Drivers of extreme daily rainfalls in New Zealand

Georgina Griffiths*

National Institute of Water and Atmospheric Research (NIWA), Auckland, New Zealand

Abstract

Extreme daily rainfalls ('Rx1day') from 22 high-quality station rainfall records across New Zealand were assessed at a monthly, seasonal and annual time scale, and associated with a corresponding daily Kidson synoptic classification ('weather') type. Three Kidson weather types were over-represented with regards annual Rx1day occurrence at many of the stations (TSW, TNW, and NE), but clear regional distinctions were observed in the dominant weather type associated with extreme daily rainfalls. This finding is consistent with the differing circulation related to each Kidson type and the large orographic component of New Zealand daily rainfall. Subtle seasonal variations in Kidson weather type dominance were observed. Monthly Rx1day anomalies were averaged for each of the four seasons, and correlated with seasonal average measures of the El Niño Southern Oscillation and the Southern Annular Mode, which are known to influence Kidson type frequency, as well as the Indian Ocean Dipole. Useful relationships were found, which varied by season and by region. However, further work is required to develop a skilful predictive scheme of extreme rainfall risk based on circulation drivers. Recent advances in the prediction of Kidson weather types, using NWP or ensemble techniques such as those currently employed at NIWA, may mean that Kidson weather typing becomes the most likely route to skilful, intra-seasonal prediction of extreme daily rainfalls in New Zealand.

1. Introduction

The synoptic climatology approach has been widely used in New Zealand to define local climate variability and its impacts. For example, the Kidson synoptic classification scheme (Kidson, 2000) has been used to determine relationships between weather type and winter hospital admissions in Auckland (Baldi et al. 2009), regional fire risk (Gosai et al. 2003), and

*Corresponding author address: G. M. Griffiths, NIWA, Private Bag 99940, Auckland 1149 NEW ZEALAND. e-mail: gm.griffiths@niwa.co.nz

east coast South Island river catchment annual peak flow (McKerchar et al. 2010). Kidson (2000) defined 12 synoptic weather types using twice-daily fields of 1000 hPa height from the NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) reanalyses (Kistler et al. 2001). These 12 weather types are shown in Figure 1, and are named "T" for Trough, "SW" for Southwesterly, "TNW" for Trough-Northwesterly,

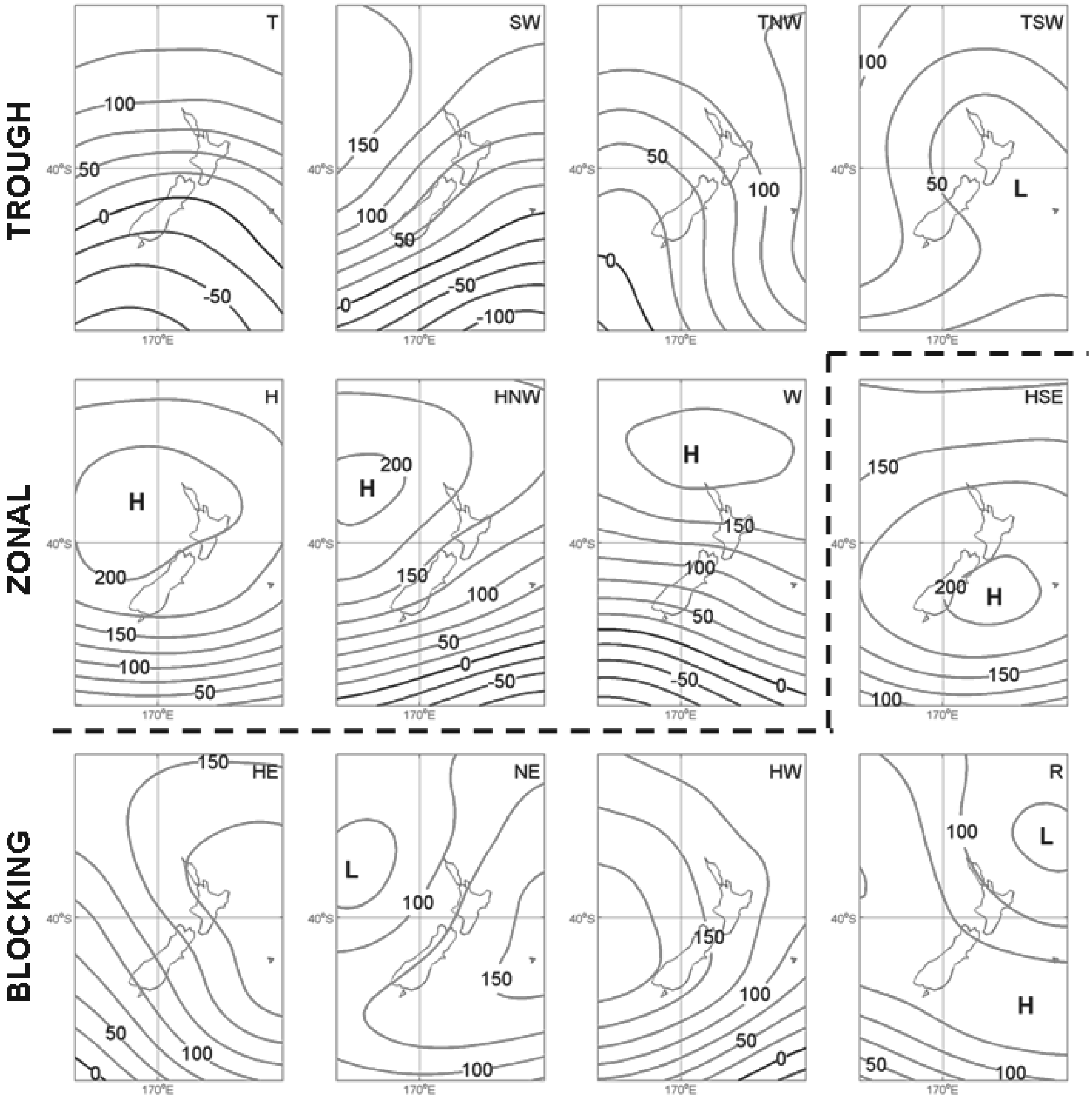

Figure 1: The twelve Kidson (2000) weather types shown as average patterns of 1000hPa height (analogous to mean sea-level pressure). Names for the types are indicated in top right of each panel, i.e. "T" stands for Trough, "SW" for Southwesterly, "TNW" for Trough-Northwesterly, "TSW" for Trough-Southwesterly, "H" for High, "HNW" for High to the Northwest, "W" for Westerly, "HSE" for High to the Southeast, "HE" for High to the East, "NE" for Northeasterly, "HW" for High to the West, and "R" for Ridge. The three regimes are indicated at left: the top row is the trough regime, the first three in the middle row are the zonal regime, and the remainder are the blocking regime. Directly from Figure 1, in Ackerley et al (2011).

“TSW” for Trough-Southwesterly, “H” for High, “HNW” for High to the Northwest, “W” for Westerly, “HSE” for High to the Southeast, “HE” for High to the East, “NE” for Northeasterly,“HW” for High to the West, and “R” for Ridge. The weather types were grouped into three “regimes” - “trough” (cyclonic, unsettled conditions; incorporating types T, SW, TNW, TSW), “zonal” (westerly flow; H, HNW, W) and “blocking” (anticyclonic, settled; HSE, HE, NE, HW, R), capturing synoptic variability in the New Zealand region. Updated twice-daily Kidson weather type data have recently been used to quantify fine-scale climate variability over New Zealand (Renwick, 2011) using ~5km x 5km gridded Virtual Climate Station Network (VCSN) data (see Tait et al. 2006 for details). In addition, the Kidson approach has also been used as a framework to handle extreme events under both current climate and climate change scenarios (i.e. Mullan et al. 2011), which linked observed extreme wind gusts to Kidson type, and assessed possible changes in Kidson regimes under various climate change scenarios. There is also on-going research into transitions of and persistence in daily Kidson weather types (James Renwick, pers. comm.).

Previous analysis of daily rainfall extremes in New Zealand using high-quality station data (Griffiths, 2007) over the periods 1930-2004 and 1950-2004 showed a clear west-east difference in trends in annual peak 24-hour rainfall magnitude (the annual ‘Rx1day’ index), with increases in extremity in western areas, and decreases in eastern regions. The extreme trends closely followed total annual rainfall trends, consistent with an increase in westerly circulation over central and southern New Zealand over that period. There were some regional variations in seasonal Rx1day trends. For example, the eastern North Island showed a less extreme summer rainfall regime, and more extreme spring regime, over the period 1930-2004. At several locations, monthly peak 24-hour rainfalls (monthly Rx1day) were highly correlated with monthly indices of zonal circulation in the region (Z1 and Z2, see Trenberth, 1976), and in some regions, with meridional Trenberth indices or monthly frequency of TSW, NE or R Kidson weather types.

