

Analysis of daily rainfall concentration in New Zealand

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Abstract A higher precipitation concentration, represented by greater percentages of the yearly total precipitation in a few very rainy days, has the potential to impact considerably on water resources. In this paper, an investigation of the spatial and temporal patterns of daily precipitation concentration in New Zealand has been carried out by means of a daily precipitation dataset. Results show a different behavior between North Island, with the most critical rainfall concentration, and South Island, where precipitation concentration values on the eastern side are comparable to those of North Island, while the western side presents the lowest values of precipitation concentration. On a seasonal scale, the spatial gradients for summer and autumn are similar to the annual one. The application of the Mann–Kendall test shows a general negative trend detected in the eastern part of North Island, in particular in winter and autumn, and a west/east difference trend in South Island, in particular in winter and summer.

Keywords Rainfall · Daily concentration · Trends · New Zealand

1 Introduction

In recent decades, understanding and predicting climate variability and change have become key issues for the research community. The Intergovernmental Panel on Climate Change (IPCC 2007) presented a substantial body of research, which supports a picture of a warming world with significant changes in regional climate systems. One of the most noticeable consequences of this global atmospheric warming is a water cycle modification, with precipitation being a key point in the process (De Luis et al. 2011). There is great interest in assessing changes in precipitation due to their importance for economic

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activities such as agriculture, energy production and drinking water supply and to their role in natural hazards such as droughts, floods, landslides and severe erosion (Ferrari et al. 2013). Precipitation variability occurs over a wide range of temporal and spatial scales. At global (Bradley et al. 1987; Diaz et al. 1989; Hulme et al. 1998; New et al. 2001), regional (Lawrimore et al. 2001; Klein-Tank et al. 2002) and subregional scales (De Luis et al. 2000; Brunetti et al. 2006a; Brunetti et al. 2006b; Norrant and Douguédroit 2006; Gonzalez-Hidalgo et al. 2011), the studies conducted so far have evidenced growing precipitation variability with increments occurring in northern and central Asia, in the eastern parts of North and South America and in northern Europe (Sharma et al. 2000; Hamilton et al. 2001; Lucero and Rozas 2002; Boyles and Raman 2003). By contrast, other areas, such as the Mediterranean area, show either a decrease in precipitation, which is not always significant, or the lack of a linear trend (e.g., De Luis et al. 1998; Lana and Burgueño 2000; Klein-Tank et al. 2002; Douguédroit and Norrant 2003; Norrant and Douguédroit 2003; Xoplaki et al. 2004; Brunetti et al. 2006a; Gonzalez-Hidalgo et al. 2011). Within such a global contest, research on the Asia–Pacific region has not shown substantial spatially coherent trends for winter and summer (Choi et al. 2009). A tendency toward a decrease in very wet or extremely wet-day precipitation has been detected in northern China, whereas the opposite trend has emerged in southern and central China, as well as in the Republic of Korea (Choi et al. 2009). As far as the southwest Pacific area is concerned, Salinger and Griffiths (2001) have investigated the climate trends for the period 1861–1990 and discovered inconsistent precipitation trends for different decades during the second half of the twentieth century. Focusing specifically on Australia, New Zealand and the South Pacific region, Salinger et al. (1996) carried out a detailed investigation of observed changes in mean climate. This study revealed increases in precipitation in the northeast of the southern Pacific area and decreases in the southwest. In particular, in the past century, an increase in summer precipitation over eastern Australia and a decrease in winter over part of southwestern Australia were observed (Salinger et al. 1996; Plummer et al. 1999). Annual total rainfall in the South Pacific region has generally decreased between 1961 and 1998. Total rainfall has increased only in some stations in French Polynesia (Manton et al. 2001) and in some areas of New Zealand, where a decrease in annual rainfall in the north of North Island and an increase in the north, west, south and southeast of South Island have been detected (Salinger and Mullan 1999; Manton et al. 2001).

