WEATHER & CLIMATE

JOURNAL OF THE METEOROLOGICAL SOCIETY OF NEW ZEALAND (INC.)

VOLUME 37 ● ISSUE 1 ● 2017

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Diurnal variations in precipitation frequency in New Zealand

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Key words: precipitation, diurnal variation, hierarchical clustering, New Zealand

Abstract

Diurnal and annual precipitation variations for 58 weather stations distributed across New Zealand are analysed. For many stations an annual peak is observed in precipitation frequencies in winter and a diurnal peak is observed in the early morning. This is in line with previous studies from a much smaller number of New Zealand stations. Station patterns are analysed using hierarchical clustering to reveal groupings of locations with similar patterns. This cluster analysis identifies differences in the peak time and diurnal pattern of rainfall frequency, associated with location and orography. The West coast of the South Island experiences the most frequent precipitation, due to prevailing westerly winds in combination with local orography. The South East of the South Island exhibits lower rainfall frequency and little seasonality. The central North Island and to a lesser extent the North coast experience relatively high precipitation frequencies in the afternoon, possibly caused by convection.

1. Introduction

This study addresses the diurnal variation of rainfall frequency in New Zealand, including how it varies spatially and seasonally. As pointed out by Rouault, Roy, & Balling Jr. (2013), significant gaps occur in the documentation of the diurnal cycle of rainfall in many parts of the world, even though this is an important component of regional precipitation variability. Such information also has important practical implications, since occurrence of rainfall affects economic and social activities ranging from agriculture to outdoor recreation. Nevertheless, no long-term nation-wide New Zealand study of diurnal rainfall patterns has yet been published, although analyses at a few sites date back to the early days of climatological research in New Zealand. A detailed documentation of the diurnal variability - and ultimately also its interaction with lower frequency meteorological oscillations - is an important first step to improve both our understanding of the processes underlying precipitation as well as our abilities to forecast it.

New Zealand Meteorological Office Note No. 1 (Kidson, 1931) reported on hourly precipitation measurements for Kelburn, Wellington in 1928 and 1929. An increase in the average amount of rainfall during the "dawn hours" and "afternoon hours" was identified. The latter was attributed to convection while the cause for the former was reported to be unknown.

The average rainfall in 3-hourly segments for 16 stations was studied by Maunder (1957), describing four stations in detail. This study also mentions convective afternoon rainfall and tentatively attributes a “nocturnal” maximum to “variation in orographic rainfall”.

A similar pattern was observed in a detailed study of rainfall patterns in the city of Invercargill (Sansom, 1988). It mentions an increase during the night due to “a convergence between night-time land breezes and the prevailing westerlies about the coast”.

Published literature on observed diurnal rainfall variations and their causes in other regions of the globe has been summarised by Yang & Smith (2006). Common features include a maximum in late–evening/early-morning hours over the ocean in tropical and sub-tropical regions, and a mid-to-late afternoon maximum over land. For the South African summer, Rouault, Roy, & Balling Jr. (2013) report a midnight to early morning maximum in the frequency of rainfall events in coastal areas, a late afternoon to early evening maximum over the continental interior, and a nighttime maximum in mountainous areas. They attribute this behavior to convection, local land/sea breeze circulations, orography, convection, and mountain–valley processes.

Several authors have focused particularly on rainfall in mountainous regions. Cotton & Anthes (1989) reported an early-morning (0300 LT) maximum in precipitation amount and frequency in northern and central Colorado mountains, with a secondary maximum in the afternoon and early evening. But stations upwind of the main mountain crest in southern Colorado exhibited a pronounced afternoon maximum in precipitation frequency. Mandapaka, Germann, & Panziera (2013) observed a late afternoon peak in rainfall frequency in the European Alps in spring and summer.

This study analyses data from NIWA’s climate database, CliDB, which serves as the national climate archive for New Zealand. The accumulation of over two decades of hourly rainfall data from stations covering the entire country allows for a comprehensive description of diurnal and annual variations in precipitation and subsequent comparison to other countries. Hierarchical clustering is performed on the derived patterns to identify regions sharing common features.

2. Methodology

2.1 Data

Hourly rainfall data in CliDB are collected from measurements using tipping-bucket rain gauges. By the beginning of 1995 this network provided reasonable coverage of the entire country. Quality assurance has been performed routinely on this data set and includes checks for inconsistencies, unrealistic values and strong divergences from nearby stations or past behaviour.

For this study, 58 stations from the two main islands as well as Stewart Island, Campbell Island and the Auckland islands were selected that started reporting hourly rainfall data on 1 January 1995 or before and were still active in 2015. Only stations with less than 10% missing data were used. The selected stations are shown in Figure 1. Note the big difference in the number of rainfall hours between west coast and inland stations on the South Island which is due to the Southern Alps mountain range combined with predominantly westerly winds. To ensure temporal overlap between the stations no data prior to 1 January 1995 were used. From the data, frequency of wet hours, defined as the number of wet hours (> 0 mm) divided by the total number of hours for which measurements were available, was derived for each station. To compare diurnal variability between individual stations, frequencies were normalised by calculating the z-score, which is obtained by subtracting the station mean and dividing by its standard deviation.

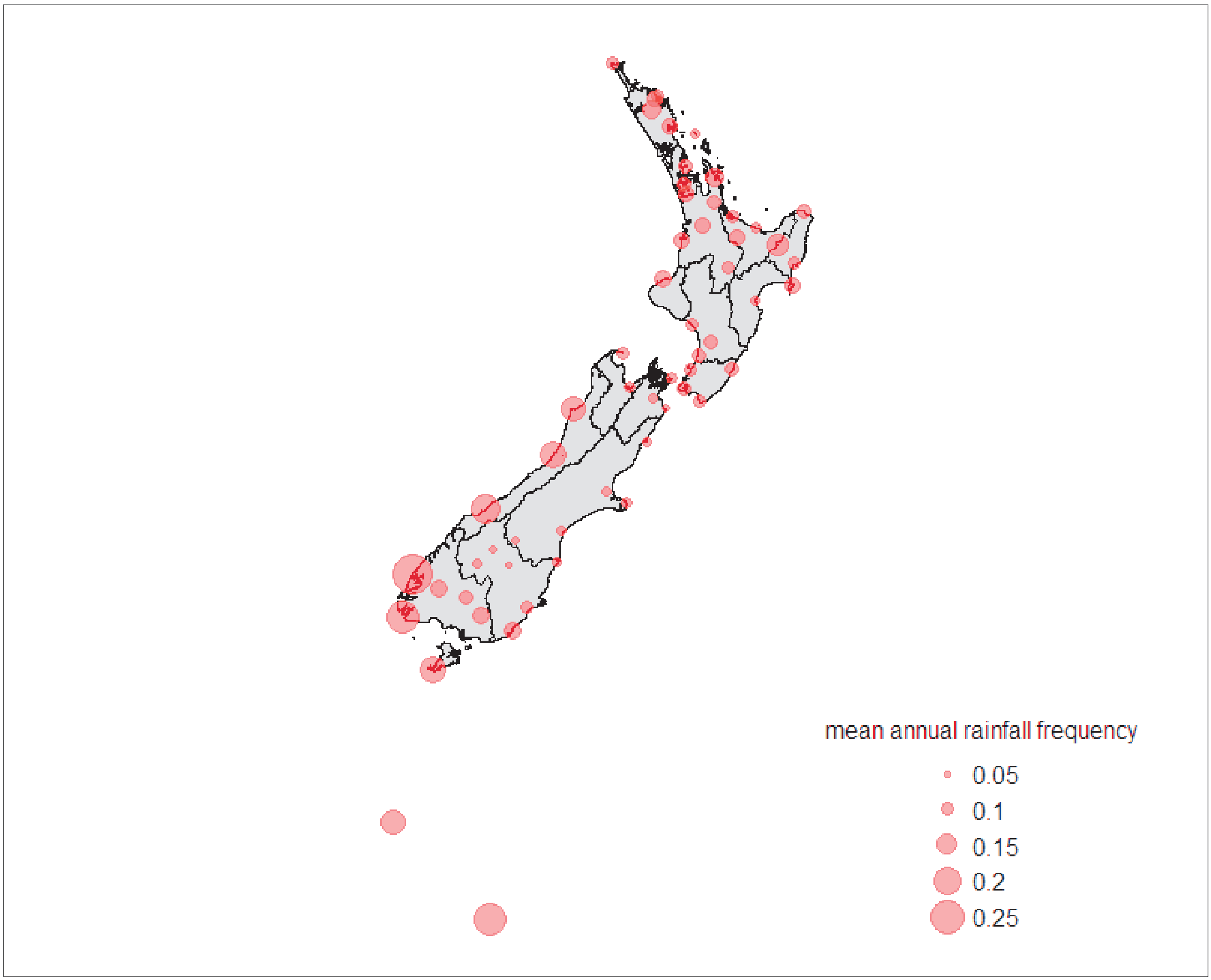

Figure 1: Locations of stations used in this study, sized by average annual frequency of wet hours.

2.2 Clustering

The complete linkage method for hierarchical clustering was used to identify possible groups of stations with similar features. Being an unsupervised method it does not require any a priori input or ground truth. An agglomerative (bottom-up) approach was used, where each station is represented by a feature vector. Pairs of stations are iteratively merged together into one, until all stations are merged. At each iteration, the two most similar stations are merged, based on a cost function representing the dissimilarity between the features of the two stations. The premise is that the cost of merging stations within a cluster is significantly smaller than the cost of merging stations representing two distinct clusters. By observing the monotonically increasing value of the cost function associated with each merge, clusters are identified by the occurrence of a strong increase between subsequent merges. For a more detailed explanation of the method see e.g. (Hastie, Tibshirani, & Friedman, 2009).

In this study, a vector of 96 features was constructed for each station by calculating the z-score of the precipitation frequency by hour of day and season, with (Austral) summer defined as the months of December, January and February, and so on. Each feature then represents the departure from the seasonal mean for a particular station in units of the seasonal standard deviation. The Euclidean distance between these feature vectors was used as the cost function representing the dissimilarity between two stations.

3. Results

Figure 2 shows the data aggregated over all stations and all years. The year has been divided by ordinal days into 24 quantiles to create a 24 by 24 grid showing frequency of rain by hour of day and time of the year. The plots show the column and row means where the red line shows the 2 dimensional Fourier fit using the first 3 by 3 components. The annual cycle peaks during austral winter. The diurnal cycle peaks early in the local morning corresponding to the late evening/early morning maxima that were reported in previous New Zealand and oceanic studies. Note that the amplitude of the diurnal cycle is about 11% of the mean, which is not far below the value of about 14%, which was reported for all tropical oceans by Imaoka & Spencer (2000).

The main aim of this study is to investigate local differences in diurnal precipitation frequency cycles.

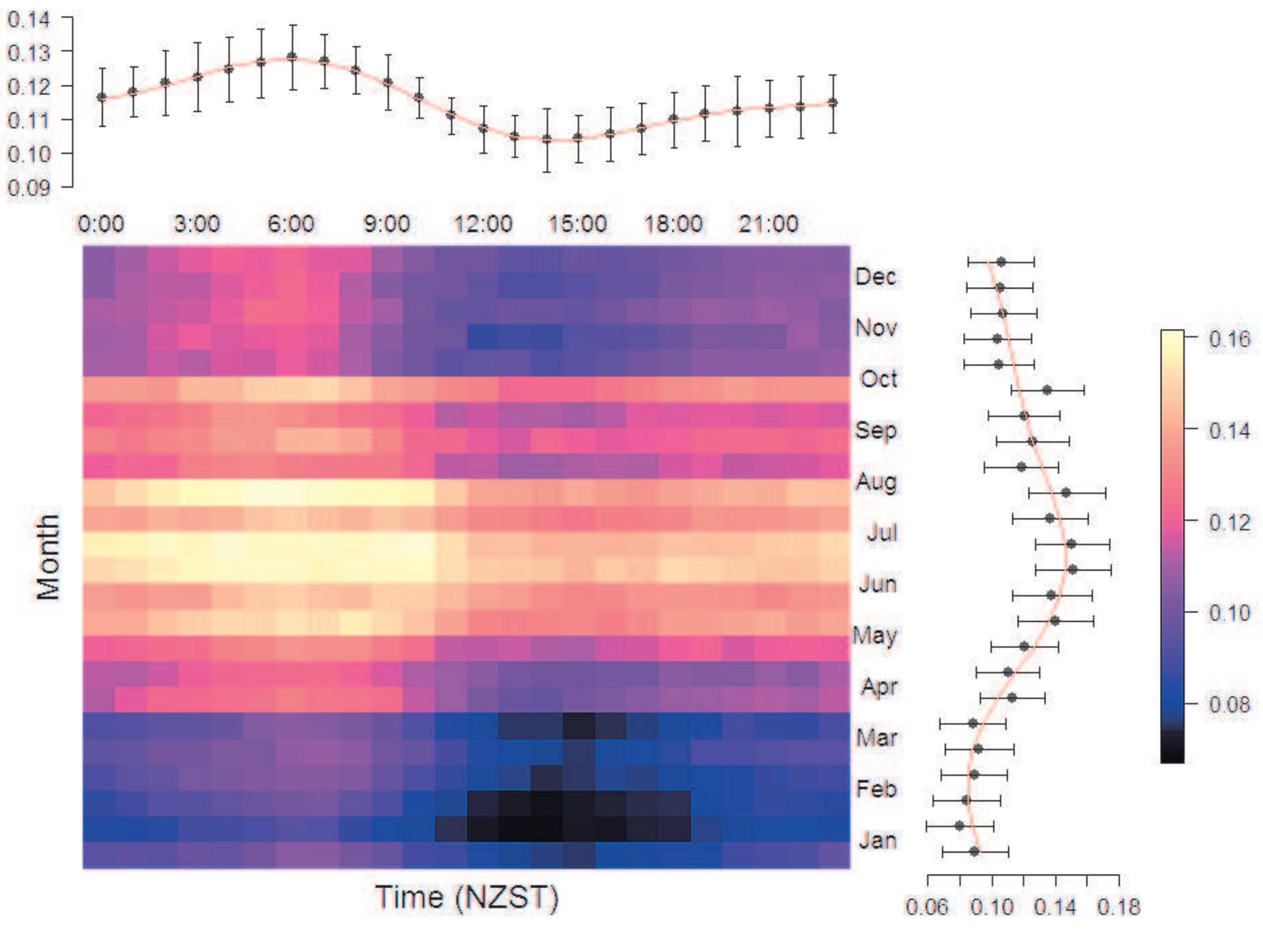

Figure 2: Diurnal and annual distribution of precipitation frequency for the entire data set. Columns represent hour of day and rows represent the ordinal day of the year divided into 24 quantiles. Side plots show the column and row means where the red line indicates a 2 dimensional Fourier fit using the first 3 by 3 components.

Figure 3 shows the dendrogram resulting from the aforementioned approach. Applying a cut-off at the biggest jump between subsequent merges yielded a separation of the stations into four distinct clusters as indicated by the red boxes. These groups also lie in close proximity spatially as shown in Figure 4.

Further investigation is needed to determine what distinguishes these groups of stations from each other. Figure 5 shows the mean frequency values for each cluster. From this the following observations were made.

The largest cluster, shown in black closely resembles the overall pattern as depicted in Figure 2 with maximum rainfall frequency in the early morning and a strong seasonality.

The blue cluster in and around the Otago region features a more or less constant mean frequency of hourly rainfall across the seasons and a strong apparent diurnal peak in precipitation frequency around noon in winter. The latter is an artefact that can be attributed to a known phenomenon in Southern stations where precipitation from e.g. fog or dew freezes onto the rain gauge during the night or morning and is released as temperatures rise above freezing point during the day.

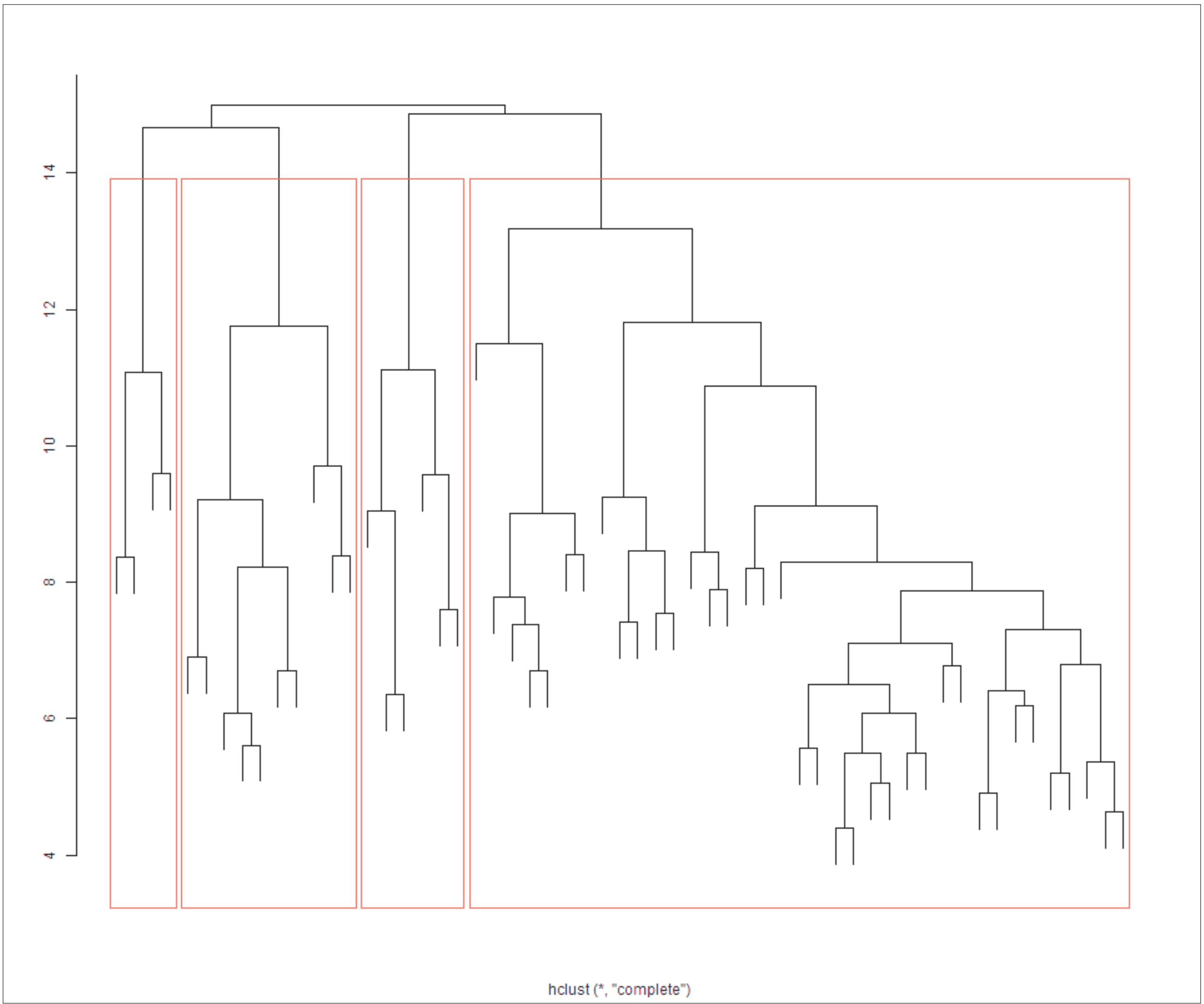

Figure 3: Dendrogram showing results of hierarchical clustering of station data.