Several large-scale climate patterns are known to affect seasonal mean rainfall in New Zealand. The El Niño Southern Oscillation (ENSO) influences mean rainfall in New Zealand through circulation and orographic processes (Salinger and Mullan, 1999). The El Niño effects are not exactly equal and opposite to the La Niña impacts (Mullan 1995). In El Niño years, New Zealand tends to experience stronger or more frequent winds from the west in summer, leading to drought in eastern areas and increased precipitation in the west. In winter, the winds tend to be more from the south, with increased rainfall in the eastern North Island and the southwestern South Island. During La Niña, more northeasterly winds occur. Winters tend to be wetter than normal for most of New Zealand, except for the coastal fringe in eastern areas south of East Cape. In summer, increased rainfall is more likely for the north and east of the North Island, and northeast of the South Island, with well below normal rainfall in the south and west of the South Island.

The Indian Ocean Dipole is a coupled ocean-atmosphere phenomenon in the Indian Ocean (Saji et al. 1999), usually developing and peaking between June and October (Ashok et al. 2007). A positive Indian Ocean Dipole implies above average sea surface temperatures (SSTs) and greater precipitation in the western Indian Ocean region, with a corresponding cooling of waters in the eastern Indian Ocean. In our region, the positive phase weakens storm-track activity over northern New Zealand, with a corresponding reduction in JJASON precipitation over northern parts of the country (Ashok et al. 2007), and is linked to negative MSLP anomalies southeast of New Zealand (Liu et al. 2006). Indian Ocean SST patterns are also known to modulate New Zealand-region winter circulation patterns (Mullan, 1998), with warmer Indian Ocean waters in autumn followed by more rainfall in western South Island regions and drier conditions in areas exposed to the north and east.

The Southern Annular Mode (SAM, e.g. Marshall, 2003) is known to be zonally symmetric during summer, but more wavelike and associated with larger meridional wind speed anomalies during winter. During the positive phase of the SAM, the summer wind anomaly over New Zealand is easterly, compared to a northeasterly anomaly over the North Island and a northwesterly anomaly over the southern South Island during winter (Kidston et al. 2009). Kidston et al. (2009) depicted seasonal relationships between New Zealand rainfall and the SAM, which reflect expected circulation and orographic effects well. In summer, the positive SAM induces wetter conditions in all coastal regions of the north and east of the North Island, for Nelson and Marlborough and coastal north Canterbury, with drier conditions elsewhere (but most markedly in Fiordland and Westland). In winter, the positive SAM induces wetter

Weather and Climate, ***31,*** *24-49*

conditions for Bay of Plenty, Gisborne and parts of Hawkes Bay, Wellington, Nelson, Fiordland and Westland, with drier conditions elsewhere.

Renwick (2011) found that ENSO and SAM significantly influence the daily Kidson frequencies, with more zonal flow during El Niño and more blocking types during La Niña (especially in summer and autumn), more trough types during the negative SAM at all times of year, and more zonal and blocking types during the positive SAM (especially in winter and summer, respectively). In an assessment of interannual variability in New Zealand rainfall, Ummenhofer and England (2007) found that for anomalously wet years for the North Island, local air-sea heat fluxes and circulation changes associated with ENSO play an important role. North Island anomalously wet years are characterised by locally reduced sea level pressure (SLP), positive sea surface temperature (SST) anomalies in the southern Tasman Sea and to the north of the North Island, and a coinciding enhanced evaporation upstream of anomalous northeasterly airflow. In contrast, South Island rainfall variability was dominated by the strength and position of the subpolar westerlies, which are modulated by the SAM. During anomalously wet years in the South Island, there is an equatorward shift and weakening of the subpolar westerlies south of 50°S, an increase in westerly winds between 30°S and 50°S, and anomalously low SSTs between 40°S and 60°S.

Given the influence of these large-scale drivers on seasonal mean rainfall in New Zealand, and the high correlation between changes in mean rainfall and changes in extreme daily rainfalls observed in the historical record (Griffiths, 2007), this paper aims to link observed extremes in daily station rainfall with a) daily Kidson weather type, and b) large-scale drivers of regional climate variability, such as the El Niño Southern Oscillation (ENSO), Southern Annular Mode (SAM), and the Indian Ocean Dipole. The ultimate aim of this analysis is to identify likely predictors of rainfall extremes at the seasonal time scale, to be used in the future to develop seasonal predictions of extreme daily rainfall risk.

In this paper, Section 2 details the data and methods used in the analyses, Section 3 contains key results, and Section 4 outlines major conclusions drawn and areas of future work.

2. Data and methods

2.1 Kidson synoptic classification data

Updated twice-daily (00Z and 12Z) Kidson synoptic classification data were obtained from NIWA for the period January 1958 – December 2009 inclusive. Fields of 1000 hPa height were downloaded from the NCEP/NCAR reanalysis web site (http://dss.ucar.edu/datasets/ds090.0/data/pgbf00-grb2d/), and classified at 00Z and 12Z daily over the New Zealand region into one of the 12 Kidson types (and hence one of the three regimes), using a principal component technique as given in Kidson (2000).

2.2 Station daily rainfall data and quality assessment

Daily (24-hour) rainfall totals read at 0900 NZST, and associated station metadata, from 22 high-quality rainfall records were extracted from the National Climate Database (http://cliflo.niwa.co.nz/), based on the author's knowledge of presently-active, long-term daily rainfall stations, and the criteria of a high percentage of data availability over the period 1950-2009, minimization of site change, and good geographical coverage across the country (Figure 2). The notable exception to the last criterion were two nearby sites in Nelson (Nelson Aero and Appleby), which were selected as a pair to test result consistency.

Homogeneity checks were performed on log-transformed monthly rainfall series at each of the 22 stations, for the period of data given in the key of Figure 2, using the homogeneity testing software package RHTestsV3 (Wang and Feng, 2009; Wang et al, 2009) which has been developed for the detection of change points in climatological datasets. Detailed information about station data used, appended series, outlier checks and homogeneity test results can be accessed directly from the author. Notably, the RHTestsV3 test appears very sensitive to missing data periods, or anomalous dry year(s). For example, change points were identified by RHTestsV3 at Whangarei (at missing data periods), Ruakura (at missing data periods), Cape Campbell (1940, and at missing data periods), Nelson Aero (at missing data periods), Chatham Island (two-year dry spell), and Campbell Island (at missing data periods). This sensitivity is unfortunate when the installation of an automatic weather station (AWS) is preceded by a period of missing data, as is the case for Whangarei and Cape Campbell. In such cases, it is difficult to determine if the period of missing data is influencing the test, or there is a real inhomogeneity. With that caveat, all 22 stations were retained for analysis