Variations in annual and seasonal precipitation can be caused by a change in the frequency of precipitation events, or in the precipitation intensity per event. In order to improve the understanding of the precipitation behavior of a region, daily precipitation series must be analyzed (Todeschini 2012). On a daily basis, in the southern Pacific area, several studies have highlighted that the number of rainy days will decrease, yet heavy precipitation is expected to increase and to become more variable (Jones et al. 1999; Griffiths et al. 2003; Lal 2004; Barnett 2011). Thus, the analysis of daily precipitation distribution and its effects on temporal concentration across this area is an important issue in climate research. Variation in the distribution of daily rainfall may lead to a higher precipitation concentration, generally resulting in an increase in yearly total precipitation over a limited number of rainy days. Consequently, changes in the temporal distribution of rainfall, and especially such a higher concentration, may severely affect water resources, modifying fluvial regimes, groundwater recharge, water availability and hydroelectric production (Aguado et al. 1992; Paredes et al. 2006; Lopez-Moreno et al. 2009). For these reasons, it is important to analyze the statistical structure of precipitation rates based on daily precipitation dataset.

A great deal of research has been carried out on daily precipitation, focusing on extreme events by means of a very heterogeneous spectrum of analysis methods, such as indices, percentiles, thresholds and extreme value theory (Cortesi et al. 2012). To evaluate the varying weight of daily precipitation, some authors all over the world used a statistical index (concentration index—CI) proposed by Martin-Vide (2004). In Spain, Martin-Vide (2004) computed the CI and then explored its spatial patterns, which clearly divide peninsular Spain into two regions: an eastern façade, which presents a high concentration of precipitation with 25 % of the rainiest days providing 70 % or more of the annual total, and the rest of the country, which presents more regular daily amounts. In Iran, Alijani et al. (2008) showed that daily precipitation tends to be irregular and intense across much of Iran and that a disproportionately large share of the annual rainfall comes from a small number of high intensity to extreme rainfall events. Zhang et al. (2009) calculated the CI based on yearly rainfall series of the Pearl River basin, also evaluating possible trends of CI for each station. Li et al. (2011) estimated the CI values for the Kaidu River basin, individuating a region of southern Xinjiang with the highest values of precipitation CI (the majority of the yearly precipitation amount deriving from 25 % of the rainiest days). Coscarelli and Caloiero (2012), for a small part of Italy, showed that a very inhomogeneous daily rainfall temporal distribution characterizes the eastern side of the region, with rain gauges in which one quarter of the rainiest days represents almost three quarters of the total pluviometric amount, and a western side presents a more homogenous temporal distribution of the rainfall. Cortesi et al. (2012) used the CI to investigate the statistical structure of daily precipitation across Europe based on 530 daily rainfall series for the period 1971–2010. The annual CI showed a northwest to southeast gradient (excluding Turkey and Greece). The same gradient was also observed in winter, spring and autumn, while in summer the gradient was detected in the north–south direction. Moreover, higher annual and seasonal daily concentrations of rainfall were detected in the western Mediterranean Basin, mainly along the Spanish and French coastlands.

The aim of this study is to analyze the time compression of daily precipitation and the changes in the wet and dry conditions over New Zealand by means of the CI. The CI values have been mapped, and the spatial pattern of this daily index has been analyzed; then, in order to study the temporal stability of the CI, a trend analysis has been performed on both annual and seasonal scales. The results of these analyses may have important effects on water management and environmental phenomena, such as soil erosion and desertification.

2 Study area and data

New Zealand is a long narrow country, in the middle latitude of the Southern Hemisphere, spanning from 34° to 47°S, with high axial ranges rising to 3,764 m and an area of 268,680 km² (Fig. 1). Weather patterns in New Zealand are typical of oceanic midlatitude locations, with precipitation often being associated with baroclinic midlatitude cyclones (Garnier 1950; Dravitzki and McGregor 2011). A preferred region of cyclogenesis is along the Australian eastern land/sea boundary, and this subsequently tracks across the Tasman Sea (Trenberth 1991; Sinclair 1994, 1995a, b). In New Zealand, the precipitation in this region is influenced by its topographic features (Dravitzki and McGregor 2011), and as a result, higher precipitation in the west and lower precipitation in their lee can be detected. Furthermore, the Southern Alps in South Island, which reaches an altitude of 1,000 m over a distance of 750 km (Fig. 1), presents a significant barrier to the mean airflow coming from the west to southwest (Tomlinson 1976). The interaction between atmospheric