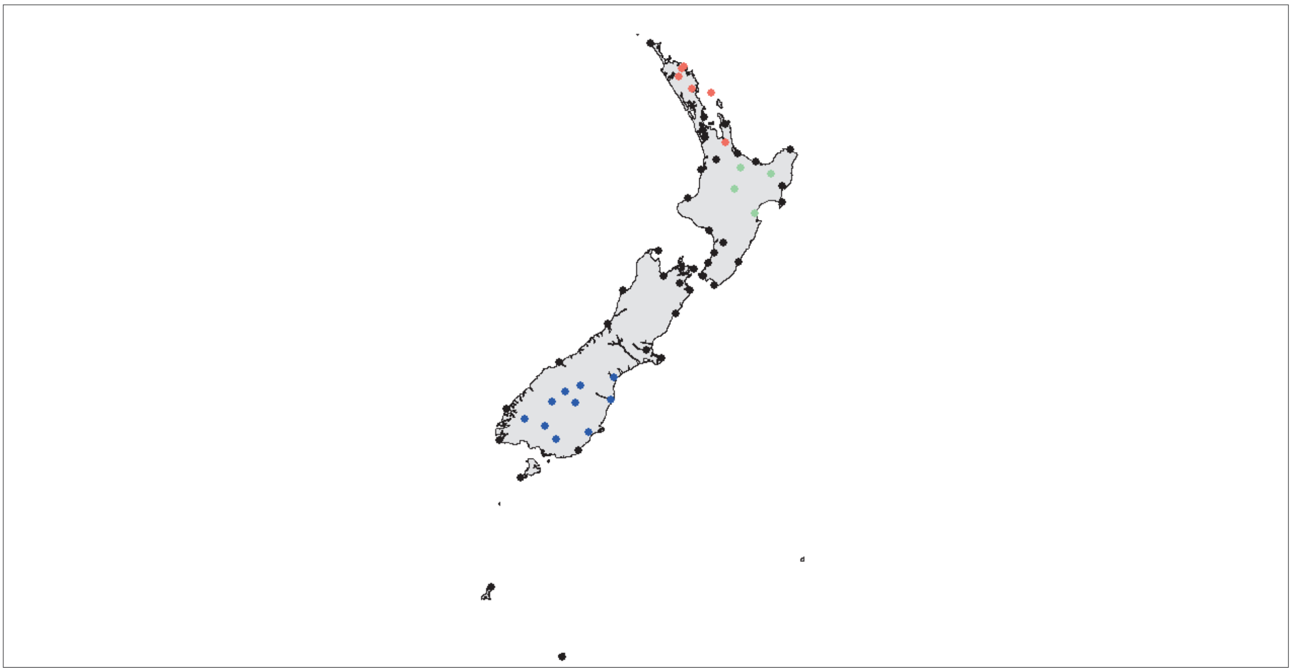

Figure 4: Spatial distribution of the four distinct station clusters, found using hierarchical clustering.

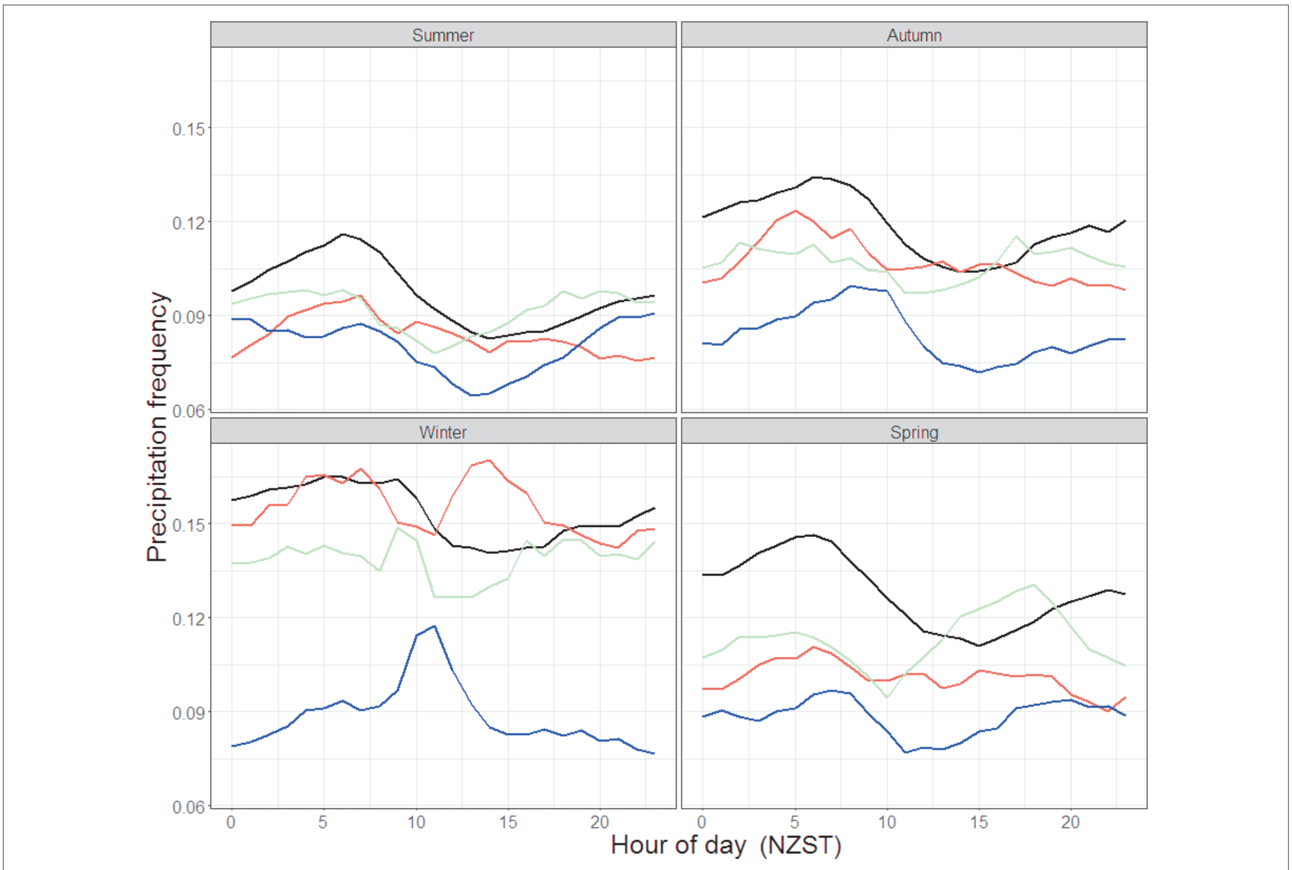

Figure 5: Mean hourly precipitation frequencies for each cluster.

The green cluster in the central North Island shows a double peak structure in precipitation frequency through the day, in which the late afternoon peak is likely caused by convective rainfall.

The red cluster around the Hauraki Gulf partly resembles both the green and black. It features an afternoon increase that is mostly weaker than the green cluster and most pronounced in winter.

From these results, the difference between precipitation frequency in afternoons and mornings as well as between summer and winter were identified as being the main distinguishing features in this data set. We define the diurnal and seasonal parameters D and S as follows.

$$D = f_{afternoon} - f_{morning}$$

$$S = f_{winter} - f_{summer}$$

Here, morning is defined as the 6 hours up until noon and afternoon as the 6 hours immediately after, while summer and winter are defined as before. Together with the mean precipitation frequency M (which did not play a role in the hierarchical clustering described earlier, because z-scores were used), these constitute three simple, interpretable statistics to describe the main features of precipitation patterns in this data set.

Figure 6 shows the station histograms for the z-scores of the D, S and M parameters. The most extreme negative values for D and S and positive values for M are colour coded and are indicated on the map in Figure 7. The West Coast of the South Island as well as the smaller islands to the South stand out by their high mean rainfall frequency, caused by moist air rising as the predominantly westerly winds from the Tasman Sea approach the Southern Alps or the small island orography (Wratt, et al., 1996). Conversely, stations to the East are sheltered by the orography and feature lower seasonality and low mean rainfall frequency. On the North Island the central stations and some of the North Coast stations show relatively high frequencies in the afternoon, resulting in a low D value.

4. Conclusions and outlook

Hourly precipitation data from the last 20 years show that many New Zealand locations experience precipitation most frequently in the early mornings and during austral winter. Hierarchical clustering was used to find regions that differ from this general behaviour. From these results three main parameters, diurnality D, seasonality S and overall mean M, were constructed that correspond to distinguishing features in the precipitation frequency patterns. The west coast of the South Island experiences the most frequent precipitation, due to prevailing westerly winds in combination with local orography. The South East of the South Island exhibits lower rainfall frequency and little seasonality. The central North Island and to a lesser extent the North coast experience relatively high precipitation frequencies in the afternoon, likely to be caused by convection.

This study was primarily focused on providing a description of the variability of diurnal precipitation patterns. Even though some tentative attributions have been mentioned, further research would be needed to provide a solid scientific understanding of the physical and meteorological processes that generate these observed precipitation patterns. In addition, scale interactions of the diurnal cycles with lower frequency modes such as the El Niño–Southern Oscillation (ENSO), the Madden–Julian oscillation (MJO) and the Southern Annular Mode (SAM) will be an important topic for further research.

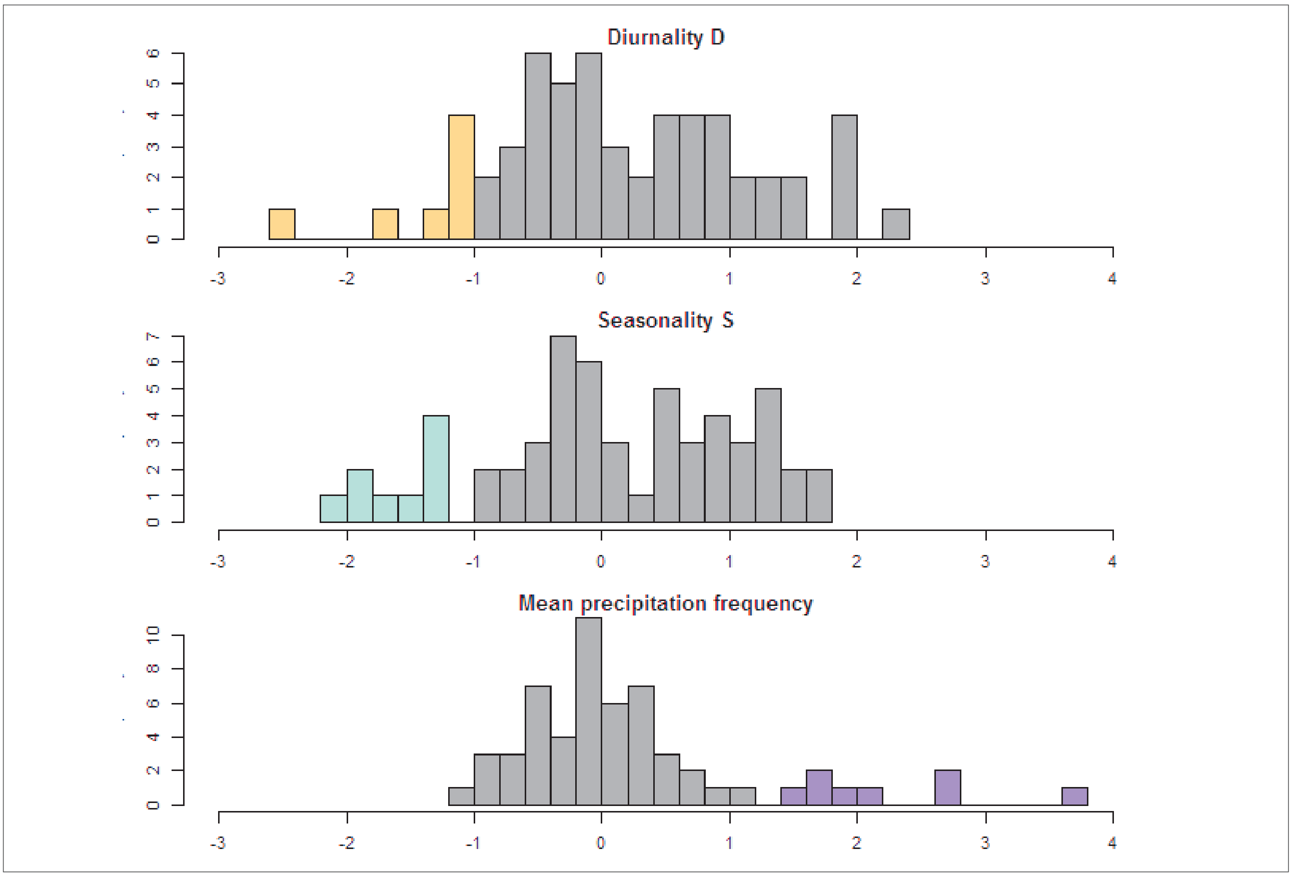

Figure 6: Histograms showing the distributions of the D, S and M parameters for individual stations. Units represent standard deviations from the mean.

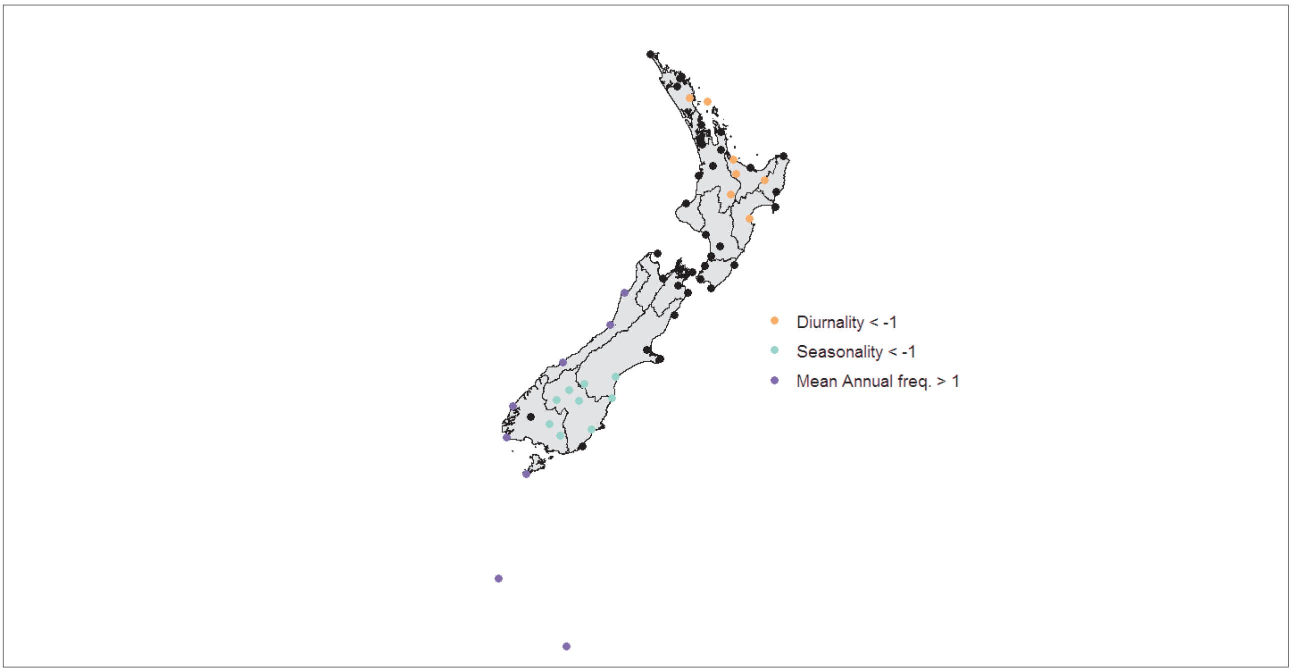

Figure 7: Spatial distribution of stations with low diurnal variation (D), low seasonal variation (S) or high mean value (M) of rainfall frequency. Units represent standard deviations from the mean.

Acknowledgements

The authors thank the late John Sansom, Mike Revell, Brett Mullan, Peter Thomson, Trevor Carey-Smith and Richard Turner for their input during discussions regarding this work. Natalie Robinson, Richard Querel and Peter Hairsine are thanked for their input during the writing of this article.

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Carbon monoxide changes in Auckland - the effects of government legislation

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Key words: government legislation, decline, vehicle emissions, carbon monoxide

Abstract

The main sources of carbon monoxide (CO) in New Zealand are motor vehicle exhaust emissions and domestic home heating. In Auckland the 2011 emissions inventory (Sridhar et al., 2014a) showed that 88-89% of annual CO emissions were attributable to petrol motor vehicles. Atmospheric CO concentrations were measured at a roadside monitoring site in central Auckland, New Zealand (Khyber Pass Road) from 1996 to 2015. Data collected at this site show a steady decline through 1996 to 2011; between 2011 and 2015 the declining trend slowed and became reasonably flat. This downward trend is consistent with observations made at several other urban sites, in New Zealand, the United Kingdom and other overseas countries. Causes of the decline include changes in vehicle and fuel technology, changes in the vehicle fleet, and most importantly, government legislation to set minimum standards for vehicle exhaust emissions and incentives for households to switch to more efficient and cleaner home heating options.

1. Introduction: why care about CO?

Carbon monoxide (CO) is a colourless, odourless gas found at trace levels, typically between 0.01-0.23 mg/m^3, in the New Zealand atmosphere. Natural sources are volcanoes, fires and metabolism of organisms. Anthropogenic sources include incomplete combustion of fossil fuels, such as petrol in internal combustion engines, wood and coal burned for home heating, and burning of crop and forest residue after harvest. Small amounts arise from certain industrial and biological processes.