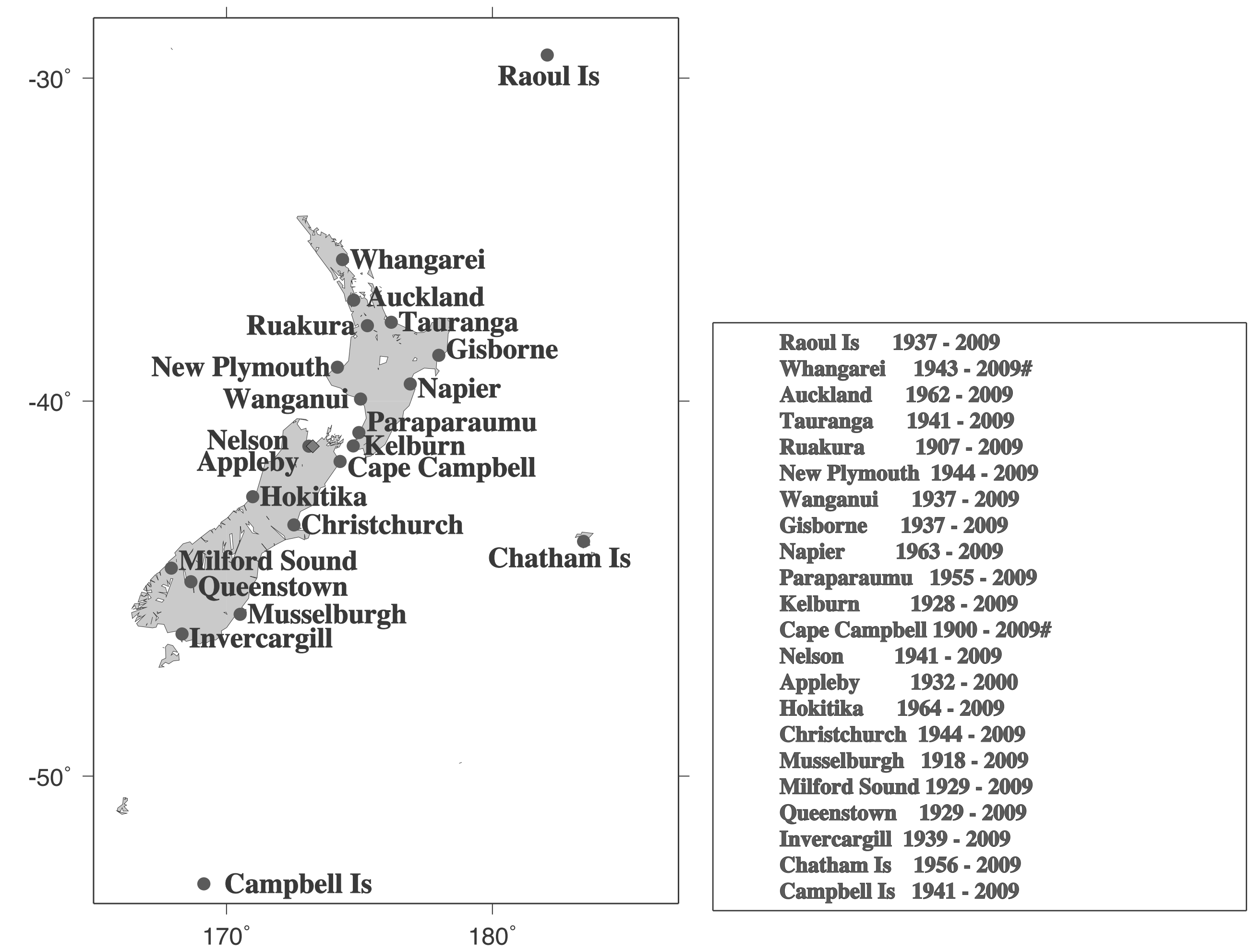

Figure 2: Rainfall stations used in the analysis. All sites shown as a black dot, except Appleby (mid grey diamond). Legend shows the period of daily rainfall data used. A # symbol indicates the station has a short gap in data due to site change. For further details on sites selected, appended records, and homogeneity test results, please contact the author directly.

(deemed *pseudo*-homogeneous), with the caution that Cape Campbell contains an undocumented inhomogeneity at 1940.

Quality checks are essential in any analysis of extreme events, and so all annual peak 24-hour rainfall totals were manually checked, looking for untagged accumulations (i.e. missing data before untagged 48-hour accumulation) and gross errors (keying errors, conversion errors when rainfall was still measured in inches, etc.). Checks included comparison with nearest neighbour(s), various flooding and hydrology publications which by nature include major extremes (i.e. Jowett, 1972; Bell, 1975), and occasionally sourcing the original paper records.

Several errors were identified in this way, and have now been rectified in the Climate Database. An example of this was at Raoul Island, northeast of New Zealand (see Figure 2), where a datum of 320 mm was originally stored in the database for 18/1/1965, but was subsequently replaced as 3.2 mm after accessing the original paper record and seeing the raw datum (in inches).

2.3 Calculation of extreme rainfall indices and corresponding Kidson type

RClimdex software (Zhang and Yang 2004) was used to calculate the magnitude (mm) of the monthly, seasonal and annual peak 24-hour rainfall (known as the 'Rx1day' index, see Equation 1) at each of the 22 stations over the period of record analysed (Figure 2). This software is freely available from (http://cccma/seos.uvic.ca/ETCCDMI/index.shtml) and was designed to compute 27 core climate indices recommended by the CCl/CLIVAR Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI), as well as some other temperature and precipitation indices with user-defined thresholds. One of the key benefits of using standardised algorithms which compute standardised indices is that global comparisons of indices of climate extremes can then be easily and rigorously performed.

Equation 1: Calculation of the Rx1day index

Let RR_{ij} be the daily precipitation amount on day i in period j. Then maximum 1-day values for period j are:

$$Rx1day_j = \max(RR_{ij}).$$

In this study, the period j was defined three times (month, season, year). Monthly indices were calculated if no more than 3 days of data were missing in a month, seasonal indices were calculated if all three monthly index values were available, while annual values were calculated if no more than 15 days were missing in a year.

To illustrate the variation in 'Rx1day' size across the country and during the year, Table 1 shows the average magnitude of the seasonal and annual 'Rx1day' indices by station, as well as the all-time maximum daily rainfall observed in the record. The all-time maximum daily rainfall is, in general, about two-and-a-half times the magnitude of the average annual Rx1day (the 22-station-average ratio is 2.4).

	Average DJF Rx1day	Average MAM Rx1day	Average JJA Rx1day	Average SON Rx1day	Average annual Rx1day	Maximum Rx1day
RAOUL IS	92	84	67	65	124	229
WHANGAREI	62	73	76	57	109	309
AUCKLAND	51	51	43	34	68	162
RUAKURA	45	45	41	35	61	148
TAURANGA	59	80	60	48	99	241
NEW PLYMOUTH	55	54	46	45	75	329
WANGANUI	37	33	29	29	48	91
PARAPARAUMU	42	43	40	41	60	114
KELBURN	47	49	51	42	68	152
GISBORNE	42	56	56	40	80	200
NAPIER	39	47	44	34	66	148
CAPE CAMPBELL	36	41	40	33	65	185
NELSON	46	52	45	41	69	138
APPLEBY	43	47	48	41	65	121
HOKITIKA	89	81	78	74	111	175
MILFORD SOUND	215	193	145	192	269	538
QUEENSTOWN	35	37	34	38	53	122
INVERCARGILL	32	32	25	28	40	73
MUSSELBURGH	32	37	30	26	51	229
CHRISTCHURCH	27	34	32	26	46	110
CHATHAM IS	32	36	30	28	47	96
CAMPBELL IS	32	31	25	27	42	86

Table 1: The seasonal and annual average magnitude (mm) of the peak 24-hour rainfall ('Rx1day') at each site, based on all available data. In addition, the largest recorded Rx1day magnitude (mm) is also shown.

Visual Basic was employed to identify the dates on which the monthly, seasonal and annual peak rainfall events occurred in the respective raw daily rainfall data series. The peak rainfall events were allocated the Kidson weather type valid at midnight (NZST) of the day before the respective daily rainfall reading (at 0900 NZST). The counts of the 12 Kidson types linked to the Rx1day events were converted to a percentage of total count at each station, and then presented as a ratio: (observed percentage)/(normal percentage). The normal percentages of each of the 12 Kidson types are shown in Table 2. The ratio was used as a simple tool to determine which weather types were providing “more than their fair share” of extreme rainfalls. For example, the HNW type occurs approximately 7.2% of the time, but across the North

	TSW	T	SW	NE	R	HW	HE	W	HNW	TNW	HSE	H
ANN	6.9%	12.0%	11.3%	6.1%	4.6%	5.5%	7.3%	4.9%	7.2%	7.3%	13.7%	13.1%
DJF	8.1%	11.0%	9.4%	9.0%	7.8%	7.2%	5.9%	3.1%	3.8%	9.4%	18.0%	7.4%
MAM	4.1%	7.8%	10.1%	5.1%	4.8%	6.8%	7.9%	4.6%	8.2%	5.1%	18.8%	16.7%
JJA	8.6%	12.2%	11.1%	4.7%	4.0%	4.5%	7.8%	5.1%	8.6%	7.8%	10.8%	15.0%
SON	6.6%	15.6%	13.9%	4.9%	3.0%	3.7%	7.5%	7.6%	7.7%	7.9%	8.6%	12.8%

Table 2: Normal seasonal and annual percentage occurrence of Kidson daily weather types, calculated over the period 1971-2002.

Annual Ratio	TSW	T	SW	NE	R	HW	HE	W	HNW	TNW	HSE	H
RAOUL IS	**2.2**	0.9	0.9	**2.4**	**2.3**	1.9	0.0	0.4	0.0	0.9	1.2	0.2
WHANGAREI	0.9	0.0	0.0	**6.6**	0.5	0.8	0.9	0.0	0.0	0.9	**2.5**	0.0
AUCKLAND	**2.6**	0.6	0.2	**3.6**	1.4	0.4	0.9	0.9	0.0	**2.1**	1.1	0.0
RUAKURA	**2.8**	0.8	0.2	**4.4**	1.3	0.3	0.0	0.4	0.0	**3.2**	0.6	0.1
TAURANGA	**3.3**	0.3	0.0	**4.8**	1.8	0.0	0.9	0.4	0.0	**2.3**	0.8	0.0
NEW PLYMOUTH	**3.0**	1.4	0.0	**3.0**	0.0	0.4	**2.0**	0.0	0.0	**3.6**	0.1	0.0
WANGANUI	**4.3**	1.6	0.7	**3.5**	0.9	0.4	0.0	0.0	0.0	1.3	0.4	0.0
PARAPARAUMU	**2.2**	**2.4**	0.5	1.3	0.4	0.3	0.5	0.8	0.0	**3.2**	0.4	0.1
KELBURN	**6.4**	1.1	0.9	**2.2**	0.8	0.0	0.8	0.4	0.0	0.8	0.1	0.0
GISBORNE	**3.5**	0.2	0.7	0.7	**7.8**	0.4	0.0	0.0	0.3	0.3	1.2	0.3
NAPIER	**3.9**	0.4	0.2	1.5	**5.3**	1.2	0.3	0.0	0.0	0.9	0.8	0.5
CAPE CAMPBELL	**4.2**	1.1	0.2	**2.2**	**4.6**	1.0	0.0	0.0	0.0	1.1	0.6	0.0
NELSON	**2.2**	1.1	0.0	**2.8**	0.9	0.0	1.5	0.4	0.0	**4.4**	0.5	0.0
APPLEBY	**2.9**	0.8	0.0	**2.0**	1.1	0.0	1.7	0.5	0.0	**5.1**	0.0	0.0
HOKITIKA	1.3	1.6	0.2	0.4	0.0	0.4	1.5	1.3	0.0	**5.7**	0.3	0.2
MILFORD SOUND	0.0	**2.1**	0.0	0.6	0.0	0.0	1.3	**3.5**	1.3	**3.4**	0.4	0.3
QUEENSTOWN	0.6	**2.6**	0.2	1.3	0.0	0.0	1.3	**3.9**	0.5	**2.9**	0.0	0.1
INVERCARGILL	0.6	**3.3**	0.9	1.3	0.4	0.7	0.5	**3.2**	0.5	1.3	0.0	0.0
MUSSELBURGH	**3.6**	**2.2**	0.9	1.6	0.4	0.0	0.3	0.4	0.0	1.8	0.7	0.0
CHRISTCHURCH	**5.0**	0.3	1.2	**2.2**	0.8	0.0	0.0	0.0	0.3	**3.2**	0.4	0.0
CHATHAM IS	**3.5**	1.0	**2.0**	0.0	1.8	1.9	0.0	0.8	0.9	1.4	0.0	0.2
CAMPBELL IS	0.0	**4.0**	0.9	0.7	0.9	0.0	0.8	**2.0**	0.0	**2.2**	0.1	0.0
Count > = 2.0	16	6	1	12	4	0	1	4	0	12	1	0
Count > = 4.0	4	1	0	3	3	0	0	0	0	3	0	0