circulation patterns and the orography is an important mechanism for determining the weather and the climate of New Zealand (Griffiths 2011; Jiang et al. 2013). The most notable effect is a west–east gradient in rainfall (Wratt et al. 1996), ranging from 3,000 to 4,000 mm per year in Westland to 12,000 mm or more in the Alps and less than 500–700 mm in Otago and Canterbury (Fig. 2).

The National Institute of Water and Atmosphere Research (NIWA) of New Zealand provided a description of the national climate with a detailed analysis for both the islands (NIWA 2013). As regards North Island, northern New Zealand is a subtropical area, with warm humid summers and mild winters. Winter usually has more rain and is the most unsettled time of year. In summer and autumn, storms of tropical origins may bring high winds and heavy rainfall from the east or northeast. The central North Island region is sheltered by high country to the south and east, and it has less wind than many other parts of New Zealand. Warm, dry and settled weather predominates during summer. Winters are cool, and this is normally the most unsettled time of the year. Because of its exposure to disturbed weather systems from the Tasman Sea, the southwest area of North Island is often quite windy, but has few climate extremes. The most settled weather occurs during summer and early autumn. Summers are warm. Winters are relatively mild and are normally the most unsettled time of the year. Sheltered by high country to the west, the eastern North Island area enjoys a dry, sunny climate. Warm dry settled weather predominates in summer. Heavy rainfall can occur from the east or southeast (NIWA 2013). With respect to South Island, northern South Island is the sunniest region of New Zealand. Warm, dry and