CO has an indirect radiative forcing effect by elevating concentrations of methane (CH_4) and ozone (O_3) through chemical reaction with other atmospheric constituents e.g. the hydroxyl radical (OH) (Riedal, 2008). Most of the trace gases found in the atmosphere are oxidised by OH into water-soluble products that are washed out by rain and snow. CO is the major reactant with OH, accounting for about 75% of OH destruction, with most of the remainder destroyed by CH4 (methane) oxidation.

$CO + OH \rightarrow CO_2 + H$ (hydrogen)

CO molecules can remain in the atmosphere for up to three months before being chemically transformed (via interaction with the OH radical) into CO_2, and is included in the amount of greenhouse gas emitted from motor transport.

Submitted: 30 August 2017
Accepted: 3 November 2017

High CO levels can be a localised problem alongside busy and congested roadways and an urban/regional problem when calm stable weather conditions trap the polluted air near ground level.

CO, which is readily absorbed from the lungs into the blood stream, interferes with the blood's ability to carry oxygen through the formation of carboxyhaemoglobin (COHb) (Blumenthal, 2001). Low level exposure causes dizziness, weakness, nausea, confusion and disorientation. At higher levels, it can be fatal. It can take the human body between 2 and 6.6 hours to metabolise half of any concentration of CO that is absorbed.

Health impairments can be experienced by the general population when the COHb levels in the body go above 2.3%, although more sensitive people can be affected by lower levels (WHO 1999).

The World Health Organisation has recommended guidelines to keep the COHb level below 2.5%. These guidelines are average exposures and cover short term exposure (100mg/m^3 for 15 minutes) to longer term exposures (30mg/m3 for 1 hour and 10mg/m^3 for an 8-hour average) (WHO 1999).

The Health and Air Pollution in New Zealand (HaPiNZ) report in 2007 found that the health effects associated with CO exposure showed a significant level of premature mortality (178 cases per year) and illness (2247 extra hospital admissions). The total economic costs of air pollution in New Zealand for both premature death and adverse health impacts were estimated at $1.14 billion per year (based on the 2001 population) (Fisher et al., 2007). In 2012 the HaPiNZ model had updates to some sections, basing the new assessment on PM10; this does not mean that all health effects are attributed to PM10 alone as urban air pollution is a complex mixture of gases and particles. The summary report stated that the total social cost (in June 2010 dollars) associated with anthropogenic air pollution in New Zealand was estimated to be $4.28 billion per year. The contribution from motor vehicles was 22% and domestic fires was 56% (Kuschel et al., 2012).

In the Auckland context (based mainly on PM10 concentrations), air pollution causes approximately 300 premature deaths, and results in an increased number of reduced activity days and hospital visits, and higher usage of medications. It is estimated that the social cost from air pollution in Auckland is $1.07 billion per year (ARC, 2012).

2. The national context and the Auckland monitoring

New Zealand has National Environment Standards (NES) for five air contaminants, which includes an 8-hour moving average (10mg/m^3) for CO (MfE, 2004). These standards, which came into force in September 2005, are concentration limits set to protect people's health and follow the WHO guidelines. It is permissible to have one exceedance of the 8-hour standard per year. Even though the CO NES only came into effect in September 2005, the same value had been a national guideline since 1994. There is also a national guideline for the 1-hour average of 30mg/m^3.

The main sources of CO in New Zealand are domestic home heating and motor vehicle emissions, with traffic being a more dominant source during the summer months. Winter months are the only time domestic home heating fires contribute significantly to pollution. A winter peak in CO occurs due to an increase of emissions but is also related to poorer dispersion conditions. Under certain meteorological conditions e.g. during intense anticyclonic conditions when light winds and near-surface temperature inversions occur, the ability for pollution to be dispersed is restricted, which can create locally elevated CO levels.

In Auckland, the 2004 emissions inventory showed that during an average winter weekday, 83% of the CO emissions were attributable to motor vehicles and were predominantly petrol engines. This increased to 94% during the summer (ARC, 2004). The 2006 emissions inventory showed that, on an annual basis, transport was responsible for 86% of the CO emissions with domestic sources being 12% and industry 2% (Xie, 2014). The 2011 emissions inventory (Sridhar, 2014a) showed that while emissions from petrol vehicles had dropped 42% from 2001-2011, petrol cars still contributed 88-89% of annual CO emissions.

From 1996 to 2015, CO was monitored for the Auckland Council at the corner of Khyber Pass and Mountain Roads in the central Auckland suburb of Newmarket (close to the Central Business District). Khyber Pass Road is oriented WNW-ESE and slopes down to the east, resulting in atmospheric effects similar to those experienced in valleys and canyons.

The location is dominated by traffic, with over 27000 vehicles passing each day. There is a major intersection controlled by traffic lights adjacent to the site which results in frequent queues of idling vehicles alongside the analyser intakes. The original measurement site, from October 1996 to January 2009, had the intake 12.5m east of the road intersection. The measurement site was relocated by September 2009 with the intake now 28m from the intersection. Both sites were on the same downhill side of the road. Co-located measurements were not possible due to site access issues.

The monitoring of CO at the Khyber Pass Road site was undertaken using an API M300 GFC-IR absorption analyser, in accordance with the Australian Standard AS 3580.7.1 which is the method mandated by the Ministry for the Environment (MfE, 2009).

3. Synopsis of results

Since 1998 there has been an overall downward trend in the 8-hour moving average of CO concentrations in Khyber Pass Road air (Figure 1). The percentage of

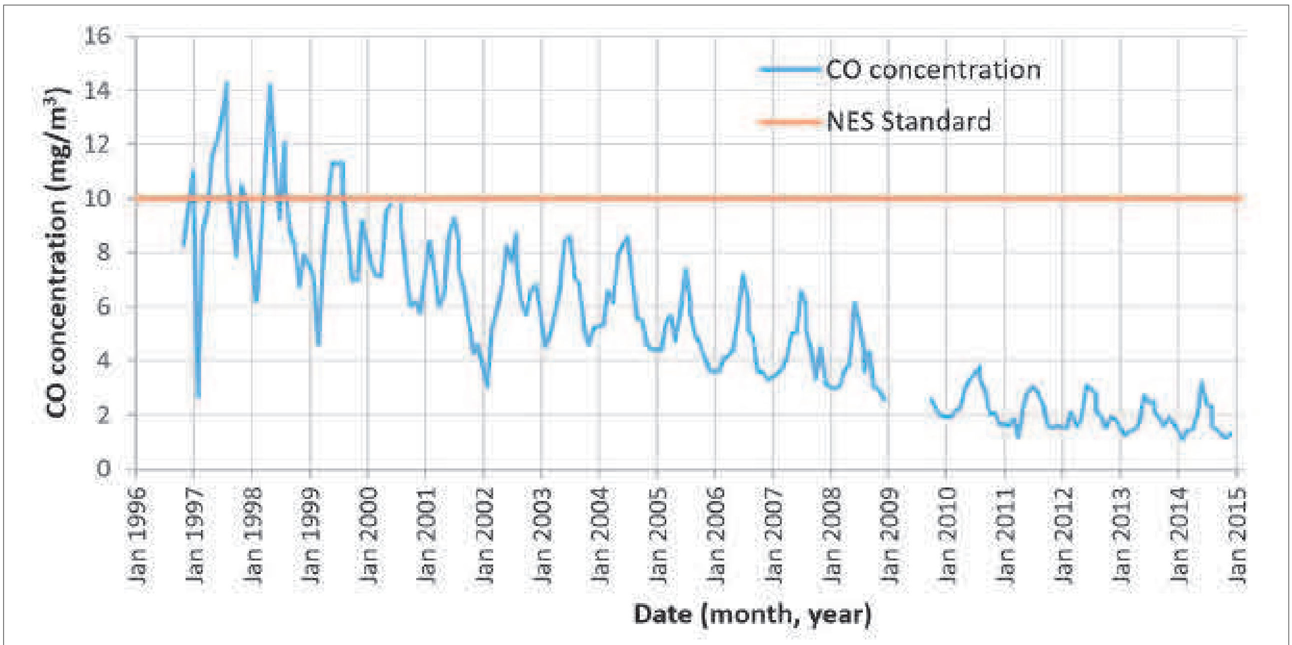

Figure 1: Khyber Pass Road: maximum 8-hour moving average CO. The red line indicates the 8-hour NES concentration. NB there was a site change in September 2009.

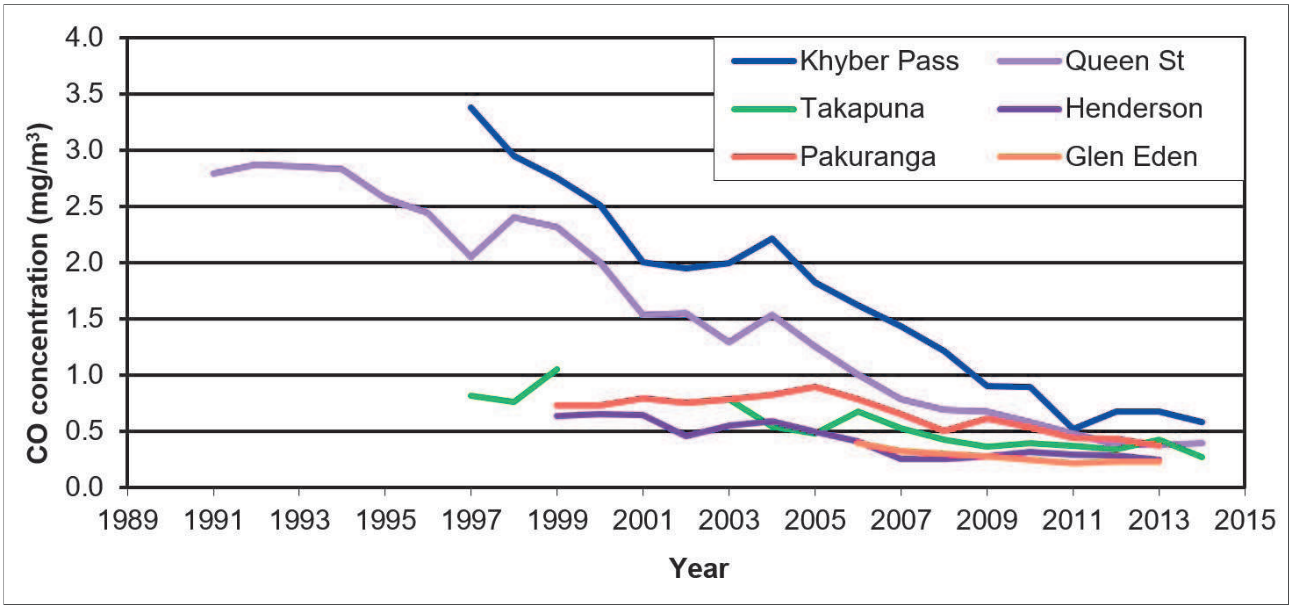

Figure 2: All Auckland CO monitoring sites - annual average.

the year where measurements were above the 8-hour standard fell from 2.3% in 1997 to 0.6% in 1999. The last exceedance occurred in August 1999. In all these years the exceedances mainly occurred in June and July, with the highest monthly percentage being 9.3% during June 1997. A seasonal cycle with a winter maximum is clearly visible in the data plot. This results from a combination of additional CO from domestic home heating fires (around 15% of total emissions) and poor dispersion associated with meteorological conditions described earlier. In February 2015, CO monitoring at Khyber Pass Road was discontinued.

Auckland Council also undertook CO monitoring at several other sites around Auckland. Annual averages from all the Auckland monitoring sites show a similar downward trend in CO over the observation period (Figure 2). Khyber Pass Road and Queen Street have the highest CO concentrations, being more traffic dominated and heavily influenced by the street canyon effect and large buildings which restrict dispersion. The other sites were in more open topography. CO monitoring stopped in Auckland during 2016 at all sites.

CO has also been monitored at other locations in New Zealand. Continuous data are mainly available from the larger towns and cities including Rotorua, Wellington and the Canterbury region. The annual maximum 8-hour moving average data is shown in Figure 3 and the annual average in Figure 4.

The data shows the highest maximum 8-hour concentration occurred at the Christchurch site of St Albans whereas the annual data plot up to 2014 shows the highest annual concentration is at the Auckland site of Khyber Pass. The reason for this difference is primarily related to the location of the sites. In these two figures, the Khyber Pass, Takapuna, Wellington Central and Queen St sites are all traffic dominated whereas the remainder are urban sites. A traffic dominated site will have higher concentrations over the entire year whereas an urban site will have higher concentrations during winter but lower concentrations in summer. All of these sites are in locations reflecting where many people live or work and are potentially exposed to pollutants. Both the 8-hour moving averages and the annual average figures show that other locations in New Zealand also have a downward trend between the 1990s and early 2000s followed by a

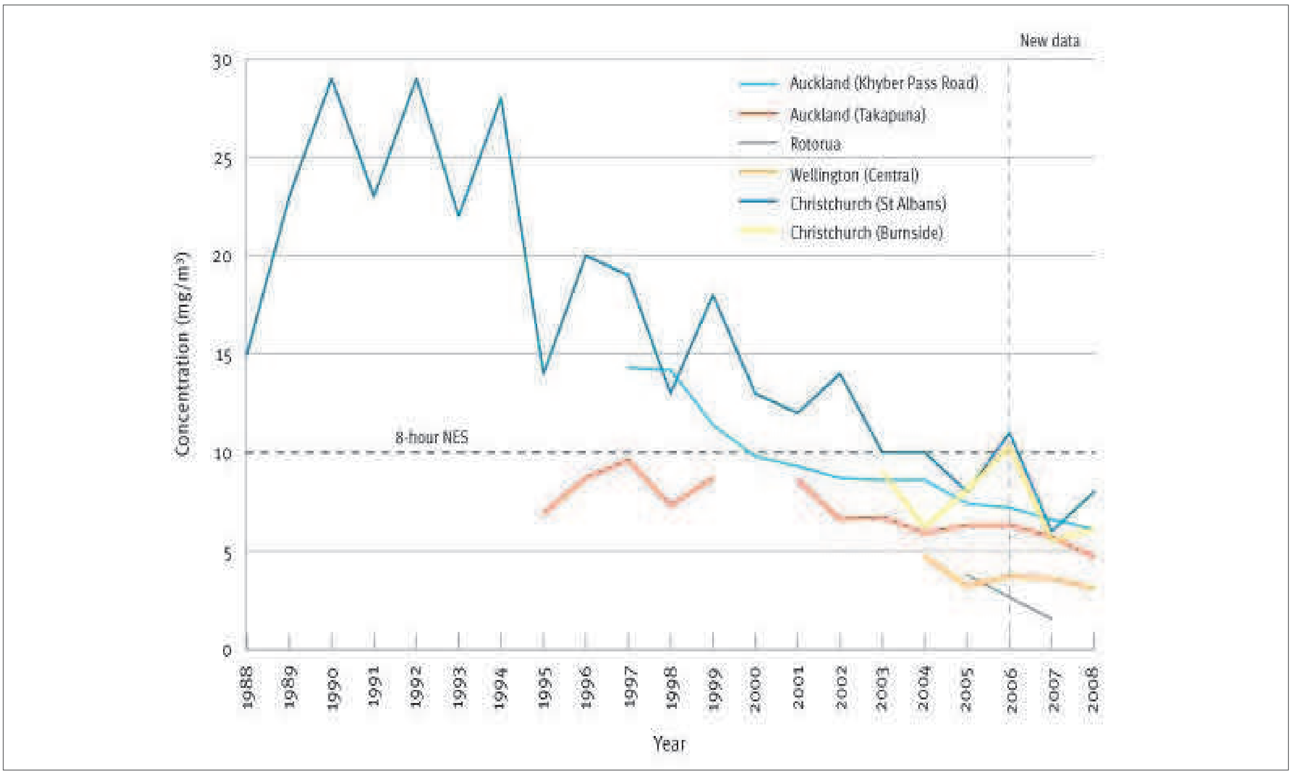

Figure 3: Annual maximum 8-hour moving average of CO for various New Zealand sites. (Graph courtesy of MfE).

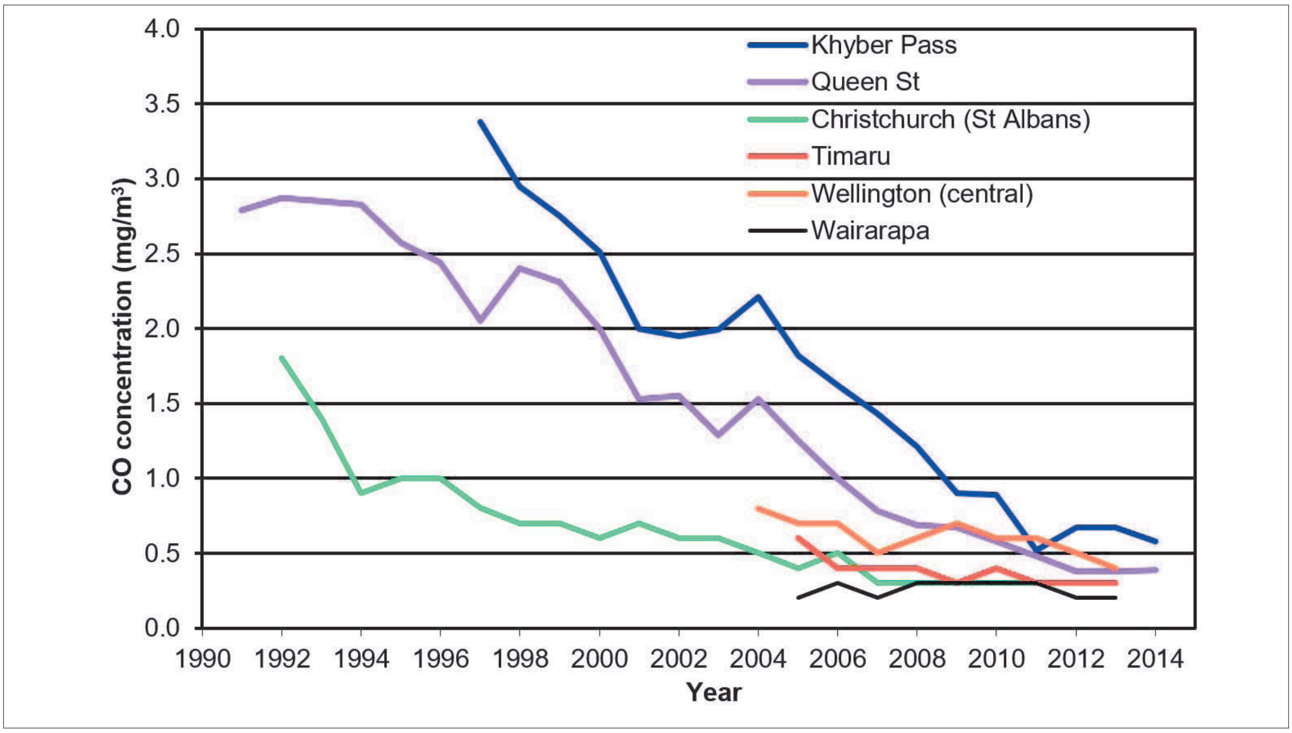

Figure 4: Annual average of CO for various New Zealand sites.