Table 3: Ratio of Kidson Type observed/normal percentages, based on Annual Rx1day. Ratios exceeding 2.0 are in bold font. Counts of stations with ratios exceeding 2.0 and exceeding 4.0 are also given.

Island accounts for virtually none of the Annual Rx1day events (Table 3). A ratio of 2 was subjectively chosen as a nominal cut-off to collate the Kidson types causing a larger-than-expected percentage of extreme events.

2.4 Seasonal Rx1day anomaly calculation

An average of the 'monthly Rx1day' values was calculated for each of the 12 months separately, based on all available monthly data at that site. Monthly Rx1day anomalies (as a percentage departure from the average) were then produced for every month, and then averaged for each of the four standard seasons (DJF, MAM, JJA, SON). For example, the Kelburn (Wellington) average Rx1day value for May is 35.0 mm. The May 2008 Rx1day value was 94.4 mm, meaning the May 2008 departure was +170%. Given that the March and April 2008 Rx1day anomaly values were +164% and -10% respectively, the MAM 2008 seasonal average Rx1day anomaly at Kelburn was 108% i.e. Kelburn was affected by much larger-than-usual peak daily rainfalls during autumn 2008.

2.5 Climate indices from KNMI

The KNMI Climate Explorer website, http://climexp.knmi.nl was used as an analysis tool to download data, upload indices, and undertake preliminary analyses of relationships between extreme daily rainfalls (22 station seasonal Rx1day anomaly time series as detailed above) and selected time series of seasonally-averaged climate indices flagged in the literature as impacting on mean rainfall in New Zealand:

- The NINO3 index, being the SST anomaly calculated over latitudes 5°S to 5°N, longitudes 90°W-150°W, relative to the 1971-2000 climatology, based on the NCDC ERSST v3b dataset (as described in Smith et al. 2008, excepting that ERSST v3b contains no satellite data).
- The Southern Annular Mode (SAM) index (Marshall, 2003), being an observation-based normalised difference in the zonal mean sea-level pressure between 40°S and 65°S.
- The Dipole Mode Index (DMI). The DMI is defined as the difference between SST anomaly in the western Indian Ocean (60°E-80°E,10°S-10°N) and the eastern Indian Ocean (90°E-110°E,10°S-0°S). The DMI selected in the KNMI Climate Explorer is a normalised anomaly based on HadISST data, sourced from FRCGC (Frontier Research Center for Global Change: http://www.jamstec.go.jp/frsgc/research/d1/iod/).

Simultaneous correlations between pre-whitened seasonal average NINO3, SAM and DMI indices and seasonal Rx1day anomaly series at 22 stations were calculated within the KNMI

Climate Explorer analysis tool, for the standard seasons DJF, MAM, JJA and SON. Note that pre-whitening removes the auto-correlation in each time series, and generally results in correlations smaller in magnitude than those produced from raw series (Mullan, 1998). However, correlation significance should remain comparable to that seen in the raw series, once proper account is taken of the number of degrees of freedom in the time series.

3. Results

3.1 Dominant Kidson weather types

The station ratios of Kidson type observed/normal percentages for the annual Rx1day are shown in Table 3, and are in bold font if the ratio exceeds 2.0 (a subjective cut-off). Three Kidson types are over-represented with regards annual Rx1day occurrence at many of the sites; these are TSW (with ratios exceeding 2.0 at 16 of the 22 stations), TNW (12 of 22 stations), and NE (12 of 22 stations). However, regional differences are evident, such as the R type for the east coast of the North Island and coastal Marlborough, which is up to 7 times (approximately) more likely than climatology to be linked to the annual extreme rainfall, or the T and W types, which are up to about 4 times more likely than climatology to be associated with extreme events in the southwest of the country. Whangarei is strongly influenced by the HSE type. All of these local results are meteorologically consistent with an analogous weather map and contribute significantly to regional extreme rainfalls.

Figure 3 is a graphical representation of the annual and seasonal dominant weather types. The annual analysis (Figure 3a) shows that the NE weather type is a dominant source of annual extreme rainfalls (i.e. with the largest ratio of observed/normal) for Raoul Island, and the north of the North Island (Whangarei, Auckland, Ruakura, Tauranga). The HSE weather type is also influential on extreme rainfall at Whangarei (Table 3), and is an important weather type there, being linked to extreme gusts in Northland (see Mullan et al, 2011, for details). The NE type is also important (Table 3) for the western North Island (New Plymouth, Wanganui, Kelburn) and north and northeast of the South Island (Cape Campbell, Nelson, Appleby, Christchurch).

Either the TNW or TSW type is annually dominant (Figure 3) for the southwest of the North Island (New Plymouth, Wanganui, Paraparaumu, Kelburn). For the east coast of the North Island and northeastern South Island (Gisborne, Napier, Cape Campbell), the R type is dominant annually, with large over-representation (with ratios in the order of 4 to 7). Nelson and Appleby annual rainfall extremes are strongly influenced by the TNW/TSW/NE weather

