreme rainfalls for 1-hour and 24-hour at Milford Sound. The annual maximum rainfall data were stratified according to phase of IPO, and fitted to an extreme value type 1 distribution using probability-weighted moments. The solid lines are the expected high intensity rainfalls from the analysis, and the dashed lines are the 90 percent confidence limits. The bold lines represent the analysis for the negative phase and the lighter lines the positive phase.

phase corresponds to the expected extreme from a 25-year storm in the following positive phase. At the 1-hour duration, the effect of stratifying the data on the frequency analysis is not as large: the 50-year extreme rainfall estimate increased from 59 mm to 61 mm from one IPO phase to the next, corresponding to about a 35-year event.

Table 2 presents probability levels of the Wilcoxon Rank Sum test and the ratios of the median annual maximum rainfall of the positive IPO phase to the negative phase of the IPO, for the three durations. At 1-hour and 12-hour durations, there are very few sites having a significant relationship according to the phase of the IPO. At 1-hour there are about as many sites in New Zealand having ratios of median annual maximum rainfall greater than unity as there are with ratios less than unity. This would suggest that at this storm scale the influence of the IPO, if present at all, is very weak, and that the convective/ mesoscale precipitation processes are dominant and overwhelms any influence due to the IPO. To what extent global warming has had an influence on the intensity of 1-hour maxima over the 54-year period is unknown. While a 1°C rise in temperature results in an 8 percent increase in water holding capacity of the atmosphere, even larger increases in precipitation are likely arising from the increases in latent heat release that in turn can further intensify storms (Gray 2003, pers. comm.).

At 12-hours, most of the North Island sites experienced generally “less intense” storms during the 1977-1999 IPO phase when compared with the earlier negative phase. For the South Island it is the opposite, with more precipitation in the positive phase of the IPO than in the earlier phase. With this type of split at 12-hours between the North and South Islands, the synoptic scale storm processes (e.g. frontal systems, extra-tropical cyclones etc.) are likely to be the dominant precipitation

Table 2. The results. Probability levels of the Wilcoxon Ranksum Test Statistic of annual maximum rainfall series, stratified according to the phase of the IPO, and ratios of median annual maximum rainfall during the positive phase (1978-1999) of the IPO to the median annual maximum rainfall during the negative phase (1946-1977) of the IPO. Results with an asterisk are significant to at least the 0.1 level of significance.

	1-hour		12-hour		24-hour	
Site	Rsum prob	Ratio	Rsum prob	Ratio	Rsum Prob	Ratio
Kaitaia	0.91	1.10	0.14	0.92	0.91	1.11
Glenbervie	0.68	0.93	0.85	1.11	0.03*	0.75*
Whenuapai	0.88	1.08	0.93	1.01	0.50	0.91
Hamilton	0.17	1.28*	0.07*	0.87	0.05*	0.82*
Tauranga	0.29	0.66*	0.19	0.87	0.03*	0.82*
Rotorua	0.37	1.13	1.00	0.95	0.05*	0.86
Taupo	0.39	0.88	0.95	0.96	0.85	0.97
Waiouru	0.43	0.91	0.40	0.96	0.59	0.92
New Plymouth	0.02*	0.80*	0.80	0.90	0.12	0.87
Gisborne	0.16	0.87	0.55	0.93	0.59	1.01
Napier	-	-	-	-	0.50	0.99
Masterton	-	-	-	-	0.17	0.76*
Palmerston North	0.89	1.00	0.31	0.91	0.11	0.84
Paraparaumu	0.19	1.13	0.73	0.88	0.96	0.96
Wellington	0.17	1.18	0.88	1.03	0.70	0.92
Nelson	0.46	0.85	0.90	0.97	0.53	1.04
Hokitika	0.73	0.99	0.18	1.18	0.25	1.10
Milford Sound	0.18	1.19	0.62	1.04	0.14	1.23*
Blenheim	0.94	1.00	0.41	1.14	0.25	1.17
Hanmer	0.57	0.93	0.97	0.90	0.62	0.87
Christchurch	0.22	1.17	0.97	1.08	0.47	1.03
Adair	0.35	1.11	0.12	1.30*	0.58	1.00
Twizel	-	-	-	-	0.92	1.14
Queenstown	0.09*	1.18	0.05*	1.21*	0.02*	1.32*
Dunedin	0.86	1.07	0.59	0.87	0.80	1.02
Manapouri	-	-	-	-	0.52	1.03
Invercargill	0.07*	1.13	0.01*	1.21	0.04*	1.12

process. One approach of identifying whether the dominant process is indeed synoptic scale, mesoscale or a combination of both is to undertake a break-point type analysis (Sansom and Thompson, 2003) on the maximum data within the framework of hidden semi-Markov models.