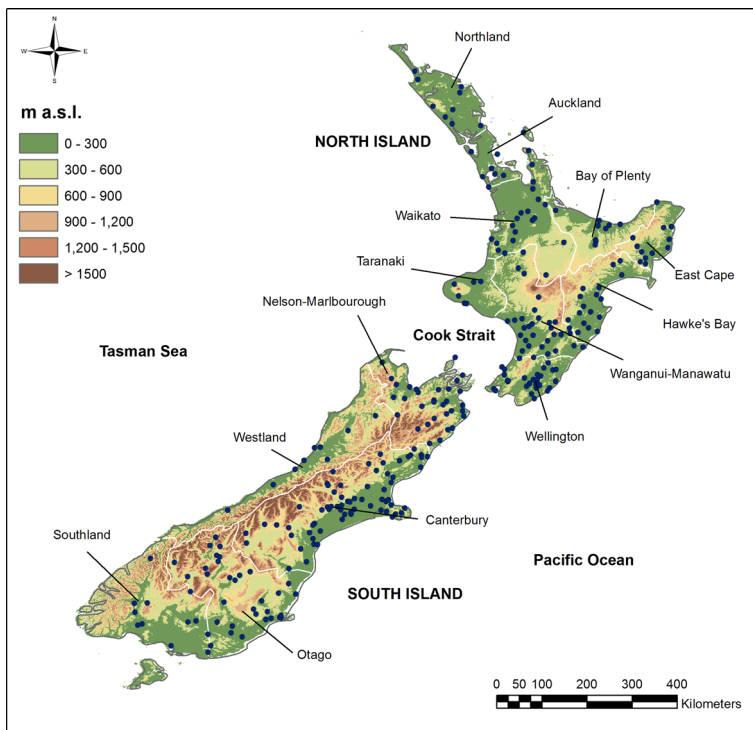


Fig. 1 Location of the selected 294 rain gauge stations on a DEM of New Zealand

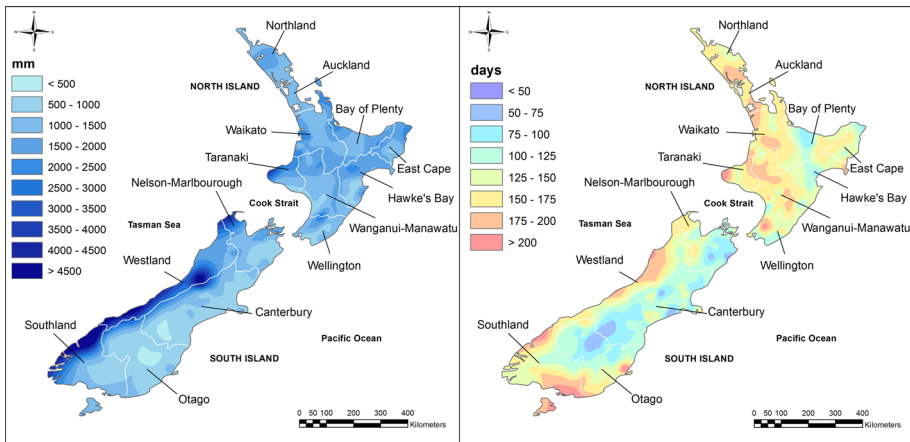


Fig. 2 Spatial distribution of the mean annual precipitation (*left*) and of the mean annual number of rainy days (*right*)

settled weather predominates during summer. Late winter and early spring are normally the most unsettled time of the year. The climate of western South Island area is greatly dependent on its exposure to weather systems from the Tasman Sea and the lie of the Southern Alps to the east. Although the mean annual rainfall here is very high, dry spells do occur, especially in late summer and during winter. Heavy rainfall occurs from the northwest. The climate of the eastern and inland areas of South Island is greatly dependent on the lie of the massive Southern Alps to the west. The mean annual rainfall is low, and long dry spells can occur, especially in summer. Most of the southern New Zealand areas are characterized by cool coastal breezes and by the absence of shelter from the unsettled weather that moves over the sea from the south and southwest (NIWA 2013).

The daily rainfall data used in this work were extracted from the New Zealand National Climate Database maintained by the NIWA. This database has been widely used in different studies on New Zealand climate (Salinger and Mullan 1999; Griffiths et al. 2003; Dravitzki and McGregor 2011) due to the quality of its data, and because its records were complete, or near complete, for the period 1900–2010. Until 2010, the New Zealand National Climate Database consisted of measurements collected at 3,011 stations, with a density of one station per 89 km². Records were checked for errors, metadata were analyzed for inhomogeneities, and stations with low-quality records, or with a significant number of missing data (more than 5 %), were not used. Therefore ultimately, 294 series longer than 50 years have been selected, with a density of 1 station per 913 km² (Fig. 1). For strict comparative analyses between observatories, temporal series must be performed during the same period, for this reason only data collected from 1951 to 2010 have been used.

3 Methodology

To determine the relative impact of different classes of daily precipitation and to evaluate the weight of the largest daily event over the total precipitation value, it is necessary to analyze the relative contribution (as a percentage) of progressively accumulated precipitation, Y , as a function of the accumulated percentage of wet days, X , during Y 's occurrence

(Riehl 1949; Olascoaga 1950; Martin-Vide 2004; Zhang et al. 2009; Li et al. 2011; Co-scarelli and Caloiero 2012; Cortesi et al. 2012), with X and Y defined as follows (Cortesi et al. 2012):

$$Y_j = 100 \cdot \frac{\sum_{i=1}^j P_i}{\sum_{j=1}^N P_j} \quad (1)$$

$$X_j = 100 \cdot \frac{\sum_{i=1}^j n_i}{\sum_{j=1}^N n_j} \quad (2)$$

where p_i and n_i are the precipitation and the number of wet days (respectively) falling into the i th category, and N is the total number of categories. If daily events are ranked in an ascending order, and X_j is the j th highest event, Y_j is the fraction of annual precipitation provided by the highest events from the first to the j th. These percentages are related to an exponential curve, which is generally called concentration curve or Lorenz curve (Shaw and Wheeler 1994), also known as normalized rainfall curve (Jolliffe and Hope 1996) when referring to precipitation. By substituting the empirical lines with fitted exponential curves, Y and X are linked by an exponential law as (Riehl 1949; Olascoaga 1950)

$$Y = aX \exp(bX) \quad (3)$$

where a and b are constants that can be determined by means of the of the least squares method.