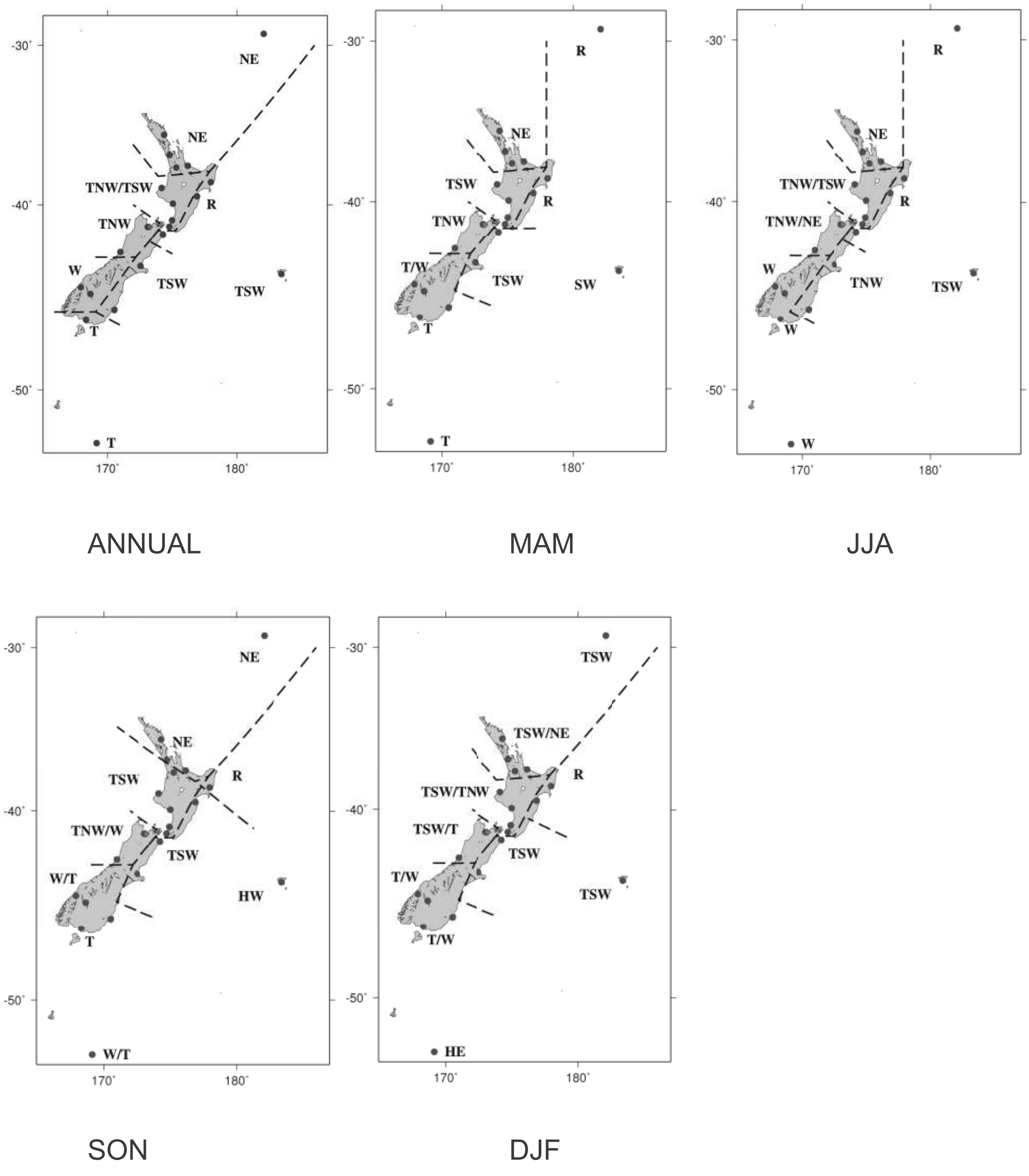

Figure 3: Dominant Kidson type, defined as the weather type linked to station extreme daily rainfalls with the largest ratio of observed/normal percentage occurrence.

types (Figure 3, Table 3). The results are consistent in Table 3 between the pair of stations. Hokitika extreme rainfall is almost exclusively driven by the TNW, consistent with the large orographic component to rainfall on the windward side of the Southern Alps (see also Milford Sound and Queenstown, Table 3). The W and T types are dominant with regards annual rainfall extremes (Figure 3) over southwestern New Zealand (Milford Sound, Queenstown, Invercargill). For the east coast of the South Island (Musselburgh, Christchurch) and the Chatham Islands, the TSW type is the dominant contributor to annual extreme rainfall, consistent with the analogous weather map. And for Campbell Island, T, TNW and W types are over-represented, consistent with lower pressures to the south of New Zealand/in the vicinity of Campbell Island.

There are subtle seasonal variations in the dominant weather types associated with extreme daily rainfalls. Table 4 counts the number of stations (out of 22) where the ratio of observed/normal Kidson type frequency associated with both annual Rx1day and seasonal Rx1day exceeds 2.0. The count of NE types is greatest in autumn and least in spring. This is consistent with seasonal rainfall anomalies for the NE type, as produced by Renwick (2011) and shown in Figure 4, which shows large positive rainfall anomalies for the North Island and the north and east of the South Island in autumn, but a muted response in spring, with large positive anomalies in the northeast of the North Island and parts of Nelson, negative anomalies in the southwest of the North Island, and small anomalies in the east of the South Island.

	TSW	T	NE	R	HW	W	TNW
Annual	16	6	12	4	0	4	12
DJF	16	6	9	3	0	3	8
MAM	15	8	13	4	1	5	17
JJA	11	8	11	4	0	4	10
SON	12	8	4	4	5	4	7

Table 4: Annual and seasonal counts of selected weather types which have ratios of Kidson Type observed/normal percentages exceeding 2.0. (Identical to the second-from-bottom row in Table 3, but for both annual and seasonal results).

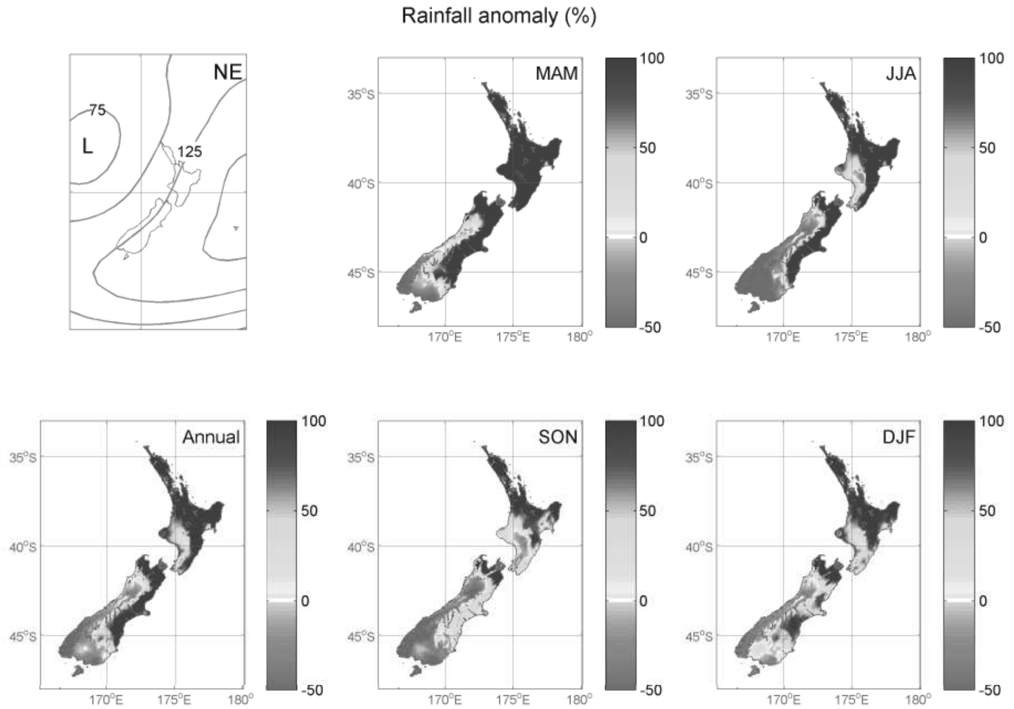

Figure 4: Annual and seasonal average rainfall anomalies associated with the NE Kidson weather type. Produced by Dr. James Renwick, NIWA, for the analysis described in Renwick (2011) but not displayed in that paper directly. Rainfall anomalies are shown as a % deviation, with darkest red/brown equating to –50% and darkest blue equating to +100%, as given in the colour scales provided.

Figure 3e markedly shows the reduced influence of the NE type in summer, the only season in which another weather type (TSW) becomes dominant in the northeast of the North Island.

From Table 4 and Figure 3 it is evident that counts of TSW and the TSW dominance are greatest in summer and autumn and least in winter (consistent with TSW seasonal rainfall anomalies as produced by Renwick (2011*),* not shown). The TNW Kidson type is counted most in autumn, with 17 of 22 stations showing a ratio exceeding 2.0 for this type (Table 4). It is least frequently observed in spring and summer. This result is also consistent with the seasonal rainfall anomalies (not shown) for this weather type as produced by Renwick (2011). In spring, the HW type becomes important (with ratio exceeding 2.0, Table 4) to extreme daily rainfall at 5 sites (Raoul Island, Wanganui, Kelburn, Gisborne, and the Chatham Islands). However, the only location where HW is actually dominant (i.e. has the greatest ratio) is at the Chatham Islands (Figure 3).

Overall, Kidson weather types are strongly linked to seasonal and annual peak 24-hour rainfall extremity in New Zealand, consistent with the highly orographic nature of our rainfall. There is clear regional distinction in the dominant Kidson weather type. Some of these effects are quite local in nature, for example the HSE is linked to extreme rainfall only at Whangarei. There are some subtle seasonal differences in dominance, probably because the Kidson circulation patterns are not anomalies, but operate against the background climatology of the seasons.

Seasonal Rx1day anomaly vs NINO3 (0 lag)	MAM corr	MAM p-value	JJA corr	JJA p-value	SON corr	SON p-value	DJF corr	DJF p-value
Raoul Is	-0.29	0.02	-0.28	0.03	-0.13	0.31	-0.10	0.45
Whangarei	-0.29	0.05	-0.25	0.09	-0.19	0.22	-0.43	0.00
Auckland	-0.25	0.11	-0.02	0.89	-0.03	0.86	-0.30	0.06
Tauranga	**0.22***	**0.09***	0.14	0.29	-0.39	0.00	-0.33	0.01
Ruakura	0.11	0.31	-0.03	0.81	-0.32	0.00	-0.08	0.45
New Plymouth	0.09	0.47	-0.23	0.08	-0.33	0.01	-0.20	0.13
Wanganui	0.12	0.34	-0.11	0.37	-0.07	0.57	-0.18	0.15
Gisborne	-0.19	0.13	-0.04	0.73	-0.16	0.19	-0.17	0.18
Napier	-0.07	0.65	0.10	0.51	-0.08	0.60	-0.37	0.02
Paraparaumu	-0.02	0.91	-0.07	0.63	-0.02	0.89	-0.22	0.12
Kelburn	0.10	0.37	0.10	0.36	0.16	0.16	-0.04	0.73
Cape Campbell	-0.12	0.30	0.11	0.31	**0.27**	**0.01**	**0.21***	**0.07***
Nelson	0.03	0.84	-0.06	0.65	0.07	0.57	-0.39	0.00
Appleby	0.07	0.59	0.04	0.74	-0.07	0.59	-0.01	0.95
Hokitika	0.19	0.20	-0.01	0.93	-0.30	0.05	-0.14	0.37
Christchurch	-0.15	0.28	-0.12	0.36	0.14	0.29	-0.21	0.12
Musselburgh	**0.25**	**0.02**	0.13	0.24	-0.08	0.48	0.14	0.22
Milford Sound	0.06	0.58	-0.14	0.21	0.09	0.44	0.13	0.26
Queenstown	0.15	0.21	-0.08	0.47	-0.02	0.88	0.11	0.34
Invercargill	0.05	0.73	0.02	0.86	-0.10	0.43	-0.11	0.40
Chatham Is	-0.16	0.29	-0.12	0.41	-0.08	0.60	0.00	1.00
Campbell Is	0.11	0.40	-0.17	0.18	-0.14	0.28	0.00	0.97

Table 5: Correlations (no lag) between pre-whitened seasonal average NINO3 and seasonal Rx1day anomaly, significant negative correlations shown in mid grey (p <= 0.05) or light grey (p <= 0.15), significant positive correlations in bold and underlined (p <= 0.05) or bold with asterisk (*), (p <= 0.15).