The results for 1- and 12-hours may be influenced by about half of the locations having relatively small sample sizes for the 1946-1977 negative IPO phase. These locations had high intensity rainfall records beginning in the mid to late 1960's (Table 1). At 11 locations having at least 22 out of 32 years of annual maximum data, the probability levels from the Wilcoxon Ranksum test were compared with those from the sites having fewer data. The mean and standard deviation (in brackets) of the probability levels are similar being 0.52(0.36) and 0.45 (0.30) for the larger and smaller samples respectively. It is therefore unlikely that the conclusions drawn from the test statistics in Table 2 arise from comparatively small samples during one of the phases of the IPO. This is further supported by the Ranksum test, which showed no significant difference in the probability levels as determined from long or short sets of data.

For longer 24-hour durations, when synoptic processes dominate, there is generally a similar pattern in the ratio of the median annual maximum rainfalls between the phases of the IPO to that seen at 12-hours. The influence of the IPO on these rainfalls appears to be stronger than at 12-hours, with several locations showing significant influences (Table 2). The north and east of the North Island, especially Northland to Bay of Plenty regions, generally experience more intense extreme events during a negative phase of the IPO, while the opposite phase brings the extreme falls to the west and south of the South Island i.e. South Westland, Fiordland, Southland and Central Otago. These are the also regions of New Zealand where IPO and also ENSO influences are felt most strongly (Salinger and Mullan, 1999, Salinger et al, 2001 for annual rainfall; McKerchar, 2002, McKerchar and Henderson, 2003 for river flows.). As with 12-hours, much of the North Island have ratios of the positive to negative IPO's median annual maxima less than unity, and for the South Island this ratio is mostly larger than unity.

The confidence limits of the ratios of the median annual maximum rainfall in the positive phase of the IPO to that in the negative phase can be assessed by resampling methods, such as bootstrapping (Efron, 1979). The bootstrap is a procedure that involves choosing random samples from a dataset and to analyse each sample in the same way. After each analysis the sample is returned to the original dataset, so that another random sample may be chosen. Applying this procedure involved generating 50,000 54-year (the combined length of the two recent IPO phases) annual maximum rainfall series from an EV1 distribution. At each iteration, two data were removed from the original dataset. The generated series was then split into two samples, representing IPO polarity, and ratios of the median annual maximum rainfalls were computed. The 5th and 95th percentiles of the ratios provide an estimate of the 90 percent confidence limit. Across New Zealand, the 90 percent confidence limit is relatively constant: at 1-hour the limits are about 0.80 and 1.25, and for 12- and 24-hours they are 0.85 and 1.20. In Table 2 ratios lying outside the 90 percent limit are highlighted with an asterisk. At 24-hours, several of the sites in Table 2 show significant results for both the ratios of median annual maximum rainfall and Wilcoxon probability levels. These are in the principal regions of New Zealand where the influence of the IPO (and ENSO) is strongest.

The most significant results occur at 24-hours. These are consistent with the findings of Salinger and Mullan (1999) and McKerchar 2002, in that extreme rainfalls and river flows in the north and east of the North

Island have decreased since the late 1970's, and rainfall and river flows have increased in the west and south of the South Island when the polarity of the IPO changes. While the rainfall climate in some regions of New Zealand is influenced by the phase of the IPO, the changes are not always large and statistically significant at the individual sites. This is the case at some the locations assessed in this study (see Table 2). Current rainfall and flood frequency analysis practice (e.g. Thompson, 2002), does not usually stratify rainfall on the basis of climate state, even in the those areas of New Zealand where the IPO impacts appear to be greatest. This may seriously overestimate or underestimate design rainfalls (Franks and Kuczera, 2002) and the potential risks associated with storms and consequential flooding and damage. Without data stratification for climate state, and separate quantile estimation, discrepancies are likely for frequent storms (e.g. the 10- or 20-year ARI events). However, the current practice can still be used to assess the longer-term risks (e.g. at the 100-year ARI) provided the extreme rainfall data adequately samples several climate states (Franks and Kuzcera, 2002). On interannual times-scale, stratification may be on the basis of ENSO, while at the multi-decadal time-scale the IPO could be used. Note that the underlying rainfall distributions in ENSO are comprised of data from different IPO phases, since Salinger et al., (2001) have shown both El Niño and La Niña episodes are modulated by the IPO.