Since 2000 Christchurch has been the only location to have recorded exceedances of the 8-hour NES. This is most likely due to the effects of the local winter meteorology inhibiting the dispersal of the emissions coupled with a greater number of woodfires used for home heating in Christchurch. There have been no exceedances of the 8-hour NES in New Zealand since 2006.

4. What impacts concentrations of CO

4.1 Vehicle Exhaust Emission Rules

Through the 1990s, used imported vehicles had better exhaust emission control technology than the same model vehicles manufactured new in New Zealand; the imports were manufactured to comply with more rigorous standards that applied in their home country than the standards required in New Zealand. In the late 1990's a voluntary agreement between the government and New Zealand car manufacturers resulted in some New Zealand-new vehicles being fitted with emission control technology. The 2003 Vehicle Emission Rule (MoT, 2003) was the first requirement in New Zealand for vehicles to have a recognised emission standard: new vehicles had to be built to a minimum standard and imported used vehicles to a recognised standard.

In 2007 the Rule was changed (MoT, 2007) so that all vehicles entering the New Zealand fleet had to meet minimum standards. If an emission standard changed in a country of vehicle origin, then that standard would apply to imported new vehicles into New Zealand two years later. For used imported vehicles there was a longer lag, e.g. the Japan 2005 Standard applied to vehicles imported into New Zealand from Japan from 2012.

4.2 Changes in the vehicle fleet

In 1998 import tariffs imposed by the government were removed, making it cheaper to import vehicles. This resulted in an influx of cheaper second-hand vehicles from overseas, mainly from Japan. A large number of these imports had been manufactured in the 1995-1997 period and these imports were built to more rigorous emission control standards than New Zealand manufactured vehicles. As the number of imported vehicles increased, the overall CO emissions started decreasing. A second peak of imported used vehicles manufactured in the years 2005-2008 is now becoming evident (MoT 2016), which is partly caused by another change in the required vehicle standard (Figure 5).

Real time emissions monitoring of motor vehicles has been done in New Zealand on a campaign basis over a number of years for the New Zealand Transport Agency and Auckland Council (ARC, 2012). During the 2009 campaign, the 1995-1997 vehicle peak translated to an average vehicle age of 12-14 years. The emissions from the Japanese imports were still lower than those for a New Zealand new vehicle. It is only for vehicles manufactured since 2000 (age groups up to 8-10 years) that CO emissions from New Zealand new and Japanese used vehicles became similar and the benefit, emission-wise, from Japanese imports became less significant (Figure 6).

4.3 Catalytic converters

Catalytic converters are devices that are fitted to the exhaust system of a motor vehicle. They use chemical catalysts to convert some pollutants, including CO, into less toxic forms, such as carbon dioxide, nitrogen and water. Over the average lifetime of a vehicle a catalytic converter can reduce total emissions of CO by up to 80% (Modhavadiya et al., 2015).

Until the 2007 Vehicle Exhaust Emission Rule, there was no legislation to prevent tampering with emission systems (MoT, 2007). The earlier Japanese imports were built with emission control systems that included catalytic converters. In many cases these were removed from the

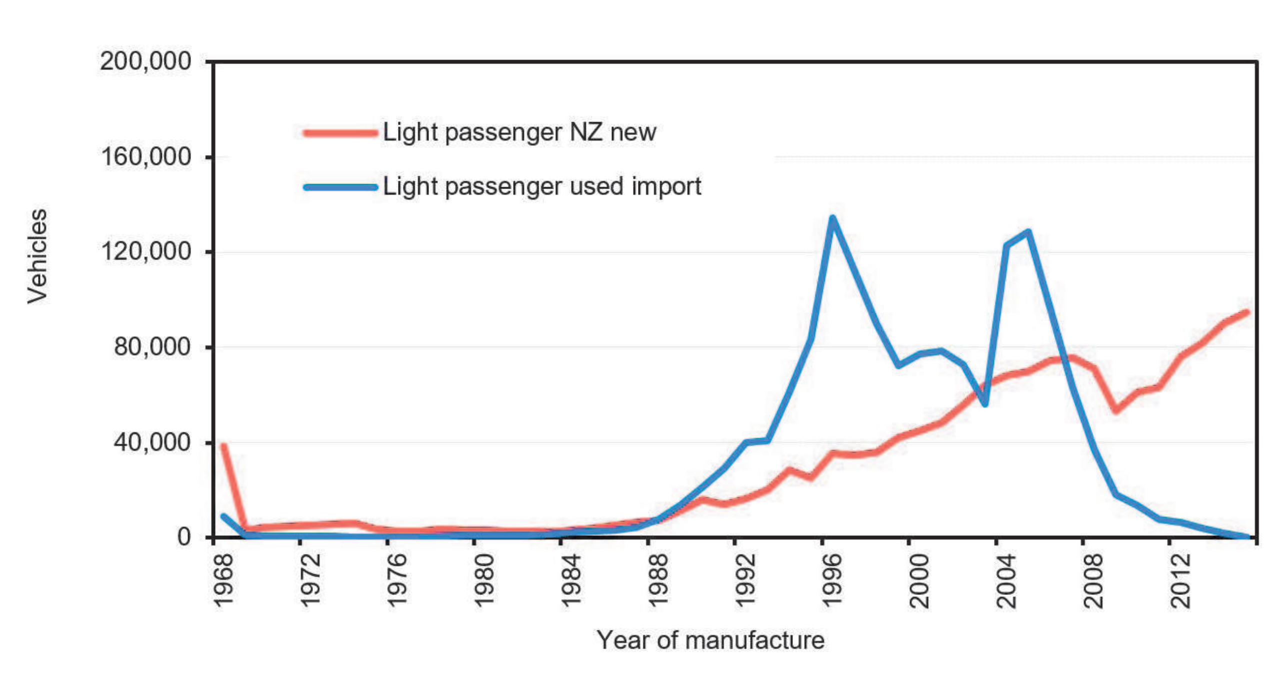

Figure 5: New Zealand vehicle fleet as at December 2015. NB The 1968 data are for years up to and including 1968.

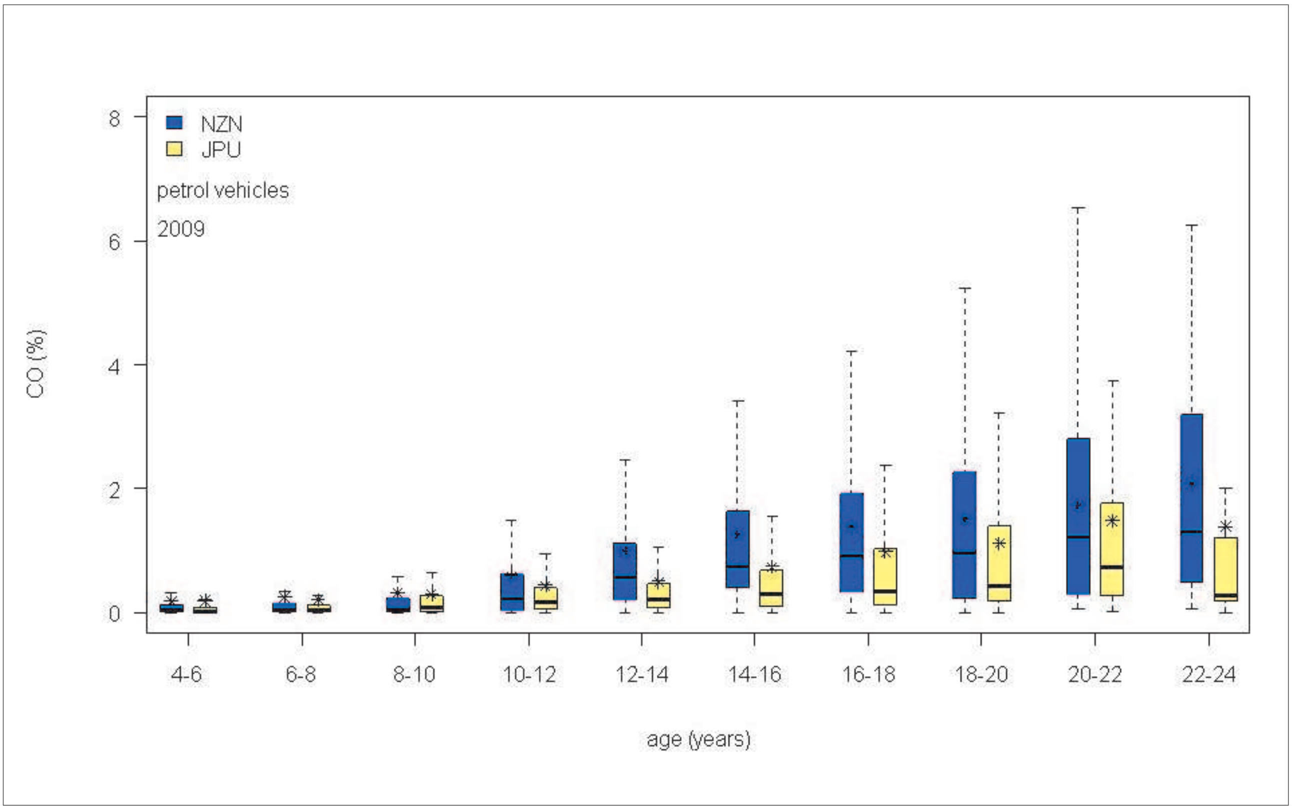

Figure 6: Vehicle age and CO emissions for Japanese used and New Zealand new petrol vehicles from the 2009 emission monitoring campaign.

vehicles as soon as they arrived in the country. This was particularly prevalent when leaded petrol was still being used. The main reason for the removal of the converter was that New Zealand drivers believed it tended to reduce the power output of the motor, and this was not popular with the New Zealand buyer (UUC, 2017).

4.4 Vehicle travel

The Vehicle Kilometres Travelled (VKT) by the New Zealand light vehicle fleet is expected to increase as the population of New Zealand increases (MfE 2009b). There was a steadying off in the late 2000s as a result of economic decline, but this has now increased again with a 5% increase in the light fleet in 2015, and a 40% overall increase since 2000 (MoT, 2016). This increase in distance travelled could lead to an increase in vehicle emissions, but improvements to engine technology, a consumer demand for lighter, smaller and more efficient vehicles, and a growing number of electric cars should result in continued low levels of ambient CO. A review of the Auckland fleet (Sridhar et al., 2014b) showed that from 2001 until 2011, even though the VKT had increased, the total CO emissions have decreased but the proportion attributed to petrol cars has remained consistent (Figure 7).

4.5 Home heating

Government incentive programmes such as "Warm Up New Zealand" (EECA, 2009), which provided subsidies for residential property owners to remove inefficient heating and replace it with cleaner more efficient options (such as electric heat-pumps and woodfires designed to burn solid fuel more efficiently) encouraged over 6000 households to take advantage of the offer during the first year in 2009. It is expected that up to 80,000 homes across New Zealand will be heated more efficiently and cleanly as a result of

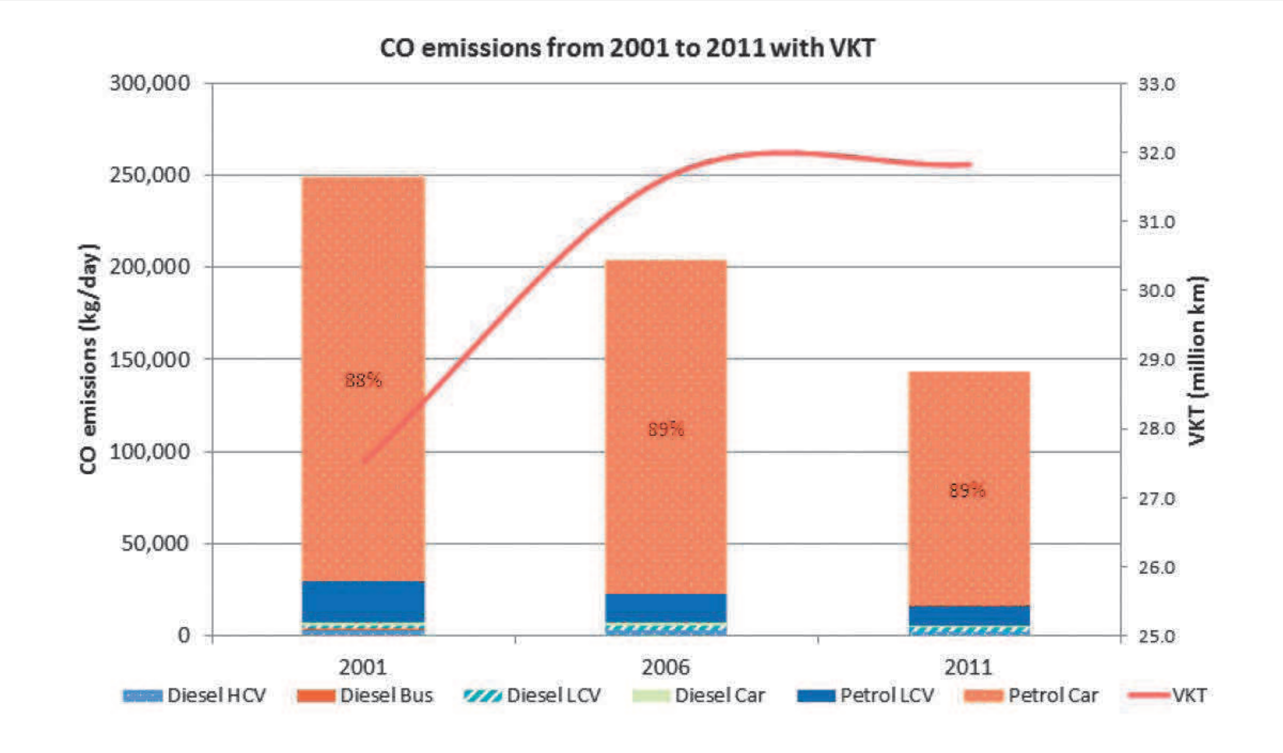

Figure 7: Vehicle age and CO emissions for Japanese used and New Zealand new petrol vehicles from the 2009 emission monitoring campaign in Auckland. Source: Sridhar et al., (2014a).

this programme (EECA, unpublished). Removing old inefficient wood-burners and open fires reduces emission of CO into the atmosphere. The reduction in CO will be more significant in more southern areas of New Zealand where winter home heating is needed more than in Auckland because of colder winter temperatures. The weather conditions in some of these cooler towns such as Christchurch, Masterton and Alexandra are also more suitable to the development of inversions which can trap and contain pollutants near ground level.

Local government programmes involving subsidies and regulations to incentivise householders to switch from solid fuels to more clean heat, especially those introduced by Environment Canterbury and Nelson City Council, have also had a large impact on improving air quality. These measures targeting domestic home heating, although successful in reducing emissions of CO, have had a relatively minor role overall compared to other measures aimed at vehicle emissions.

5. International CO decline

Overseas data have also shown that many countries have experienced a similar decline in ambient CO to that described for Auckland (Lowry et al., 2016). Figure 8 shows the Auckland Queen Street annual average CO concentrations compared to concentrations measured in London (Marylebone and North Kensington), Cardiff, and Belfast in Northern Ireland.

The Marylebone and Queen Street data track downwards at a remarkably similar rate. Marylebone Road is a very busy urban street canyon on the northern edge of the inner London congestion charge area; the sustained decline in average CO implies strict controls on vehicle emissions introduced by the UK government (the 1991 Road Vehicles Regulations, the 1997 National Air Quality Strategy and other measures such as the London congestion charge in 2003) have been effective in reducing vehicle emissions (Lowry et al., 2016).

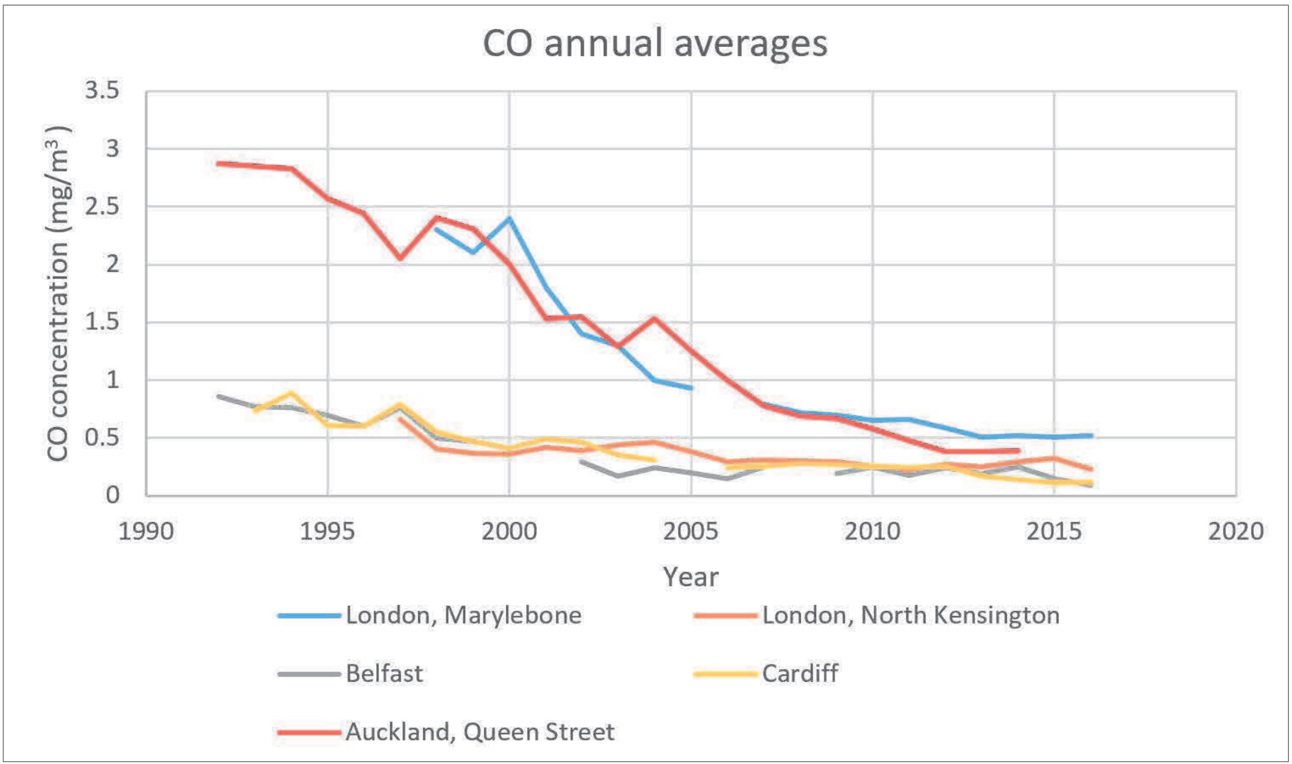

Figure 8: CO annual average concentrations in London, Cardiff, and Belfast compared to Queen Street, Auckland concentrations.