3.2 Drivers of extreme daily rainfall in New Zealand

Simultaneous correlations (0 lag) between seasonal Rx1day anomalies and the three climate indices NINO3, SAM, and DMI are shown graphically in Figures 5, 6 and 7. And in the case of NINO3, the raw correlations and p-values are given in Table 5. In the Figures and Table, significant correlations ($p <= 0.05$) and weakly significant correlations ($p <= 0.15$) are shown. Both levels of significance are referred to as 'significant' in the text below, since previous work analysing extreme daily rainfalls (Griffiths, 2007) showed geographical consistency in extreme rainfall trends and in their responses to circulation - which was useful when trying to understand the physical mechanisms behind the observed changes - and those results were clearer when the strict p-value <= 0.05 criterion was relaxed. An illustration of a seasonal Rx1day anomaly time series, and how it compares to the seasonal average climate indices, is given in Figure 8. In Figure 8, a time series of the Raoul Island JJA R1xday anomaly is shown, as are the winter average NINO3, SAM and DMI indices. In this case, there were significant correlations between the variables. Raoul Island JJA Rx1day was significantly correlated ($p <= 0.05$) with all three of these indices, with (pre-whitened) correlations of -0.28 (JJA NINO3), 0.31 (JJA SAM) and -0.34 (JJA DMI), respectively.

Most of the significant correlations between seasonal Rx1day and NINO3 (Figure 5, Table 5) occur at sites in the northern North Island, as would be expected from a tropical driver of climate variability. The NINO3 relationships are strongest and extend furthest south during summer, when the magnitude of ENSO peaks (Table 5). During autumn, El Niño (La Niña) implies reduced (enhanced) seasonal extreme rainfall in the northeast of the North Island i.e. at Raoul Island, Whangarei, Auckland, and Gisborne. Interestingly, Tauranga shows a weak significant positive correlation, which appears inconsistent with the general southwest (northeast) circulation anomaly observed under El Niño (La Niña). Very few winter correlations are significant. In spring and summer, all stations in the North Island (excluding Kelburn) show negative correlations between seasonal Rx1day anomaly and NINO3, although many are not statistically significant (Figure 5, Table 5), with El Niño (La Niña) implying a reduction (increase) in seasonal peak daily rainfalls. This finding is consistent with the general circulation and mean rainfall response expected under ENSO.

In contrast, some results in Table 5 appear contrary; Cape Campbell shows strong positive relationships to NINO3 in spring and summer, implying increased (reduced) extremity during El Niño (La Niña), yet for the north and northwest of the South Island (Nelson, Hokitika) in spring and summer, there is a tendency towards decreased (increased) seasonal rainfall extremity

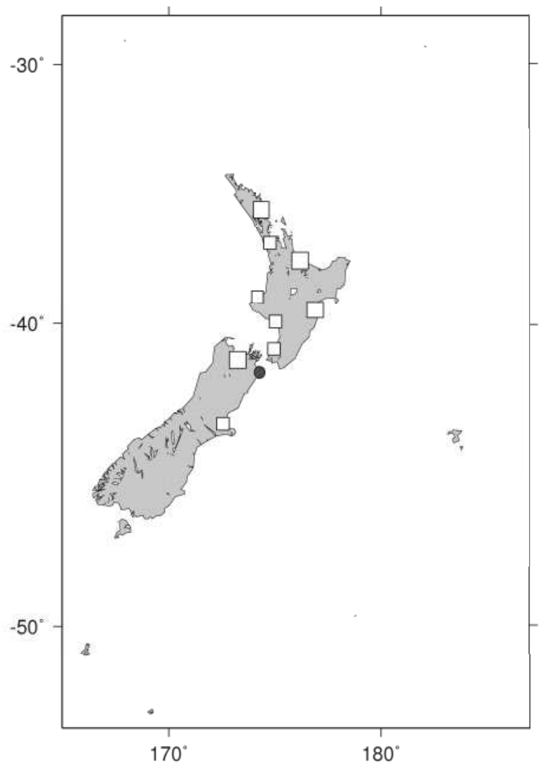

Figure 5: Significant correlations between DJF seasonal Rx1day anomaly versus DJF seasonal average NINO3. Black circles indicate positive correlation, white squares negative correlation. Large symbols p <= 0.05, small symbols p <= 0.15.

in El Niño (La Niña). To check this result, important Kidson types (with ratios of observed/normal Kidson frequency exceeding 2.0) in spring and summer at Cape Campbell were identified, being TSW and NE, and TSW, respectively. Observed changes in individual Kidson weather type frequencies by SOI phase (obtained directly from James Renwick, pers. comm., not shown here) clearly show that TSW and NE are more common under La Niña, during all four seasons. This implies that increased extreme rainfalls *should* occur during La Niña at Cape Campbell, using the Kidson weather type-extreme rainfall relationships found. So the Cape Campbell results using Kidson weather types versus the NINO3 index are at odds, and this either reflects data quality issues, or a real (but unknown) climatic response at this site.

In comparison, the results at Nelson and Hokitika give confidence in the general Kidson weather type approach, overall. At Nelson, the only significant correlation between seasonal Rx1day and seasonal average NINO3 occurs in DJF (Table 5), implying increased summer rainfall extremes during La Niña. In summer, important Kidson types (ratios exceeding 2.0) at Nelson are TSW, NE, TNW (in that order, not shown). All three of these Kidson types are more common under La Niña (James Renwick, pers. comm.) in summer, agreeing with a decrease (increase) in seasonal rainfall extremity in El Niño (La Niña).

For Hokitika, the only significant correlation in Table 5 is in SON, implying increased spring rainfall extremes during La Niña. In spring, influential Kidson types (ratios exceeding 2.0) at Hokitika are W, TNW, T (in that order, not shown directly). Spring is the only season when the W type has a ratio exceeding 2.0 at Hokitika, and it is the only season when TNW or T are displaced as the largest ratio there. The TNW and T types are more common during La Niña springs, while the W type is *less* common (James Renwick, pers. comm.). In this case, there is a mixed response during spring at Hokitika, but in all other seasons, TNW and T types dominate, and imply decreased (increased) seasonal rainfall extremity in El Niño (La Niña).

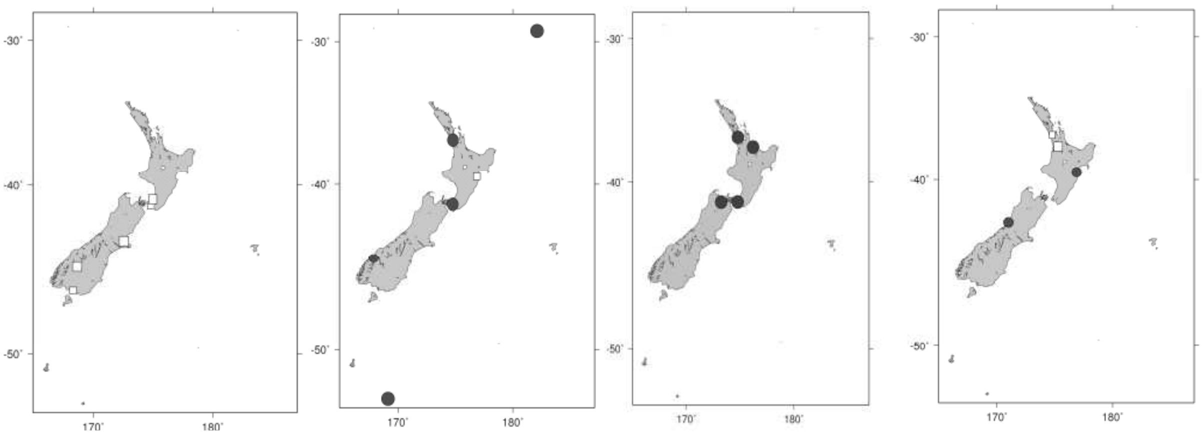

Figure 6: Significant correlations between from left to right: MAM, JJA, SON and DJF seasonal Rx1day anomaly versus seasonal average SAM. Black circles indicate positive correlation, white squares negative correlation. Large symbols p <= 0.05, small symbols p <= 0.15.