Table 3 gives a selection of results for New Zealand where the extreme rainfall record was stratified on the basis of ENSO into "major" El Niño and La Niña episodes. For this purpose, the Southern Oscillation Index (SOI) was used as the indicator of ENSO. Since the transition from one ENSO state to another usually occurs between March and May, a mean SOI was computed over a June to May year. An El Niño episode occurred when the mean SOI was less than –0.5, a La Niña greater than +0.5. Annual maximum rainfalls for the same "SOI year" were also extracted for the three durations. Of the 27 locations, just three 24-hour duration rainfalls in the north and northeast of the North Island

Table 3. For a selection of the 27 New Zealand locations, probability levels of the Wilcoxon Ranksum Test Statistic of annual maximum rainfall series, stratified according to the episode of ENSO, and ratios of the median annual maximum rainfall during El Niño episodes to the median annual maximum rainfall during La Niña episodes. An asterisk in the table indicates a significant result to at least the 0.1 level of significance.

	1-hour		12-hour		24-hour	
Site	Rsum Prob	Ratio	Rsum prob	Ratio	Rsum prob	Ratio
Kaitaia	0.60	0.84	0.78	0.98	0.09*	0.84
Tauranga	0.99	0.92	1.00	1.08	0.11	0.85
Wellington	0.85	0.94	1.00	0.67	0.94	1.03
Christchurch	0.40	0.88	0.38	0.79	0.74	0.96
Hokitika	0.67	0.94	0.70	1.02	0.84	0.98
Milford Sound	0.34	1.18	0.59	0.96	0.95	0.99
Invercargill	0.16	0.91	0.83	1.01	0.98	0.90

showed a significant influence with ENSO. For the rest of New Zealand, and for the other two shorter durations, the influence of ENSO on extreme rainfalls appears to be small. Stratification of extreme rainfall on the basis of ENSO includes annual maxima that have occurred in one or other phase of the IPO: some of the maxima are large and some are small. The resultant Wilcoxon Ranksum tests in Table 3 suggests that there are a relatively even number of high and low ranked data from each phase of the IPO within the ENSO stratification. Any frequency analysis, providing estimates of high intensity rainfall for risk assessment, is likely for the most part to be similar, at least in the statistical sense.

In this study, annual maximum rainfall series have been used for a priori stratification by climate state, and a similar analysis exercise could be undertaken using partial duration series of maximum rainfalls above some threshold value. Partial duration series usually have more data than in annual maximum rainfall series, and can be used to better capture the underlying processes and distributions of the extreme rainfall, especially when the sample size of the annual series is relatively small.

Conclusions

Previous studies of annual rainfall and monthly river flows have shown that in some areas of New Zealand, namely the north and northeast of the North Island and the southwest and south of the South Island, there have been changes in intensity and mean levels that can be attributed to multi-decadal persistent climate states such as the IPO. At very short durations, extreme rainfalls are used amongst other things for design purposes and hazard mitigation strategies by applying a frequency analysis that is assumed to have independent data, and have expected frequencies that do not change over time. Splitting the extreme rainfall series to reflect the two phases of the IPO has shown that for the 1-hour duration the IPO influence is weak, if present at all, and the noted changes in this study may be a reflection of the mesoscale/convective precipitation processes. However, for 24-hour storm durations in two regions of New Zealand (given above), the rainfall series may not be statistically similar, but appear to be influenced by the climate state which may persist, in the case of the IPO, for two or three decades. As Franks and Kuzcera (2002) have stressed, this has an important implication for assessing the risk of severe storm events. There is a need to distinguish between frequently occurring storm events (e.g. intra-episode ARIs such as a 1 in 20-year storm) on the basis of prevailing climate state, and the less frequently occurring storm (e.g. a 50-year ARI event) where the annual maximum rainfalls span and incorporate the underlying processes of the different climate states.

Acknowledgements

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