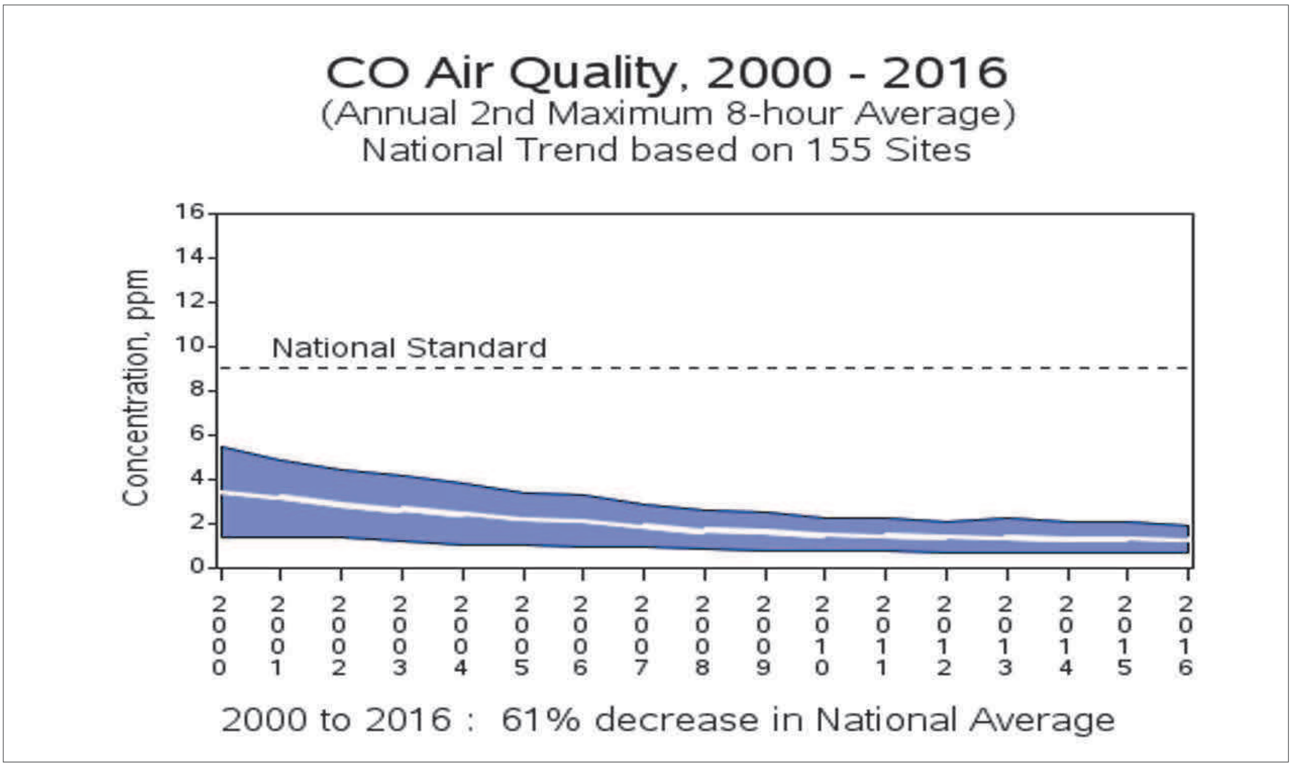

Figure 9: Ambient CO decrease in the USA. Source: EPA, 2017.

CO concentrations in major urban areas in Korea have decreased from 2001 in similar fashion (Kim et al., 2015). This rather abrupt reduction is attributed to a combination of technological improvements and government emission mitigation strategies, as well as a shift away from coal and oil burning to alternative energy fuels.

In the USA, the National Ambient Air Quality Strategy for CO, implemented in 1971, and reviewed in 1994 and 2011, has resulted in a 61% decrease in the national maximum 8-hour average concentration between 2000 and 2016 (Figure 9) (EPA, 2017).

6. Summary

The monitoring at Khyber Pass Road showed a general long-term decrease in CO concentrations. The maximum 8-hour moving average concentration dropped from 14mg/m^3 in 1997 to around 3mg/m3 in 2014 when monitoring ended. The last exceedance of the 8-hour NES was in 1999. The annual average dropped from 3.4mg/m^3 to 0.6mg/m^3 during the same time frame. This downward trend is also evident at other sites around Auckland and in other localities in New Zealand.

The decrease is largely due to changes in the vehicle fleet as a result of government legislation and international trends in improving emissions controls. In 1998 import tariffs were removed, resulting in a large number of used Japanese vehicles entering the New Zealand vehicle fleet; at this time, these imported vehicles had been built to a much more rigorous emission control standard than their New Zealand-built equivalent. Exhaust emission rules were introduced in 2003 with a later update in 2007, when all vehicles, entering the New Zealand fleet both new and used, had to meet minimum standards.

The "Environment Aotearoa" report (MfE, 2015) found that CO emissions in New Zealand from transport had declined by 46% since 2001, due to improvements to fuel and stricter emission limits on new vehicles.

The vehicle kilometres travelled (VKT) by the New Zealand light vehicle fleet is expected to increase as the population of New Zealand increases. This could lead to an increase in vehicle emissions for some contaminants, but improvements to engine technology, a consumer demand for lighter, smaller and more efficient vehicles, and a growing number of electric cars should result in continued low values of ambient CO.

Government incentive programmes to encourage households to replace inefficient solid fuel heaters with cleaner technology such as heat pumps or modern cleaner-burning woodfires, has also been a factor in the overall reduction of CO, especially during the colder winter months.

Decreases in the level of CO pollution will continue to benefit the health of the New Zealand public and reduce the level of premature mortality and hospital admissions that are directly related to the inhalation of CO. Reducing CO levels will also assist New Zealand to achieve its greenhouse reduction targets under the Paris Agreement.

Although CO is only a very weak direct greenhouse gas, it has important indirect effects on global warming. CO reacts with hydroxyl (OH) radicals in the atmosphere, reducing their abundance. As OH radicals help to reduce the lifetimes of the stronger greenhouse gases, such as methane, CO indirectly increases these gases.

The large decrease in New Zealand's ambient CO levels has occurred in a relatively short time, just over a decade, through strong targeted government legislation backed by effective scientific monitoring and advice.

Acknowledgement

The authors acknowledge and thank Auckland Council for the use of their data, and all those staff involved in the collection and processing of the data.

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An automated drought monitoring system for New Zealand

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Key words: drought, drought monitoring, drought index, New Zealand

Abstract

A daily-updated web-based drought monitoring system for New Zealand is presented. Map and time series products are based on the newly-developed New Zealand Drought Index (NZDI), which is derived from four commonly-used base indices: the Standardised Precipitation Index (SPI), the Soil Moisture Deficit (SMD) and its anomaly (SMDA), and the Potential Evapotranspiration Deficit (PED). The NZDI products have been reviewed by several stakeholders from the meteorological, agricultural and government sectors, with excellent feedback received and integrated into refinements of the products. Historic 'adverse event' declarations in New Zealand have been used to qualitatively validate the drought monitor products, with very good agreement shown, though more in-depth comparative studies are warranted and suggested, together with assessing the potential seasonal predictability of the NZDI. The New Zealand Drought Monitor webpage is currently operational and provides a decision support service that can be applied to many uses, as needed and determined by the users.

1. Introduction

Droughts are a regular natural hazard in New Zealand that particularly affect the agricultural sector. Severe and prolonged droughts can have a significant impact on agricultural production and animal health, and hence can impact the wellbeing of farmers, their communities, agricultural businesses and, ultimately, the nation's economy. As an example, the 2013 drought is estimated to have had a negative effect of 0.6% on GDP and 3% on the exchange rate (Kamber et al., 2013). However, many of the risks associated with the detrimental impacts of drought can be reduced by regular and consistent monitoring of up-to-date drought conditions, combined with effective drought risk management strategies (Hao et al., 2014).

Droughts typically develop slowly, and result from an extended period of time (e.g. several weeks or months) when precipitation is less than normal for a given region. Drought monitors, defined here as systems (usually web-based) for regularly updating drought conditions for an area (often an entire country or larger region) enable the development of drought conditions over time to be assessed. There are a number of drought monitoring systems operational around the world (e.g. Svoboda, et al., 2002; Yan, et al., 2016; Cammalleri, et al., 2016). Such drought monitors utilise a range of observations,

Submitted: 11 August 2017
Accepted: 26 October 2017

including rainfall, soil moisture and satellite imagery, to enable assessment of the spatial and temporal variability of drought conditions.

One of the major challenges to New Zealand's agricultural sector is how to reduce the impacts of droughts. Droughts impact agricultural systems economically as well as environmentally. Economically, droughts reduce agricultural production (particularly pasture-based and crop production), can affect animal health (due to dehydration and malnutrition), can disrupt industries connected to agricultural production, and often result in economic (and mental) hardship to farmers and rural communities. From an environmental perspective, droughts can deprive soils of essential moisture, which can lead to higher rates of erosion, soil and stream/river/estuary health issues, and can stress plants to the point where they become highly susceptible to disease and/or die from wilting (Mishra & Singh, 2010).

To mitigate these impacts of drought, a monitoring system with extensive geographic coverage producing timely regularly-updated information is required. Real-time monitoring of droughts can aid in developing a Climate Risk Early Warning System (CREWS is a major global initiative of the UN Sendai Framework for Disaster Risk Reduction). An objective evaluation of the current drought condition is the first step of a CREWS, leading to better long-term strategic planning on water storage options, sources of supplementary feed, optimum herd size and forward contracts, and improved short-term tactical decision-making on the efficient use of available water, feed, off-site grazing and financial resources for selling and purchasing decisions. An additional component of a CREWS is a reliable forecast of drought conditions for the near future (forecasts are not addressed in this paper, but the potential predictability of drought conditions is currently under investigation). This combination of long- and short-term consideration of options is often termed drought risk management (Wilhite et al., 2010).

Drought risk management is highly context specific. It is a management process that is situation-dependant and evolves over time, given the almost unique climatic and financial pressures experienced during each drought event (Clark, 2001). Drought policy or decision-making during times of drought should be based on risk management practices, the context of the policy or decision, and a reliable standardised index of drought that provides guidance on the historic, current, and potentially future drought conditions at a relevant scale (Nelson et al., 2008; Steinemann and Cavalcanti, 2006).

1.1 Definition of drought

Droughts, as any natural hazard, impact a variety of natural, social and economic processes. As a consequence, definitions of drought differ depending on context and application. Wilhite (2000) categorises droughts into three major groups as shown in Figure 1; meteorological, agricultural and hydrological. Meteorological drought is characterised by the degree of dryness and the duration of the dry period, and is considered region-specific based on the typical rainfall regime of a given region. Agricultural drought is comprised of the agricultural impacts associated with precipitation shortfalls, differences in potential and observed evapotranspiration, and soil moisture deficits. Hydrological droughts refer to the reduction in surface or subsurface water supply (i.e. river flow, lake levels and groundwater) resulting from periods of meteorological drought, and inherently lag the onset of meteorological and agricultural drought (Wilhite, 2000).

The New Zealand Drought Monitor uses meteorological observations as well as water balance and evapotranspiration models to quantify drought conditions. In the above scheme that would place it in the meteorological and agricultural categories.

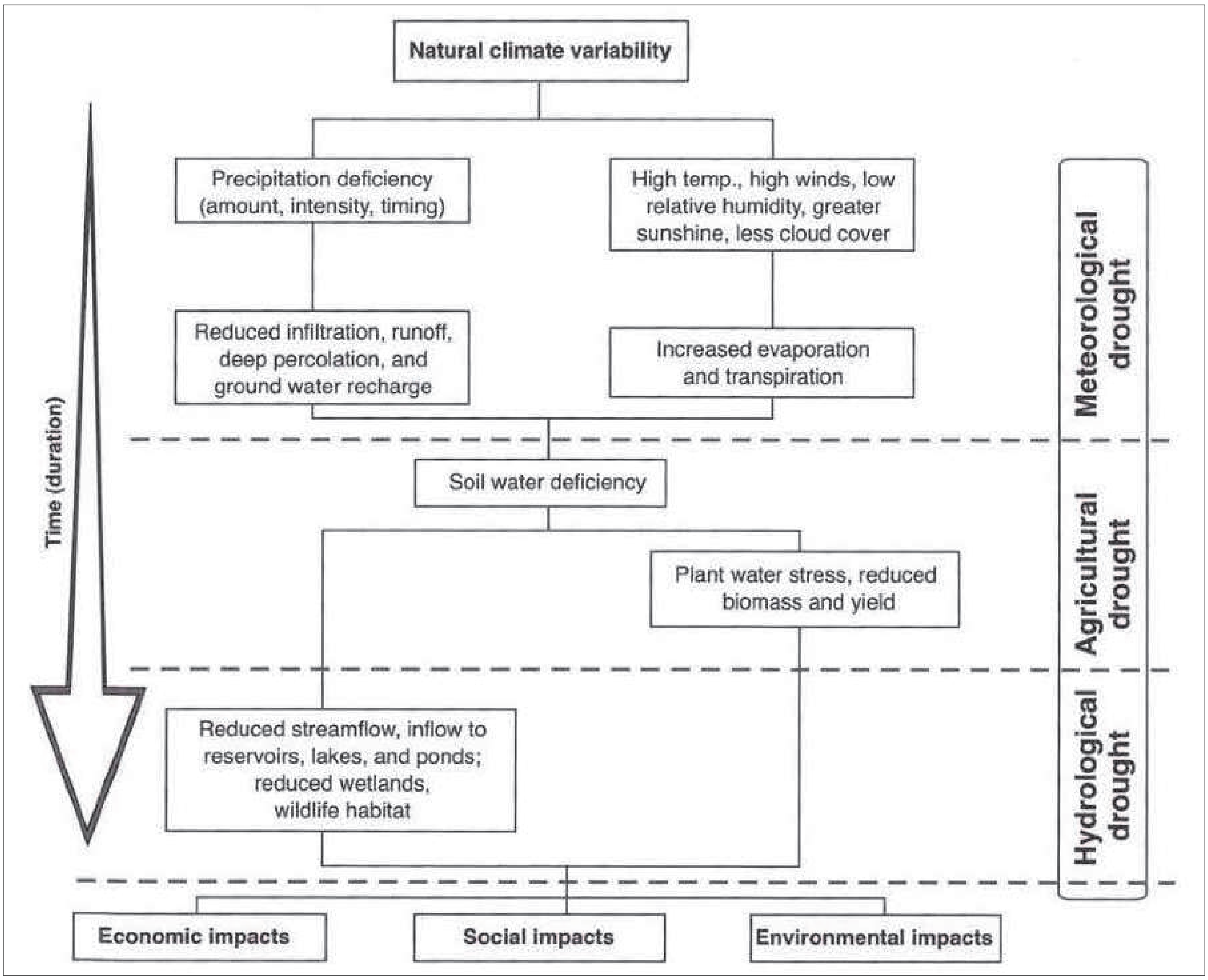

Figure 1: Relationship between various types of drought and duration of drought events. Sourced from (Wilhite, 2000).

1.2 Aims of the New Zealand Drought Monitor

This paper describes the design and development of an automated drought monitoring system for New Zealand based on a newly-developed New Zealand Drought Index (NZDI). The principal aims of the New Zealand Drought Monitor are: 1) to present to the user, in a simple and insightful format, products representing the three main aspects of drought: severity, duration and spatial extent; and 2) to be the single definitive drought information service for the entire country. To achieve this, a composite index called the New Zealand Drought Index (NZDI) is created from four existing drought indicators, serving as a measure of the severity. This index is then presented to the user as an interpolated map (providing information spatial extent) and spatially-aggregated time series charts (providing information on duration), both of which are updated on a daily basis and made freely available online (the New Zealand Drought Monitor is located on the National Institute of Water and Atmospheric Research (NIWA) webpages at www.niwa.co.nz/drought-index.).

The principal users of the New Zealand Drought Monitor are expected to be representatives from the country's primary sector (including farmers, growers, foresters, business consultants and advisors, primary sector organisations, and the Ministry for Primary Industries). However, the service will also be extremely valuable to other drought-sensitive users, such as Regional and Local Councils, the Rural Fire Authority, conservation authorities and organisations, and hydroelectricity generation companies. In all cases, it will be up to the users to determine how they can best utilise the service. It is envisaged that some users will apply the information as guidance only, while others may develop an action plan which includes set thresholds of the NZDI. With the onus on the user to determine the application of the information, the New Zealand Drought Monitor can be clearly defined as a decision support system (Power and Sharda, 2009).

2. Methods

The NZDI is calculated from four base indices: the Standardised Precipitation Index (SPI), the Soil Moisture Deficit (SMD) and its anomaly (SMDA), and the Potential Evapotranspiration Deficit (PED). The choice of these indices was based on sensitivity to rainfall and soil moisture, real-time data availability, good spatial coverage of data, familiarity for intended users (each of these indices has been presented either as maps or charts on the NIWA webpage for some time), and a balance of absolute and relative drought indices (World Meteorological Organization and Global Water Partnership, 2016). There are many other candidate indices that could be used, such as the Palmer Drought Severity Index (PDSI; Palmer, 1965) and the Standardised Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2015). However, several studies have shown that there is often a high correlation between drought indices (e.g. Guttman, 1998; Keyantash and Dracup, 2002; Jain et al., 2015), so adding additional indices or substituting the chosen indices for others is unlikely to add information. Furthermore, the PDSI and SPEI are not currently displayed as maps or charts on the NIWA webpage (or other New Zealand websites), so users will have less familiarity with these indices, in general.