An example of the annual concentration curve of Y versus X for the Wellington rain gauge is presented in Fig. 3 together with the fitted exponential curves.

By defining A the area under the Lorenz curve, the area (S) enclosed by the bisector of the quadrant (perfect distribution, $Y = X$) and the Lorenz curve can be evaluated as

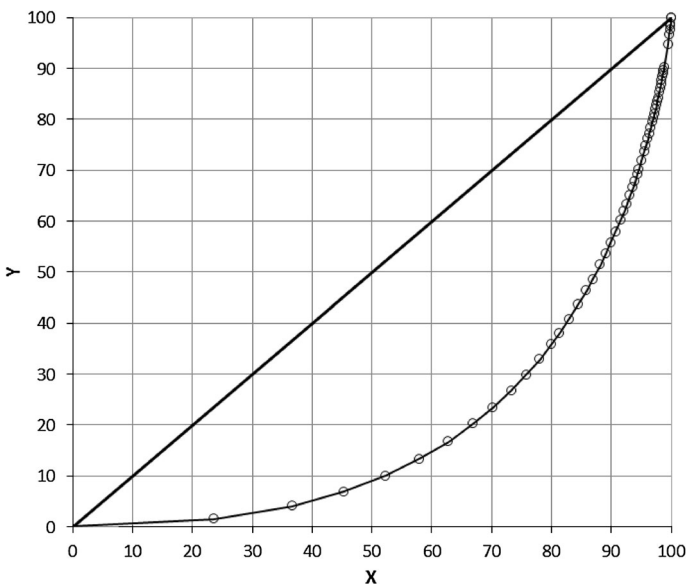


Fig. 3 Example of the annual concentration curve of Y versus X for the Wellington rain gauge

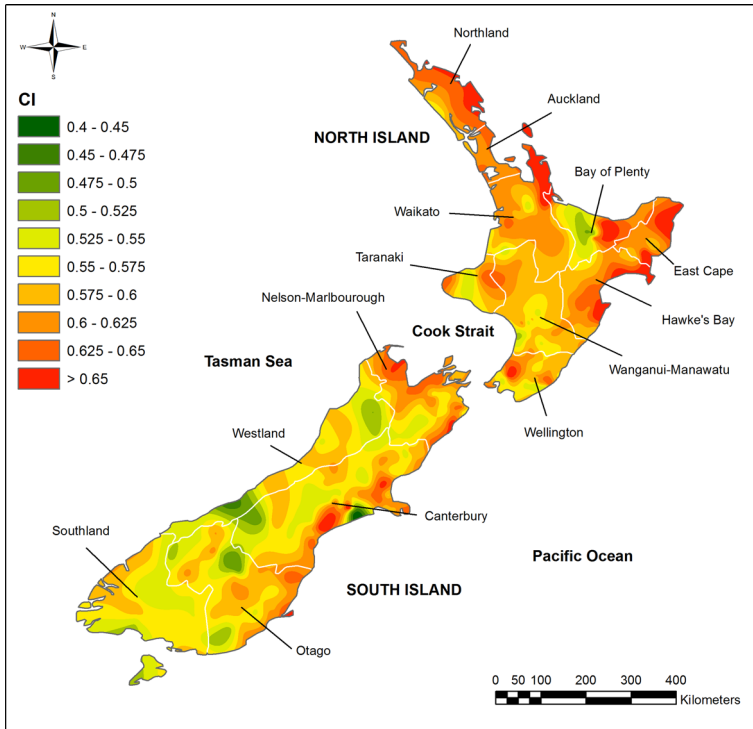


Fig. 4 Spatial distribution of the CI on the investigated area

$$S = 5000 - A \tag{4}$$

being 5,000 the area under the equidistribution line.