Overall, the consistency in responses between ENSO correlations and Kidson weather types (even in the limited illustration given) does give confidence that Kidson-typing of daily extreme rainfalls is a useful technique. Significant relationships between seasonal Rx1day anomaly and SAM (Figure 6) tend to occur in three clusters: around Auckland, around Cook Strait, and over the southwest of the country (Milford Sound, Queenstown, Invercargill). There are positive correlations in JJA at Auckland and Raoul Island, and at Auckland and Tauranga during SON, implying increased rainfall extremity with positive SAM, consistent with the northeasterly anomaly over the North Island in JJA (Kidston et al. 2009). Negative correlations are seen at Auckland and Ruakura for DJF, which is consistent with the summer pattern of zonal easterly anomalies during positive SAM (Kidston et al. 2009) and the likely sheltering effect in the Auckland and Waikato regions from the mountainous terrain of Coromandel Peninsula and the Kaimai Ranges. For Kelburn and Paraparaumu, negative correlations in MAM imply reduced rainfall extremity in the positive SAM mode, consistent with orographic sheltering during easterly flows. The reverse applies at Kelburn in winter and spring, when the northeasterly anomaly seen in the positive SAM mode in JJA is linked to increased rainfall extremity there (Figure 6). Negative correlations are observed between seasonal Rx1day anomaly and SAM in autumn at all sites in the lower half of the South Island (not shown directly), but only a few relationships are significant (Figure 6). The autumn South Island results are consistent with the summer rainfall pattern observed in Figure 8a of Kidston et al. (2009). In winter, Kidston et al. (2009) observed an anomalous northwesterly airstream around Fiordland during the positive phase of the SAM, consistent with the significant positive correlation seen at Milford Sound for JJA (Figure 6), implying increased extremity.

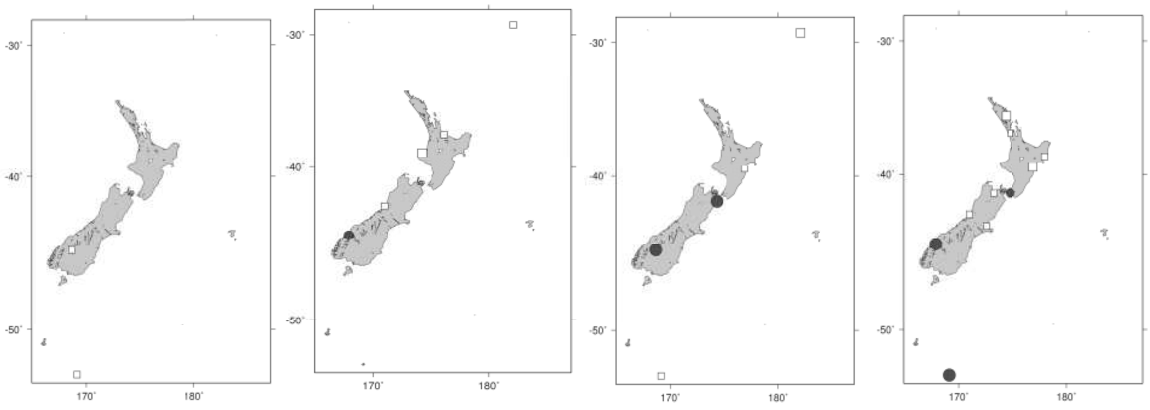

Figure 7: Significant correlations between from left to right: MAM, JJA, SON and DJF seasonal Rx1day anomaly versus seasonal average DMI. Black circles indicate positive correlation, white squares negative correlation. Large symbols p <= 0.05, small symbols p <= 0.15.

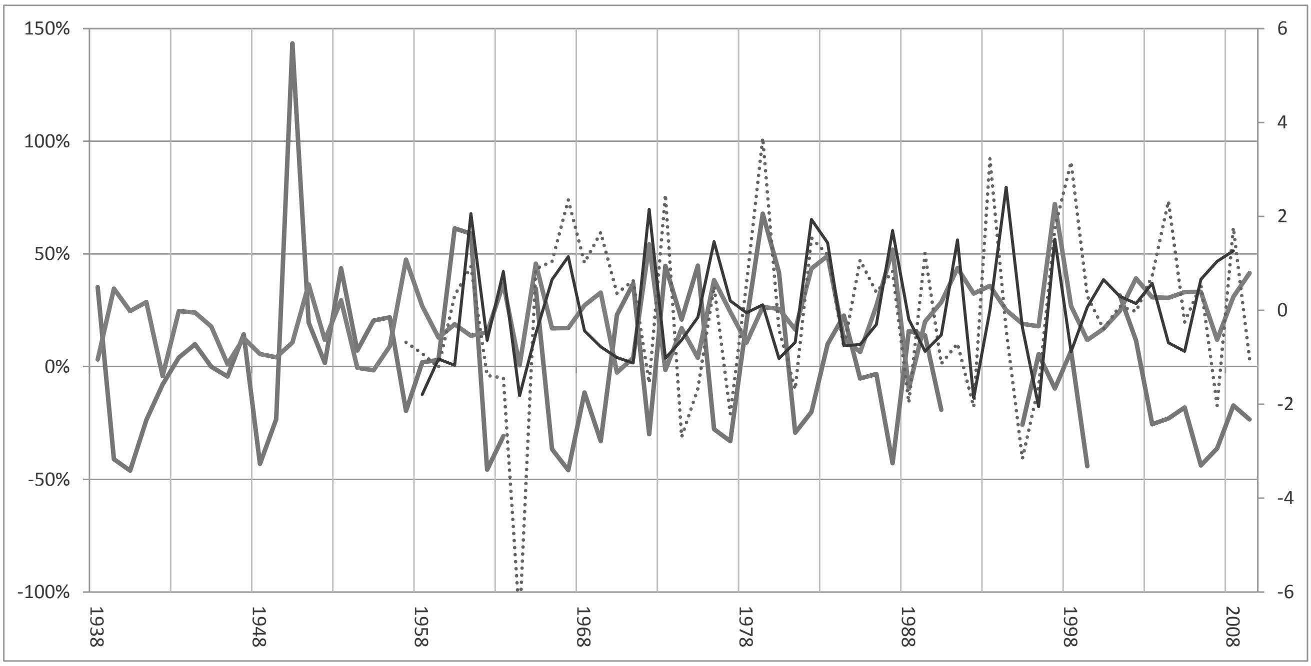

Figure 8: Time series of Raoul Island JJA Rx1day anomaly (blue line) 1938-2009 versus selected seasonal average indices: JJA NINO3 (solid grey line), JJA SAM (thin dotted line), JJA DMI (black line). The left hand side axis indicates % departure of Raoul Island JJA Rx1day anomaly. The right hand side axis indicates the value of the NINO3, SAM and DMI indices. The Raoul Island JJA Rx1day anomaly was significantly positively correlated with JJA SAM and significantly negatively correlated with both JJA NINO3 and JJA DMI.

Correlations between the Dipole Mode Index and seasonal R1xday anomaly are shown graphically in Figure 7. There is an absence of significant DMI correlations in autumn (except at Queenstown and Campbell Island), when the Indian Ocean Dipole is weakest (Figure 7). In spring and summer, almost all of the correlations for the North Island north of Paraparaumu are negative (not shown directly), but most are not statistically significant (see Figure 7 for those that are). The number of significant negative correlations is greatest in DJF, and extends southwards through central New Zealand (the exception is Kelburn, with a significant positive correlation) and onto the northern South Island. Milford Sound, Queenstown, and Campbell Island also show some significant relationships with the Indian Ocean Dipole over selected seasons, being positive (increased extremity in positive DMI) when significant at the 5% level. These results are consistent with known circulation/rainfall impacts of the Indian Ocean Dipole (namely, positive DMI phase induces weaker storm track/higher pressures/reduced rainfall over northern New Zealand but lower pressures to the southeast of the country).

Overall, simultaneous relationships between seasonal Rx1day anomaly and various drivers of climate variability are complex; the impacts of climate drivers (such as ENSO, the Indian Ocean Dipole and the SAM) on extreme rainfalls are both regional and seasonal in nature, so should be treated as such in any predictive scheme. ENSO affects seasonal extreme rainfalls in northern New Zealand (with positive NINO3 associated with reduced extremity), although this influence pushes south across all of the North Island, and into the north of the South Island, during summer. The Indian Ocean Dipole shows most influence between spring and summer, with positive DMI associated with reduced daily rainfall extremes in the North Island in spring, extending southwards to the north of the South Island during summer, and increased rainfall extremes at some sites in the southwest of the country. The SAM influences rainfall extremes in small clusters of sites around Auckland, Cook Strait and the far south of the country.