2.1 Base indices

The SPI (McKee et al., 1993) is a widely used drought indicator throughout the world and is based solely on precipitation data. It compares the total precipitation over a certain fixed timespan to its long-term average. The SPI is a relative measure of precipitation, and enables the comparison of precipitation variation between locations with different precipitation regimes. This is especially relevant in New Zealand, where mean annual rainfall exhibits considerable spatial variability. For the NZDI, 60 days is used as the accumulation period. This is an arbitrary choice (other common periods used internationally are 30, 90 and 120 days), and for some regions of the world even longer periods are used (e.g. Van Loon and Van Lanen (2012) note that a 6-month accumulation period corresponds well to both rainfall-deficit and snow-based droughts in Europe). For New Zealand, a period of around two months with well-below normal rainfall is usually sufficient to trigger drought-like conditions (pers comm., Alan Porteous, NIWA). For example, the Waikato region experienced a severe drought in the summer and early autumn of 2007/08 which was initiated by very low rainfall in December 2007 and January 2008 (rainfall anomalies for these months for this region were between 10 and 30 percent of normal, with some locations (e.g. Ruakura) receiving record low January rainfalls (4 mm; the lowest January total since records began in 1906)). A gamma distribution is fitted to the historical precipitation data and transformed into a normal distribution. The SPI value is then defined as the z-score on that distribution. Negative (positive) SPI values represent less (greater) than median precipitation, and application-specific SPI thresholds can be defined to characterise the onset and conclusion of drought conditions (Guttman, 1998).

The SMD is the amount of water (expressed in mm) the soil is short of full capacity. This number is estimated using a simple single soil layer water balance model (Porteous et al., 1994), which adds moisture to the soil through rainfall and removes it through evapotranspiration (ET). A single soil moisture holding capacity of 150 mm is used for all soils. This value is based on field experiments and is generally typical for loam soils in New Zealand (Porteous et al., 1994). While it is recognised that different soil types do have varying soil moisture holding capacities, the use of the single value of 150 mm for calculating soil moisture deficit has been shown to be sufficient for representing broad patterns of dryness for the country, particularly in lowland agricultural regions (pers comm, Alan Porteous, NIWA). ET is assumed to continue at its potential rate (the potential evapotranspiration, PET) until half of the water available to plants is used up (referred to as the plant wilting point), whereupon it linearly decreases, in the absence of rain, as further water extraction takes place. ET is assumed to cease if all the available water is used up. Porteous et al. (1994) show that this simplified model of ET, related to PET and available soil water, is a reasonable representation of the drying characteristics of loam soils in New Zealand. The SMD anomaly is calculated with respect to the 30-year (1981-2010) SMD normal. If the SMD is less than -110 mm and the anomaly is less than -20 mm, then soils are often referred to as 'severely drier than normal' and drought conditions (if not present already) may be imminent.

The PED is the difference between PET and actual evapotranspiration (AET) (Mullan et al., 2005). PET is the amount of water that could evaporate and transpire given sufficient available water (Lu et al., 2005), and is calculated using the FAO-56 Penman-Monteith method (Allen et al., 1998). Note, the FAO-56 Penman-Monteith method calculates the evapotranspiration rate from a hypothetical grass reference crop of 0.12 m height, with a fixed surface resistance of 70 s m-1 and an albedo of 0.23 (Allen et al., 1998). AET is the actual water loss from a vegetative surface by evaporation from soils and from plants, given the prevailing water availability (Rana & Katerji, 2000; Stephenson, 1998). Based on the simple water balance model of Porteous et al. (1994), if half or more of the total soil moisture capacity is available, potential and actual ET are set equal, so PED is 0. If less than half of the total soil moisture capacity is available, actual ET will be smaller than potential ET and PED becomes positive. Days when the water demand is not met (i.e. positive PED), and pasture growth is reduced, are often referred to as days of potential evapotranspiration deficit. As a rule of thumb, an accumulation of 30 mm more PED corresponds to an extra week of reduced grass growth (Mullan et al., 2015).

2.2 Combining the indices

The SMD and PED indices depict water shortage as positive values (there are no negative values), while the SPI and SMD anomaly have both positive and negative values. Since we are only interested in the 'dry' values, only the negative (i.e. drier than normal) part of the SPI is used by setting positive SPI values to 0. The remaining negative values are then changed in sign so that, similar to SMD and PED, a strictly non-negative scale is obtained where increasing values indicate drier conditions. For the same reasons, only the drier than normal positive SMD anomalies are used.

Another difference between the indicators is the sensitivity. The SPI scale gets more sensitive as conditions get drier, whereas the others do not. To introduce a similar behaviour in the other indices the following transformation is applied:

$$x' = -\log_2 \frac{x}{x_{max}} \qquad (1)$$

For the SMD and its anomaly the maximum value (xmax) is the total soil moisture capacity. For the PED the maximum value is determined per station based on all available data (and is updated if a new maximum value is observed). After transformation, the indices are multiplied by a scaling factor so all have similar

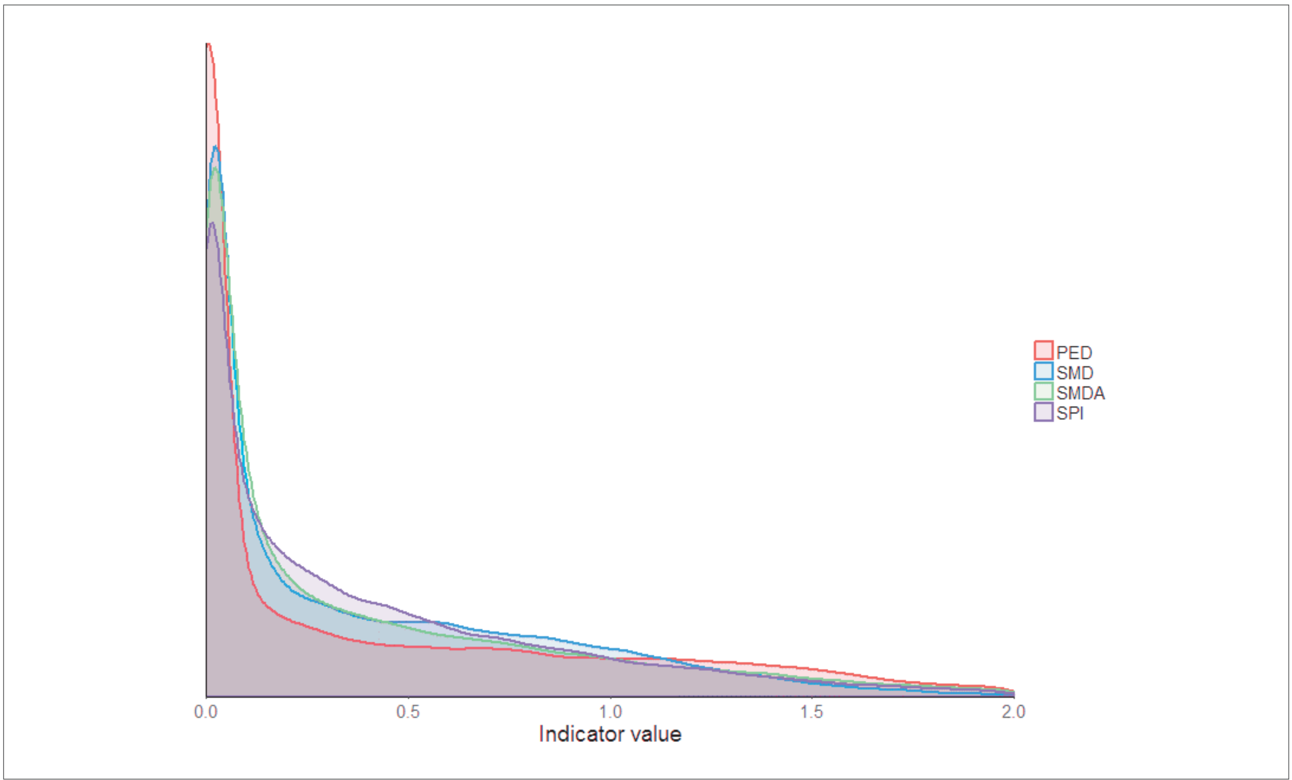

Figure 2: Density distributions of the regional values of the four base indices over the period 2007-2017.

distributions. This is illustrated by the density plot in Figure 2 showing the distribution of the base indices after transformation and scaling over the last 10 years. Having all indices on a similar scale allows for the NZDI to be obtained as the simple unweighted average of the four indices.

2.3 Product generation and feedback

The base indices are calculated and transformed on a daily basis using data from every available climate station in New Zealand that has the necessary observational data. Presently, there are around 100 automatic climate stations distributed around New Zealand that have the necessary data for the daily NZDI calculations. These stations are nearly all located in low elevation (less than 500m elevation above sea level) locations (Figure 3).

The daily NZDI is calculated at these climate stations, and then a thin plate smoothing spline interpolation is applied using the anusplin package (ANUsplin v4.2; Hutchinson, 2017) to produce NZDI values on a nationwide 0.005° (approximately 500m) resolution grid. The gridded data are then used to create daily maps and calculate spatially-aggregated values presented as time series charts. As with any spatial interpolation, the accuracy of the interpolated data is highly dependent upon the number and location of the input data sites (Tait, 2008; Tait and Macara, 2014). In this case, while the spatial coverage of climate stations is good for most areas below 500m in elevation (where the majority of the country's agricultural land is located), the coverage is poor in higher elevation locations hence caution should be used when interpreting the NZDI values in these areas.

In August and September 2016, a NZDI review document was circulated to several stakeholders in the meteorological, agricultural and government sectors in New Zealand (Mol, 2016). The document briefly outlined the proposed new NZDI and asked participants to

Figure 3: Location of presently-open climate stations (as at October 2017) where daily NZDI calculations are made.

comment on the sample maps and time series products. Excellent feedback was received from the stakeholders, much of which was implemented when finalising the NZDI products.

In summary, the feedback centred on the following four topics:

- Duration and intensity – Could the area under the curve in the time series plots be considered as another indicator of drought severity? It's quite possible that a long duration drought event is more severe that a short duration but more intense event;

- Spatial divisions – In most cases district boundaries (Territorial Local Authorities; TLAs) are a useful spatial division for the time series plots, but some eastern TLAs span both coastal and hill country and it would be better to sub-divide these areas;

- Weighting of indices – Currently the NZDI component indices are equally weighted, but perhaps there should be more weighting to the soil moisture anomaly, since this index shows winter time droughts more significantly than the other indices; and

- Classification scale – The NZDI scale should be classified using the following divisions and terminology:

0.75 Dry

1.00 Very dry

1.25 Extremely dry

1.50 Drought

1.75 Severe drought

Some of these suggested changes were made immediately (e.g. the classification scale/terminology and spatial subdivisions), while others (e.g. the weighting of indices and integrated values) will require more research and will be potentially implemented over time.

3. Results

One of the main challenges for any drought indicator is the absence of an objective independent ground truth that can be used for validation. Since the main purpose of the NZDI is to provide insight into the spatial extent, duration and severity of extreme events, past severe droughts are used to qualitatively assess its usefulness. In the case of severely dry conditions, the New Zealand Ministry for Primary Industries (MPI) may declare an 'adverse event' for a particular part of the country (MPI, 2017). Importantly, meteorological conditions are an important factor in this decision process, but other aspects, such as social and economic impacts are also taken into account. As a result, drought conditions may exist in a location but if there are relatively few social and/or economic impacts (i.e. people are generally coping with the dry conditions) then an adverse event will not be declared. Understanding the limitations, these declarations can serve as an indicator for the occurrences of severely dry conditions over the past 10 years and hence can be qualitatively compared with the NZDI values.

3.1 The 2013 drought

The 2012-2013 drought was one of the most extreme droughts on record. It affected almost the entire North Island as well as western coastal areas of the South Island (Porteous and Mullan, 2013).

Figure 4 shows the declarations of drought related adverse events during the 2012-2013 summer and autumn period. For comparison, Figure 5 shows the NZDI maps corresponding to these declarations. Qualitatively, the

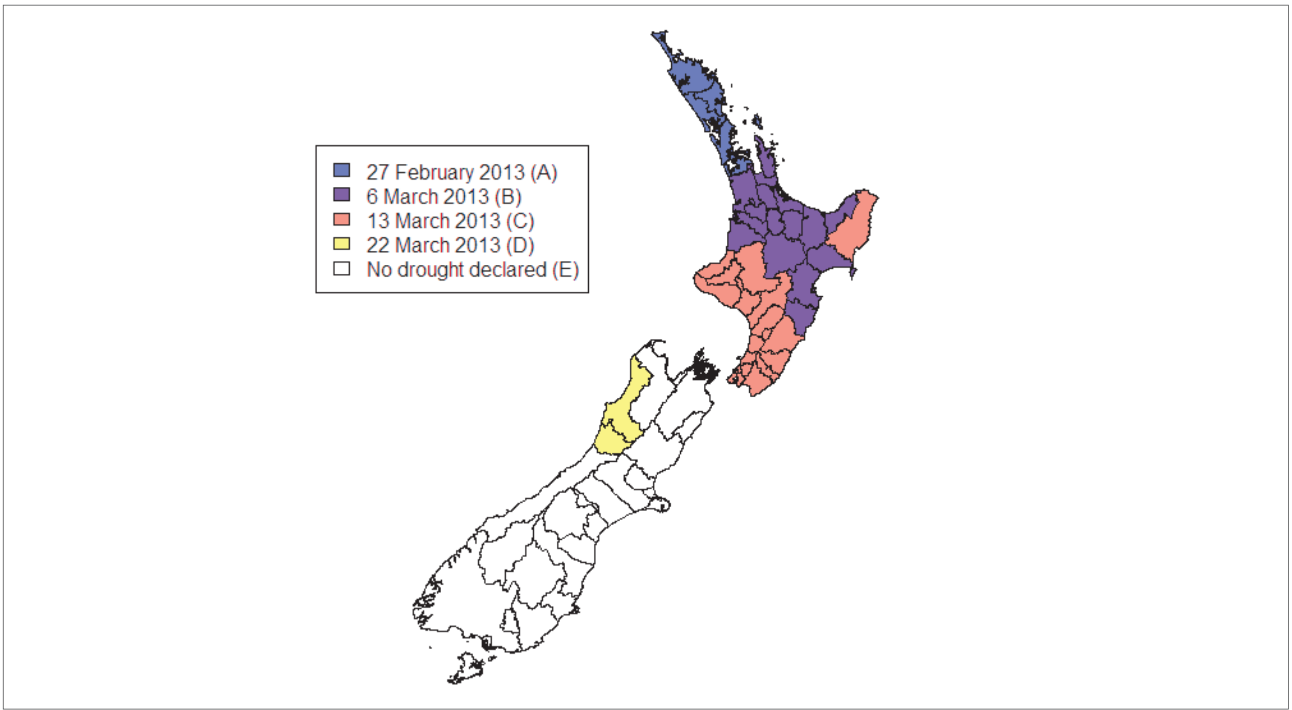

Figure 4: Drought related adverse events declared by the Ministry for Primary Industries during the 2012-2013 drought.

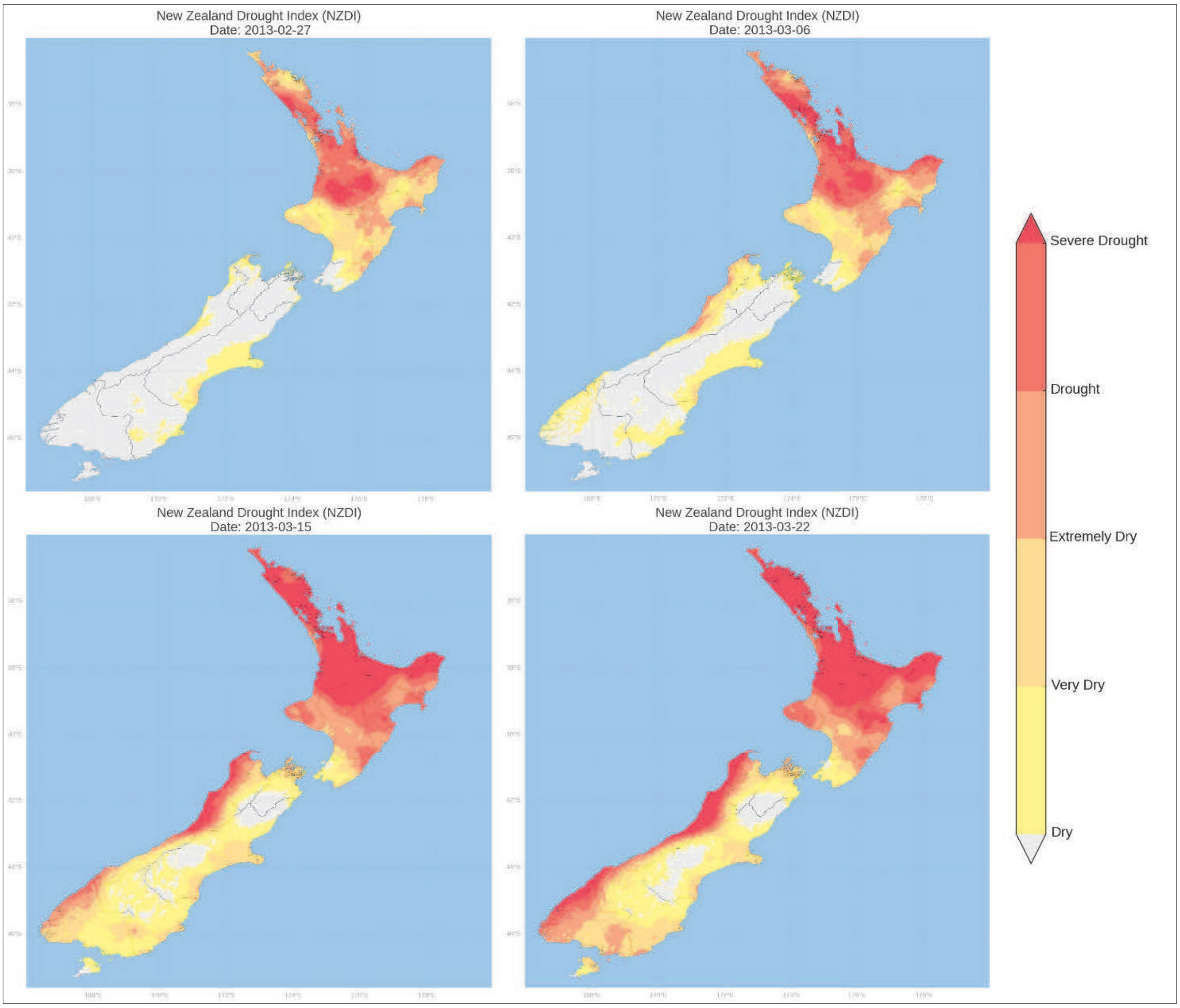

Figure 5: Drought related adverse events declared by the Ministry for Primary Industries during the 2012-2013 drought. NZDI maps for the dates on which drought related adverse events were declared during the 2012-2013 summer and autumn.

areas with high NZDI values correspond well with the locations where drought was declared. Based on the NZDI only, drought might have been declared in more locations in the South Island during mid- to late-March 2013. However, as noted previously, declarations are not solely based on the meteorological conditions present, so presumably the socioeconomic impacts of the dry conditions were not particularly adverse in these other regions such that drought was not declared there.