4. Conclusions and future work

The synoptic climatology approach has been used here to assess extreme daily rainfalls from 22 high-quality stations across New Zealand. Kidson synoptic classification (‘weather type’) data were strongly linked to seasonal and annual peak 24-hour rainfall totals (‘Rx1day’). Three Kidson weather types were over-represented with regards annual Rx1day occurrence at many of the stations (TSW, TNW, and NE), but clear regional differentiation was observed, such as the R type for the east coast of the North Island and coastal Marlborough, which was up to about 7 times more likely than climatology to be linked to annual extreme rainfall, or the T and W types, strongly associated with extreme events in the southwest of the country. All of the local results were meteorologically consistent with an analogous weather map and the largely orographic nature of rainfall in New Zealand. Subtle seasonal variation in Kidson type dominance was observed, reflecting that the Kidson classification patterns are not anomalies, but rather operate against a seasonal background.

Given the strong relationship between daily Kidson weather type and extreme daily rainfalls, and the influence that climate drivers such as ENSO and SAM have on Kidson regime frequencies, significant simultaneous relationships between station seasonal rainfall extremes and climate drivers (ENSO, SAM and the Indian Ocean Dipole) were expected, and were indeed identified. The sign and magnitude of simultaneous correlations between seasonal Rx1day anomaly and the climate drivers were often found to be 'regionally coherent'. For example, all of the North Island station correlations with NINO3 were negative in spring and summer (excluding Kelburn), implying reduced (increased) rainfall extremity during El Niño (La Niña), even if not all were statistically significant, consistent with an increase in Kidson blocking regimes (which includes the NE and R weather types) during La Niña. The SAM influenced rainfall extremes in small clusters of sites around Auckland, Cook Strait and the far southwest of New Zealand. And there was a prevalence of negative correlations with the DMI in spring and summer at many sites in the North Island (although many were not statistically significant), and some positive correlations in the southwest of the country.

In addition, the results were 'seasonally coherent'. For example, the greatest number of significant NINO3 correlations was observed in summer, at the peak of ENSO magnitude; there were a lack of significant DMI correlations in autumn when the Indian Ocean Dipole is weakest, and an absence of significant NINO3 correlations in winter.

Individual relationships between particular climate drivers and station rainfall extremity were complex, varying in sign and significance across the seasons. For example, under positive (negative) SAM conditions, Auckland seasonal rainfall extremity was increased (reduced) in winter, but reduced (increased) in summer. The positive SAM was related to a reduction in the frequency of the trough regime (which includes both TSW and TNW) at all times of the year. Notably, Auckland's dominant Kidson weather type was TSW in summer –the only season in which the NE type was displaced from dominance – which is consistent with this result. For Wellington, positive SAM conditions implied reduced rainfall extremity in autumn (consistent), but increased rainfall extremity in winter and spring (inconsistent since TSW is dominant at Kelburn in all seasons).

It appears significant further work is required to develop a skilful predictive scheme of extreme rainfall risk in New Zealand. A very preliminary analysis attempting to 'hindcast' seasonal extreme rainfalls at three main centres (Auckland, Wellington, Christchurch), based on circulation drivers alone, was undertaken by the author at the end of the work detailed here. But seasonal measures of ENSO, SAM and the Indian Ocean Dipole showed no better skill in 'forecasting' seasonal rainfall extremes than persistence, and much future work is needed in this area. However, recent advances in the prediction of Kidson weather types, using NWP or ensemble techniques such as those currently employed at NIWA, may mean that Kidson weather typing becomes the most likely route to skilful, intra-seasonal prediction of extreme daily rainfalls in New Zealand.

Acknowledgements:

The updated twice-daily (00Z and 12Z) Kidson synoptic classification data and Figure 4 were provided by Dr. James Renwick. Thanks to Elaine Fouhy for her expertise in checking outlier data and accessing original records, and to Drs. James Renwick and Drew Lorrey for their review comments. This work was funded through the New Zealand Foundation for Research, Science and Technology (FRST) contract C01X0701.

References:

Ackerley, D., Lorrey, A., Renwick, J.A., Phipps, S.J., Wagner, S., Dean, S., Singarayer, J., Valdes, P., Abe-Ouchi, A., Ohgaito, R., and Jones, J.M. (2011). Using synoptic type analysis to understand New Zealand climate during the Mid-Holocene. *Climates of the Past*, In review.

Ashok, K., H. Nakamura and T. Yamagata, (2007). Impacts of ENSO and Indian Ocean Dipole events on the southern hemisphere storm track activity during austral winter, *J. Climate,* Volume 20, Issue 13, pp.3147-3163.

Baldi, M., Salinger, J., Dirks, K.N., McGregor, G. (2009). *Winter hospital admissions and weather types in the Auckland Region.* Paper presented at the Internation Conference on Southern Hemisphere Meteorology and Oceanography (full paper published).

Bell, D.H., (1975). High intensity rainstorms and geological hazards: Cyclone Alison, March 1975, Kaikoura, New Zealand Bulletin of Engineering Geology and the Environment, Volume 13, Number 1 / June, 1976.

Gosai, A., G. M. Griffiths, and M. J. Salinger, (2003). *Climate and severe fire seasons: Part IV - Daily fire weather sequences and high fire severity in Auckland West/Waikato, North Canterbury, Mckenzie Basin and Central Otago/Inland Southland.* NIWA Client Report AKL2003-026, for National Rural Fire Authority, 54 pp.

Griffiths, G. M., (2007). Observed changes in New Zealand daily rainfall extremes 1930 – 2004. *Weather and Climate,* 27, 3-44.

Jowett, I.G. (1972). Waikato River Power Development flood hydrology and flood routing. Power Division, Ministry of Works and Development. 115 p.

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

Kidston, J., J. A. Renwick, and J. McGregor (2009). Hemispheric-scale seasonality of the Southern Annular Mode and impacts on the climate of New Zealand. *J. Climate*, 22, 4759-4770.

Kistler, R., and Coauthors, (2001). The NCEP–NCAR 50–year reanalysis: Monthly means CD–ROM and documentation. *Bull. Amer. Meteor. Soc.*, 82, 247–268.

Liu, N., Jia, Z., Chen, H., Hua, F., and Li, Y., (2006). Southern high latitude climate anomalies associated with the Indian Ocean dipole mode. *Chinese Journal of Oceanology and Limnology* Vol. 24 No. 2, P. 125-128.

Marshall, G. J. (2003). Trends in the southern annular mode from observations and reanalyses. *J. Climate*, 16, 4134-4143.

McKerchar, A. I., J. A. Renwick, and J. Schmidt (2010). Diminishing streamflows on the east coast of the South Island New Zealand and linkage to climate variability and change. *New Zealand Journal of Hydrology*, 49, 1-14.

Mullan, A. B. (1995). On the linearity and stability of Southern Oscillation-climate relationships for New Zealand. *International Journal of Climatology*, 15: 1365–1386. doi: 10.1002/joc.3370151205.

Mullan, A. B. (1998). Southern hemisphere sea-surface temperatures and their contemporary and lag association with New Zealand temperature and precipitation. *International Journal of Climatology*, 18: 817–840.

Mullan, A.B., Carey-Smith, T., Griffiths, G.M., Sood, A. (2011). *Scenarios of Storminess and Regional Wind Extremes under Climate Change.* NIWA Client Report WLG2010-31, prepared for Ministry of Agriculture and Forestry in March 2011.

Renwick, J.A., (*2011*). Kidson's Synoptic Weather Types and Surface Climate Variability over New Zealand. *Weather and Climate,*31, 3-23. (This volume).

Saji N.H., Goswami B.N., Vinayachandran P.N., Yamagata T., 1999: A dipole mode in the tropical Indian Ocean, Nature, 401, 360-363.

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

Smith, T.M., R.W. Reynolds, Thomas C. Peterson, and Jay Lawrimore, (2008). Improvements to NOAA's Historical Merged Land-Ocean Surface Temperature Analysis (1880-2006). *Journal of Climate,* 21, 2283-2296.

Tait, A., R. Henderson, R. Turner, and X. Zheng, (2006). Thin-plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. *Int. J. Climatol.*, 26, 2097-2115, DOI:2010.1002/joc.1350.

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

Ummenhofer, C. C., and M. H. England. (2007). Interannual extremes in New Zealand precipitation linked to modes of Southern Hemisphere climate variability. *J. Climate,* 20, 5418–5440.

Wang, X. L., and Feng, Y. (2009). RHtestV3 User Manual, Published online at http://cccma.seos.uvic.ca/ETCCDMI/software.shtml, December 2009.

Wang, X. L., H. Chen, Y. Wu, and Q. Pu, (2009): New techniques for detection and adjustment of shifts in daily precipitation data series. *J. Appl. Meteor. Climatol*. (submitted).

Zhang X. and Yang. F., (2004). RClimdex (1.0) User Manual, downloaded from cccma.seos.uvic.ca/ETCCDMI in October 2009

Submitted to *Weather and Climate* on 8 December 2010, Revised on 13 April 2011