Figure 6 shows the time series of the NZDI averaged over the declaration regions A through E, from Figure 4. In each case the declarations were made after a steady build-up of the average NZDI, but before reaching the peak. However, the actual NZDI value reached at the time of declaration varies between declaration regions: around 1.5 for regions A and B, around 1.3 for region C, and around 2.1 for region D. Based on Figure 6, it could be argued that an adverse event should not have been declared for all of region C (especially in the Wellington Region, as shown in Figure 5) and that an adverse event should have been declared earlier for region D. This example demonstrates the potential for using a standardised drought index for adverse event declarations, and is one of the core reasons the Ministry for Primary Industries (MPI) strongly supported the development of the NZDI. MPI have indicated that they will adopt a set of 'trigger' thresholds of the NZDI in their declaration process (similar to a 'watch/warning' system), but will still include an assessment of the socioeconomic impacts before declaring an adverse event.

3.2 Northland

Northland is a region of New Zealand that is frequently affected by droughts. Four drought related adverse events were declared for the Northland region between 2007 and 2017. These events coincide with the four highest peaks in the NZDI for the region over the same period, as shown in Figure 7, indicating that the NZDI is performing very well at identifying these relatively short-lived but intense repeated events.

3.3 The 'Hurunui drought'

One of the longest droughts in recent history occurred in North Canterbury. The official adverse event declaration of the so-called 'Hurunui drought' started at 2 February 2015 and only finished on 31 December 2016. Figure 8 shows the NZDI for the east part of the Hurunui District, which was the most seriously affected area of this relatively localised drought. This event is particularly

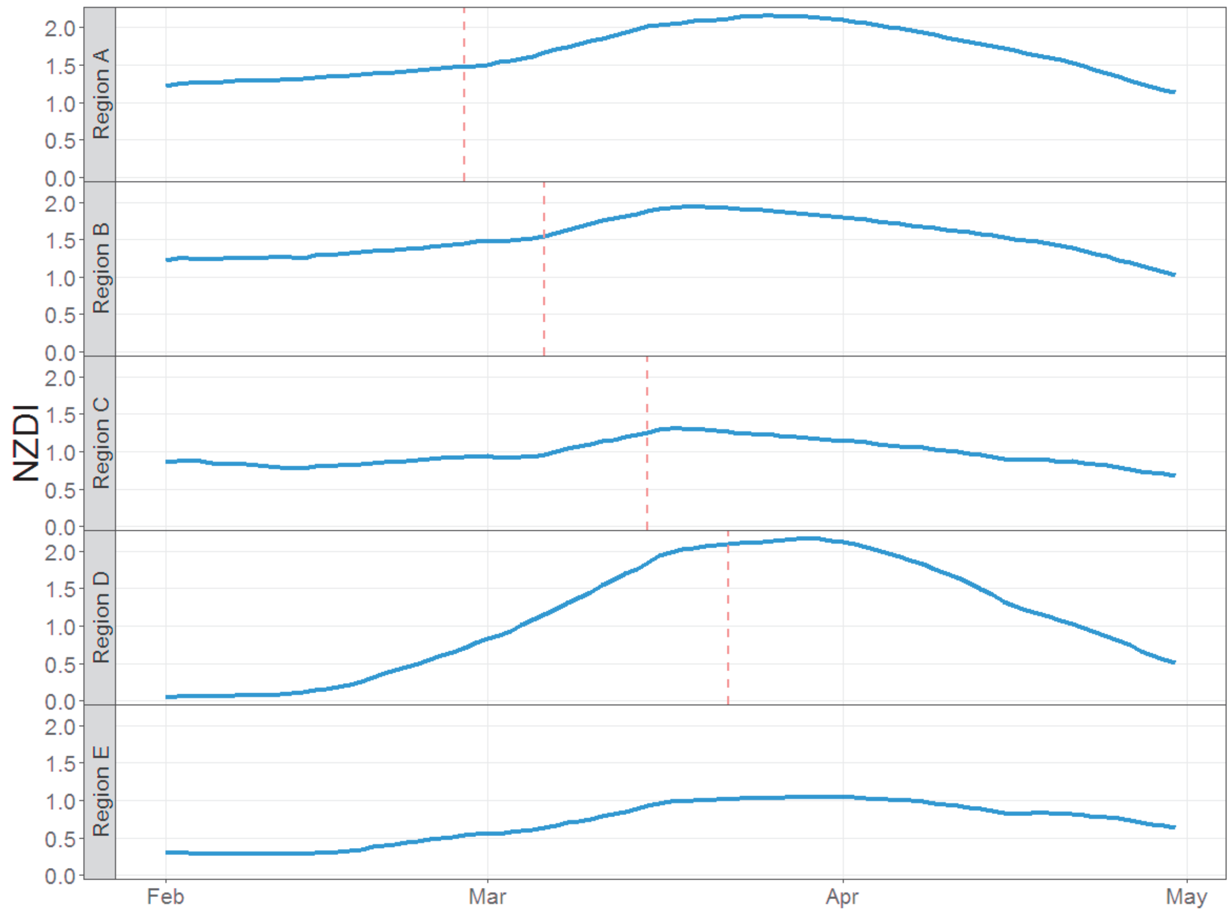

Figure 6: Average NZDI over regions shown in Figure 4 during the 2012-2013 drought (months shown are for 2013). Vertical dashed lines indicate declarations of an adverse event.

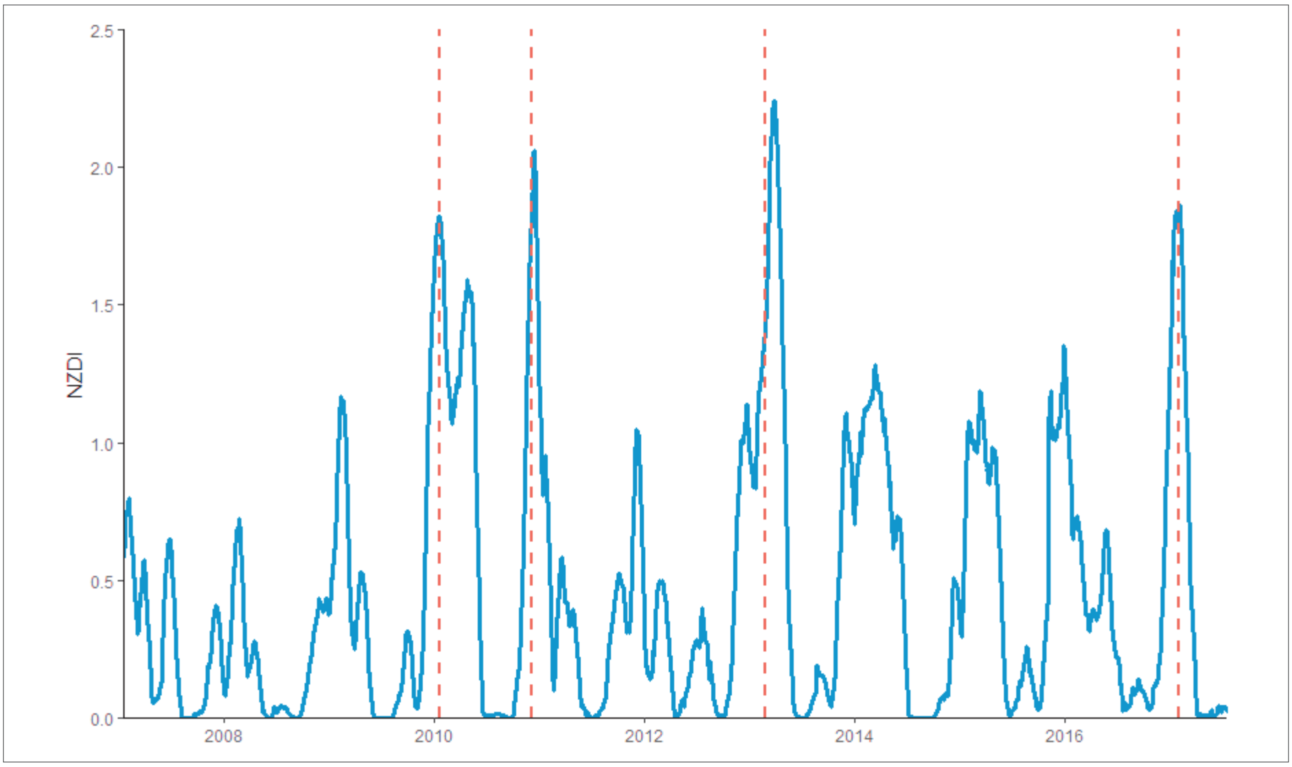

Figure 7: NZDI for the Northland region. Vertical dashed lines indicate declarations of drought related adverse events.

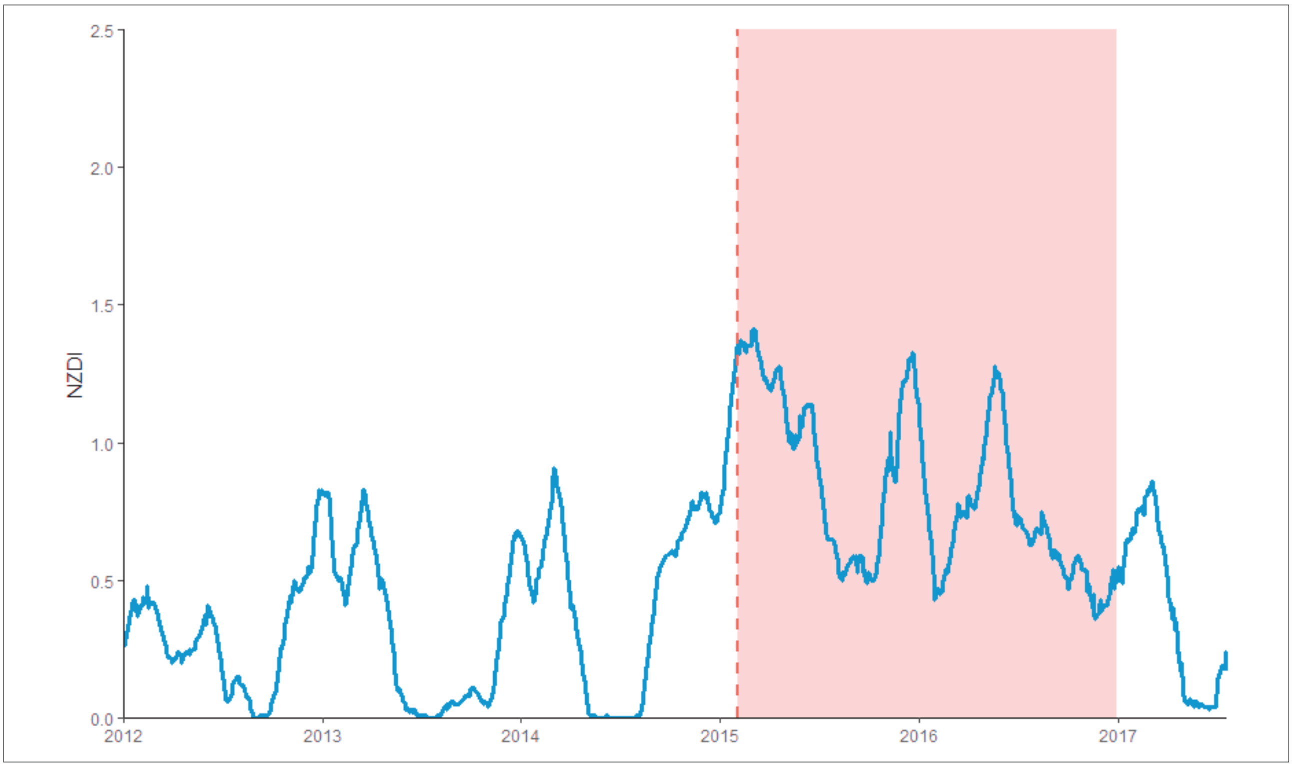

Figure 8: NZDI for Hurunui-East from January 2012-July 2017. The vertical dashed line indicates the official start of the adverse event and the shaded area indicates the duration of the declared event.

interesting because it lasted through two winters and winter droughts are extremely rare in New Zealand. In this case the winter dryness is definitely noticeable in the NZDI. Generally, NZDI values across the country fall to near zero during winter months, with the nationwide average being about 0.1 for July through to September. Here they remain well above 0.4 during both winters, indicating a sustained dry period. Without the usual winter soil moisture recharge, droughts in the following spring and summer have a greater impact on farmers, as late-winter and spring grass growth is severely reduced often meaning drastic mitigation measures (such as complete or near-complete destocking) are required. Figure 8 suggests that a combination of summer- and winter-time NZDI thresholds could be used to identify prolonged dry periods.

4. Discussion and next steps

Drought is a complex phenomenon that cannot be completely captured in a single number. However, for many purposes it is very desirable to have a single drought index that can be used to indicate the severity, extent and duration of a dry spell. The NZDI has been developed with that particular aim. It is a combined index with five meteorological/agricultural drought categories, from 'dry' to 'severe drought'.

The main users of the New Zealand Drought Monitor are representatives of the primary sector, at all levels. Importantly, several stakeholders from the primary sector were consulted and asked for their feedback once demonstration products were available. Feedback was excellent, with participants very happy with the depiction of previous drought events using the NZDI, and also offering good suggestions for improvement – some of which have already been implemented.

Qualitatively, the NZDI agrees well with known drought related adverse events declared in the recent past. In particular, test cases using the 2013 drought, which extended over a large proportion of New Zealand, and smaller-scale droughts in the Northland and North Canterbury regions, confirm the occurrences of severe dry spells known from adverse event declarations. From the 'Hurunui drought' it appears the NZDI might decrease during winter even in dry conditions due to the transformation used (Eq. (1)), where the maximum values for SMD or PED might only be approached during summer. This can be adjusted by either using a variable maximum, depending on time of year or by lowering the thresholds during colder months. In the first case, caution will have to be taken as the transformation is not defined when the parameter in question reaches the maximum value. Nevertheless, the NZDI during this event was still anomalously high during the winters of 2015 and 2016, which combined with high summer values in these years is highly indicative that this drought was indeed a multi-year event.

A full quantitative assessment of the NZDI in comparison with other drought indices, including some not included as base indices for the NZDI, has not yet been undertaken but could be the topic of future research. However, it is unlikely that any single index, or even combination of indices, will capture all the intricacies of drought. This is because drought is highly location- and context-specific, and managing drought is as much about risk-based decision-making as it is about how dry the conditions are and for how long. It is for this reason that the New Zealand Drought Monitor is best described as a decision support system, with the particular use of the NZDI maps and charts wholly dependent upon the users' needs. Future research should focus on whether and how these needs are being met through the practical use of the NZDI products.

The next step to produce a fully-functional CREWS for drought risk management in New Zealand is currently being developed through a new research project with two inter-related research aims: 1) Drought monitoring and forecast development; and 2) Use of drought information for risk management. The first research aim will focus on producing, validating and operationalising objective regional 1- to 3-month drought forecasts for all New Zealand. The second research aim will assess methods for better managing drought risk by New Zealand's agricultural sector using up-to-date drought monitoring and forecast information combined with good practice drought risk management strategies. Working with end-users throughout the entire project period will ensure that the results of this research are not only understandable and straightforward to use but are tailored to their specific requirements.

Acknowledgements

The authors would like to thank Vijay Paul for the spatial visualisations, the Ministry for Primary Industries (MPI), in particular Tony Schischka, and members of the stakeholder review group for their input. This work was co-funded by NIWA core research funds and MPI.

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Book Review: *New Zealand's Worst Disasters. True Stories That Rocked a Nation*

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New Zealand's Worst Disasters. True Stories That Rocked a Nation. By Graham Hutchins and Russell Young, 2016. Auckland, New Zealand, Exisle Publishing. 224 pages. 80 Illustrations. Paperback. ISBN: 978-1-77559-270-9. $34.89. Also available in Hardback. 2015. ISBN: 978-1-77559-203-7. $49.99.

On April 12, 2017, the residents of New Zealand braced themselves for a potentially devastating weather event: the incoming ex-tropical storm called Cyclone Cook. At the time, the North Island and parts of the South Island were still recovering from being hit by the left-overs of ex-tropical Cyclone Debbie. From April 4 to April 6, 2017, Debbie had brought widespread heavy rain and gale force winds, and caused floods, landslips and a great deal of property damage. The entire town of Edgecumbe had been evacuated after the Rangitaiki River breached its stop banks, and some residents were also evacuated in Whanganui (Hutching et al., 2017).

Now, the forecasters warned of the potential for another bout of heavy rain, damaging gales, enormous storm surges and widespread flooding. In anticipation, Civil Defence issued a national warning for an 'extremely serious weather event'. The Thames-Coromandel District Council declared a civil defence emergency, Waikato Civil Defence warned residents to stock up on enough food and water for seven days, and Aucklanders were advised to prepare for savage winds and avoid travel (NZ Herald, 2017).

The experts warned us that Cyclone Cook could be as bad as Cyclone Giselle, which hit New Zealand in April in 1968 (NZ Herald, 2017). From April 9 to April 15, 1968, New Zealand was pounded by heavy rain, strong winds, destructive wind gusts, high seas, flooding and landslips. On April 10, 1968, the inter-island ferry Wahine was wrecked as it entered Wellington Harbour. This was the most destructive storm event to strike the country since European settlement (NIWA, 2016). Understandably, in April 2017, people were right to be concerned.

Cyclone Cook made landfall in New Zealand in the Bay of Plenty on April 12, 2017. It brought heavy rain, strong winds, 6 m coastal waves, landslips, floods, power failures and travel disruptions and there were more evacuations. No lives were lost. Fortuitously, the storm had weakened as it approached, was compact and fast moving, and had not tracked across any of our largest cities (Kenny, 2017).

Cyclone Cook was not another Giselle—but it could have been. New Zealand remains vulnerable to extreme weather events. One way to better understand the potential risk to life and property, is to learn about our past disasters.

New Zealand's Worst Disasters. True Stories That Rocked a Nation (Hutchins and Young, 2016) includes a chapter dedicated to the impact of Cyclone Giselle and the

Submitted: 19 July 2017
Accepted: 23 July 2017

sinking of the Wahine. Graham Hutchins has written a considerable number of non-fiction books, mostly dealing with railways, rugby, the New Zealand way of life, but also the history of floods in New Zealand (Hutchins, 2006). Russell Young published a history of the town of Te Kuiti in 2013.

New Zealand's Worst Disasters addresses 31 disasters that have featured large in New Zealand's history since European settlement. These include fires, mine disasters and transportation accidents, but also natural events, such as earthquakes, volcanic activity, floods and storms. The book does not deal with incidents involving epidemics, or with enemy action during wartime.

Hutchins and Young begin with the Wellington earthquake of 1855 ("The big one", Chapter 1), and conclude with the Carterton ballooning tragedy in 2012 ("Sky high", Chapter 31). The 7.1 magnitude earthquake in Christchurch in 2011 is included ("On shaky ground", Chapter 30). However, the 7.8 magnitude Kaikoura earthquake in November 2016 occurred after the book's publication date.

There is much in New Zealand's Worst Disasters to interest those who enjoy reading about meteorology and the impact of extreme weather events. Roughly a third of the disasters are strongly associated with severe weather conditions. However, weather plays some role in about half of the events addressed in the book.

Chapter 2 ("Of shipwrecks and flooding") deals with the Great Storm of 1868. This caused at least 40 deaths, 12 shipwrecks and the widespread destruction of roads, bridges, crops and livestock. The east coast from Christchurch to Dunedin bore the brunt of the storm, but it caused floods and shipwrecks as far north as Thames and Hokianga Harbour. It was deemed to be the worst storm in New Zealand history since the 1840s, until Cyclone Giselle arrived in 1968.

Overnight on March 18, 1918, a massive bushfire destroyed forest, sawmills, farms and villages on the Central Plateau, North Island ("For as far as the eye could see", Chapter 10). Most residents were able to flee, or found refuge in waterways, and only three lives were lost. Weather conditions played an important part. Raetihi village was only engulfed when the north-east gale changed to a northerly. Ohakune was saved by a change in wind direction and, later, heavy rain. The wind carried the smoke pall south: it was too dark to work in Palmerston North and Masterton, the ferry from Lyttleton couldn't find Wellington harbour, and dawn was delayed in Christchurch.

The story of the Kopuawhara flash flood of 1938 was a new story for me ("A wall of water", Chapter 13). A Public Works camp had been built beside the Kopuawhara Stream for workers building the Napier-Gisbourne railway. After torrential rain, a wall of water 5 m tall swept down the valley. It arrived at the camp on the river flats soon after 3:30 am, and carried away huts, tents, vehicles and people. The death toll from the flood was 21. Roads and bridges were damaged downstream, thousands of sheep and cattle swept away, and farmers were still dealing with silt and water six months later.

Say 'tornado' and I am more inclined to think Oklahoma, USA, before I think of New Zealand. However, we do get them and fairly frequently. Most of our 30 or so tornadoes per year are small and/or in sparsely populated areas. Fatalities are rare. The Frankton Tornado of 1948 ("Out of a black sky", Chapter 17) lasted 10 minutes. Three people died, 80 were injured, and 150 houses were destroyed or badly damaged. Fatalities occurred also in Taranaki in 2004 (3 people) and Auckland in 2012 (3 people). NIWA reports that tornado activity has increased since 2000, so risks may increase in future years.

New Zealand is renowned for its beautiful mountains and intrepid mountain climbers. Many of our alpine areas are accessible and are suitable for day-trips, during clement weather. In July, 1953, a group of Auckland nurses went on a guided climb to the summit of Mount Egmont, now more commonly known as Mt Taranaki ("Because it was there", Chapter 20). All 31 in the group made it to the summit, albeit rather late in the day. While descending, the weather deteriorated, the snow surface turned to ice, and seven climbers roped together fell over a bluff. Darkness had fallen—it was 6:30 pm on a winter evening—and by the time rescuers reached them, it was blizzard conditions. Four of the seven who fell died on the mountain, one later in hospital. What became known as 'the nurses' accident' helped to drive the establishment of an official Search and Rescue service in New Zealand. It is a poignant reminder that lack of time, inexperience and inadequate equipment can conspire with harsh weather, with tragic consequences.

Cyclone Giselle is addressed in Chapter 24 ("Any port in a storm"). Its association with the sinking of the Wahine is so strong, that the event is commonly known as 'The Wahine Storm'. In April, 1968, a deep depression from the north developed into a hurricane and met a cold front approaching from the south in an "unlikely, hellish confluence" (Hutchins and Young, 2016, p166). The outcome was nationwide storm damage and New Zealand's worst modern maritime disaster (NIWA, 2016). On the morning of April 10, 1968, 734 people—610 of them passengers—were on the Wahine as it entered Wellington heads. In severe winds, huge seas and poor visibility, the ship went onto Barrett's Reef. It was badly damaged, the engines failed, and the ship started taking on water and listing to the side. Eventually, fearing that the ship would sink with a great loss of life, the Captain gave the order to abandon ship. Most people made it to shore alive, albeit in great physical and emotional distress. More than 50 people died: 51 on the day, and two more at later dates.

Once you start looking, weather features in many of the stories presented in this book. For example, in 1880, train carriages on the Rimutaka track were blown off the tracks by a severe wind gust ("Blown off the tracks", Chapter 4). In 1900, a canoe carrying two adults and 16 children capsized in the Motu River, when it was swollen after heavy rain ("The New Zealand Death", Chapter 6). In 1951, yachts in the Wellington to Lyttleton yacht race were overtaken by a severe storm. The crews of the Husky and the Argo were lost at sea, presumed drowned ("Hollow victory", Chapter 19). The 'Kaimai Breeze'—a churning, howling gale that sometimes forms in the lee of the Kaimai Ranges—caused the crash of a DC3 aircraft in 1963, with 23 lives lost ("Battling the 'Kaimai Breeze'", Chapter 23). In 2008, six students and a teacher from the Outdoors Pursuit Centre at Tongariro, lost their lives during a canyoning trip, when water levels rose after a heavy rain event ("Sure to rise", Chapter 28).

I enjoyed reading this book. It was hard to not feel a personal connection. I used to live in Ohakune, close to the location of the 1918 Raetihi Bushfire (Chapter 10). My cousin was born during Cyclone Giselle—after the roof came off her parents' house (Chapter 24). In Dunedin in 2015, I saw the musical Seacliff: The Demise of Ward 5, written by Renee Maurice about the 37 women killed in the 1942 Seacliff Fire (Chapter 14). And all of us can relate to stories from Erebus, Cave Creek, Pike River and the Christchurch Earthquake (Chapters 25, 27, 29 and 30).

I have only a few minor criticisms. I would have loved to see larger photographs on the book's cover. A timeline of events could have been included. And I did cringe at some of the 'cute' chapter titles, for those chapters that describe recent fatalities. Those 'fun' titles just seemed a little bit insensitive.

New Zealand's Worst Disasters. True Stories That Rocked a Nation is well written. There are abundant and crisply reproduced images, mostly photographs, and a comprehensive index. Hutchins and Young balance nicely historical facts, people's anecdotes, science and social issues. The stories are fascinating, without dwelling on the gruesome. It is a 'popular history', but meaty enough to be very satisfying. It should appeal to many scientists, teachers, students and general readers who enjoy New Zealand history, science, natural disasters and reading about the weather.

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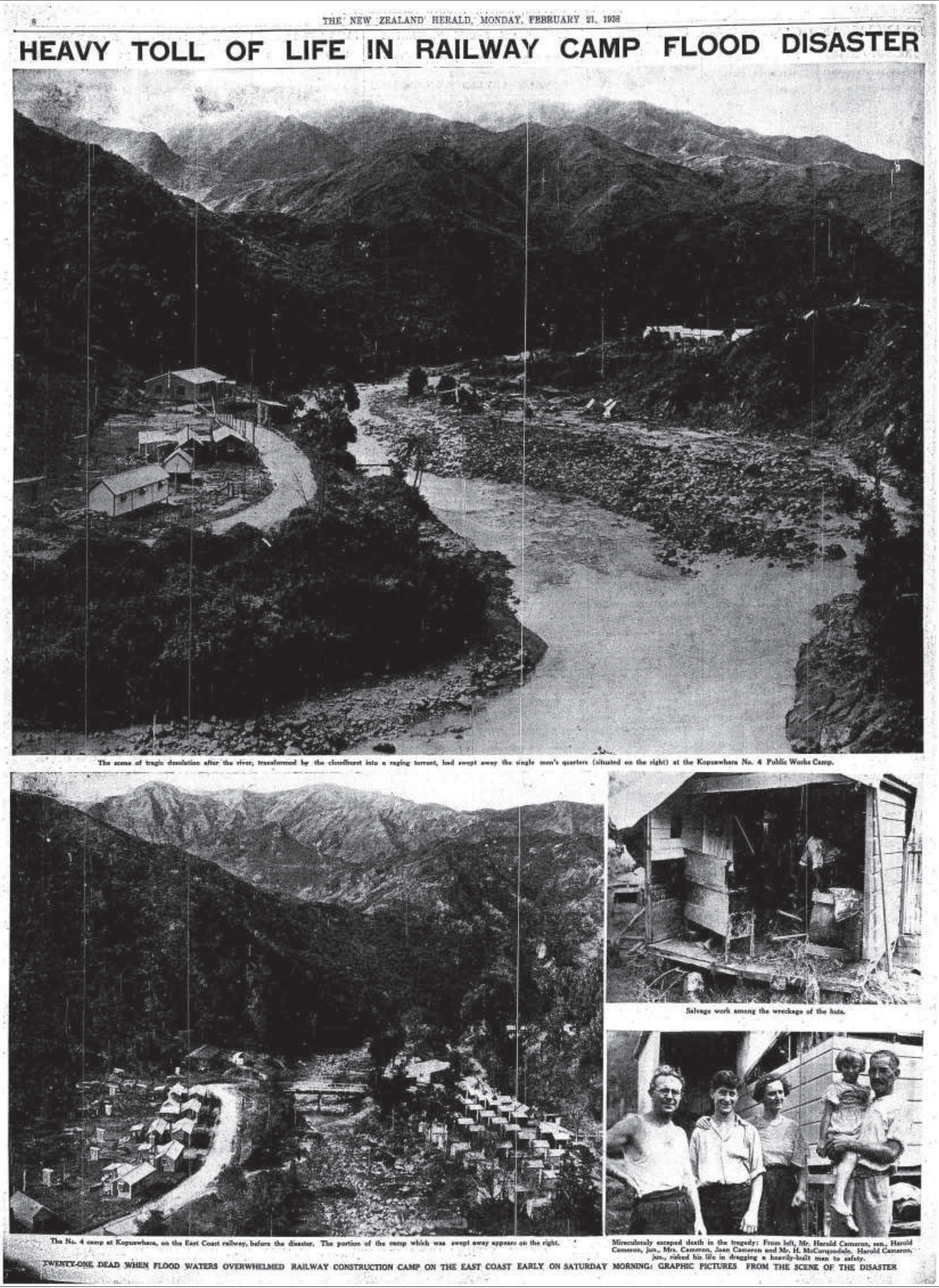

8 THE NEW ZEALAND HERALD, MONDAY, FEBRUARY 21, 1938

HEAVY TOLL OF LIFE IN RAILWAY CAMP FLOOD DISASTER

The scene of tragic desolation after the river, transformed by the cloudburst into a raging torrent, had swept away the single men's quarters (situated on the right) at the Kopuawhara No. 4 Public Works Camp.

Salvage work among the wreckage of the huts.

The No. 4 camp at Kopuawhara, on the East Coast railway, before the disaster. The portion of the camp which was swept away appears on the right.

Miraculously escaped death in the tragedy: From left, Mr. Harold Cameron, sen., Harold Cameron, jun., Mrs. Cameron, Joan Cameron and Mr. H. McCorquodale. Harold Cameron, jun., risked his life in dragging a heavily-built man to safety.

TWENTY-ONE DEAD WHEN FLOOD WATERS OVERWHELMED RAILWAY CONSTRUCTION CAMP ON THE EAST COAST EARLY ON SATURDAY MORNING: GRAPHIC PICTURES FROM THE SCENE OF THE DISASTER

Figure 1: HEAVY TOLL OF LIFE IN RAILWAY CAMP FLOOD DISASTER:(upper) The scene of tragic desolation after the river, transformed by the cloudburst into a raging torrent, had swept away the single men's quarters (situated on the right) at the Kopuawhara No. 4 Public Works Camp. (centre right) Salvage work among the wreckage of the huts. (lower left) The No. 4 camp at Kopuawhara, on the East Coast railway, before the disaster. The portion of the camp which was swept away appears on the right. (lower right) Miraculously escaped death in the tragedy: From left, Mr. Harold Cameron, sen., Harold Cameron, jun., Mrs. Cameron, Joan Cameron and Mr. H. McCorquodale. Harold Cameron, jun., risked his life in dragging a heavily-built man to safety. Source: New Zealand Herald, Volume LXXV, Issue 22968, 21 February 1938. Retrieved on 19 July 2017 from https://paperspast.natlib.govt.nz/newspapers/new-zealand-herald/1938/2/21/8. Reproduce from digital image supplied by the National Library of New Zealand under a Creative Commons New Zealand BY-NC-SA licence.

Honour Roll for the Meteorological Society of New Zealand

K. Richards

The Meteorological Society of New Zealand was inaugurated in Wellington, New Zealand, in 1979. Its members share an interest in the weather, climate and atmosphere, particularly as these topics relate to New Zealand, the Pacific and Antarctica. Members include meteorologists, climatologists, operational forecasters, hydrologists, research institutions, educators and weather enthusiasts. The Society is a Constituent Member of the Royal Society of New Zealand (RSNZ). It contributes to national and international discussions on weather, climate and science, hosts seminars and an annual conference, and publishes a peer-reviewed, scientific series, Weather and Climate (1981–).

Honorary membership is the highest recognition that may be awarded by the Society. It is awarded to an individual member for exceptional contributions to meteorology or climatology. Nominees may have undertaken outstanding research, be exceptional leaders in operational forecasting or applied climatology, or have served to increase public and Governmental understanding of issues concerning weather and climate. To date, seven Honorary Memberships have been awarded.

Dr J. Thomas Steiner

Tom was instrumental in the formation of the Meteorological Society of New Zealand and its subsequent development. He was the Society's first President, serving from 1979 to 1981. Tom had a distinguished career in research and forecasting, training meteorologists and pilots, as well as leading meteorological research and administration at the Meteorological Service of New Zealand (Met. Service). He was at the coal face when New Zealand restructured its government research institutions in the late 1980s and early 1990s. Among many publications, he co-authored "Commercialisation in the provision of meteorological services in New Zealand" (published in Meteorological Applications in 1997), which continues to be of relevance today. After leaving the Met. Service, Tom taught aviation meteorology at Massey University in Palmerston North. Tom was awarded an Honorary Membership in 1996. He passed away in 1998.

Dr John S. Hickman, QSO

John was the Director of the Met. Service for 12 years (1977–1988) and revolutionised meteorological practice in New Zealand. He obtained the first computer for operational numerical weather prediction and first high-res meteorological satellite receiving station. He served as the President of Regional Association V of the World Meteorological Organisation (WMO), was a WMO consultant, and chaired the climate committee of the RSNZ. John was awarded a Companion of the Queen's Service Order in 1989, the New Zealand 1990 Commemoration Medal for services in the field of science, and an honorary doctorate from Victoria University, Wellington. John was made an Honorary Member in 1998. He passed away in 2014.

Alex A. Neale

Alex was Chief Forecaster at the Met. Service, and an active researcher in the field of meteorology. He has published numerous papers and books, including the popular "A Practical Guide to Weather Forecasting in New Zealand", which was reprinted in a revised edition in 1993. He was the President of the Meteorological Society from 1983 to 1985, a committee member from 1990 until 2003, and very active on the committee. He founded the popular Wairarapa Weather Watchers, whose meetings in Masterton frequently drew large numbers of supporters. Alex was awarded an Honorary Membership in 1998.

Dr John F. Gabites

John joined the Met. Service in 1934, and served as a pilot and forecaster with the RNZAF in the Pacific during World War II. Over his career, he worked tirelessly to improve the scientific level of meteorology in New Zealand. He instigated scientific seminars at the Met. Service, and developed liaisons with universities and government departments. He was President of the WMO Commission for Atmospheric Sciences in 1965–68, and the Director of the Met. Service from 1965 to 1973. After his retirement, he became the first Director of the Fiji Meteorological Service. John was a Fellow of the RSNZ and the Institute of Physics, London. He was awarded Honorary Membership in 1999. He passed away in 2001.

Cliff G. Revell

Cliff first joined the Met. Service in 1948, then spent some years serving in the RNZAF and teaching. He returned to the Met. Service in 1960, working as a forecaster and researcher until his retirement in 1988. His fascination with tropical cyclones, and his research on this topic, has significantly influenced forecasting practice. Cliff was a member of the Meteorological Society's committee from 1989 to 1998, and served as Treasurer from 1998 until 2009. Cliff was awarded Honorary Membership in 2002.

Erick Brenstrum

Erick has been an operational weather forecaster since the mid-1970s and is a leader in the forecast room at MetService (the Meteorological Service of New Zealand). Forecasting notwithstanding, Erick is better known as an exceptional science communicator. He writes for both scientific and popular series, gives radio interviews, is the author of the best-selling "The New Zealand Weather Book" and is passionate about meteorology, climate and science history. His recent writings include a poignant review of the weather conditions at Passchendaele during World War I. Erick has been awarded the MetService Henry Hill award and has twice won the New Zealand Association of Scientists' Science Communicator award. He was a member of the Meteorological Society's committee in 1998–1999 and 2001, and a Vice President (Wellington region) in 1999–2000. He was made an Honorary Member in 2002.

Dr Neil D. Gordon

Neil joined the Met. Service in 1968 and was Chief Meteorologist from 1988 to 1992, after several years of forecasting-related research. He implemented many changes, including centralisation. Neil led the National Weather Services division of MetService from 1992 to 2005, and was involved in research, development and international affairs until his retirement in 2011. He was very active in the WMO, was the WMO Permanent Representative for New Zealand in 1992 and 2008–2011, and represented New Zealand at numerous international meetings. Neil was the Secretary of the Meteorological Society in 1983–1984, and served as Circulation Manager in 1984–1985. He was made an Honorary Member in 2012.

The author wishes to thank the members of the Meteorological Society of New Zealand, and others, who have provided insights and photographs concerning our Honorary Members.