Being the exponential curve expressed as in Eq. (3), the area A can be calculated as

$$A = \left[\frac{a}{b} e^{bx} \left(x - \frac{1}{b} \right) \right]_0^{100} \tag{5}$$

The daily precipitation CI resembles the Gini coefficient and is the ratio between *S* and the surface area of the lower triangle delimited by the equidistribution line (Martin-Vide 2004):

$$CI = S/5000 \tag{6}$$

The procedure used in this work analyzes the daily data distribution for each rain station, using a limit of 1 mm/day as precipitation class interval and evaluating for each class: (a) the number of recorded precipitation days (absolute frequency) and (b) the pluviometric total. The cumulative frequencies, obtained by adding the absolute frequencies, in percentage are the *X* values of the exponential curve; the progressive sum of the pluviometric totals (in percentage) gives the *Y* values. Equation (3) has been checked in order to verify the adequacy of such form to capture the measured data. After the log transformation of Eq. (3), the usual formula of the least squares method allows the estimation of *a* and *b* and, consequently, the calculations of *A*, *S* and CI for each rain gauge. A

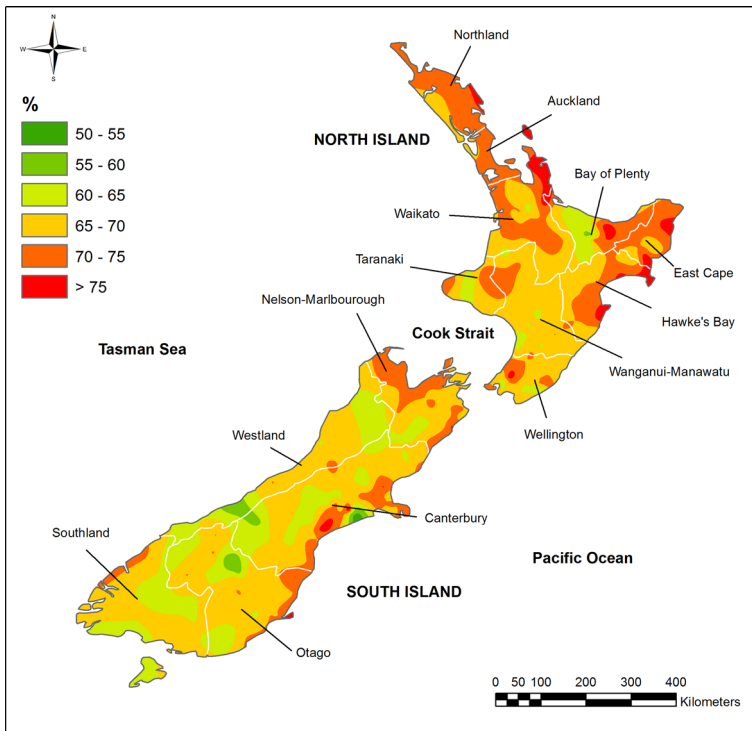


Fig. 5 Spatial distribution of the percentage of precipitation contributed by 25 % of the rainiest days

high precipitation CI value indicates that precipitation is more concentrated within few rainy days during the year and vice versa.

Moreover, following Zhang et al. (2009), in this paper the precipitation CI has been calculated on a yearly and on a seasonal scale, and a trend analysis has been performed in order to detect the temporal behavior of the index using the well-known rank-based nonparametric Mann–Kendall test (Mann 1945; Kendall 1962). This test is highly recommended for general use by the World Meteorological Organization (Mitchell et al. 1966) because it does not require normality or linearity conditions in a time series (Wang et al. 2008).

4 Results and discussion

CI values were estimated for all the stations (Fig. 4), ranging from a minimum of 0.47 (in Westland) to a maximum of 0.70 (in Hawke’s Bay and Auckland). Generally, from the spatial distribution of CI on New Zealand (Fig. 4), a different behavior emerged between North and South Islands and, in the latter, between the eastern and the western sides. In fact, while North Island presents the most critical rainfall concentration, South Island can be divided into two parts: the western side of the island with the lowest values of CI and the eastern side with CI values comparable to those of North Island. The highest CI values have been estimated near the reliefs, in the Northland area, in the northern Waikato region,

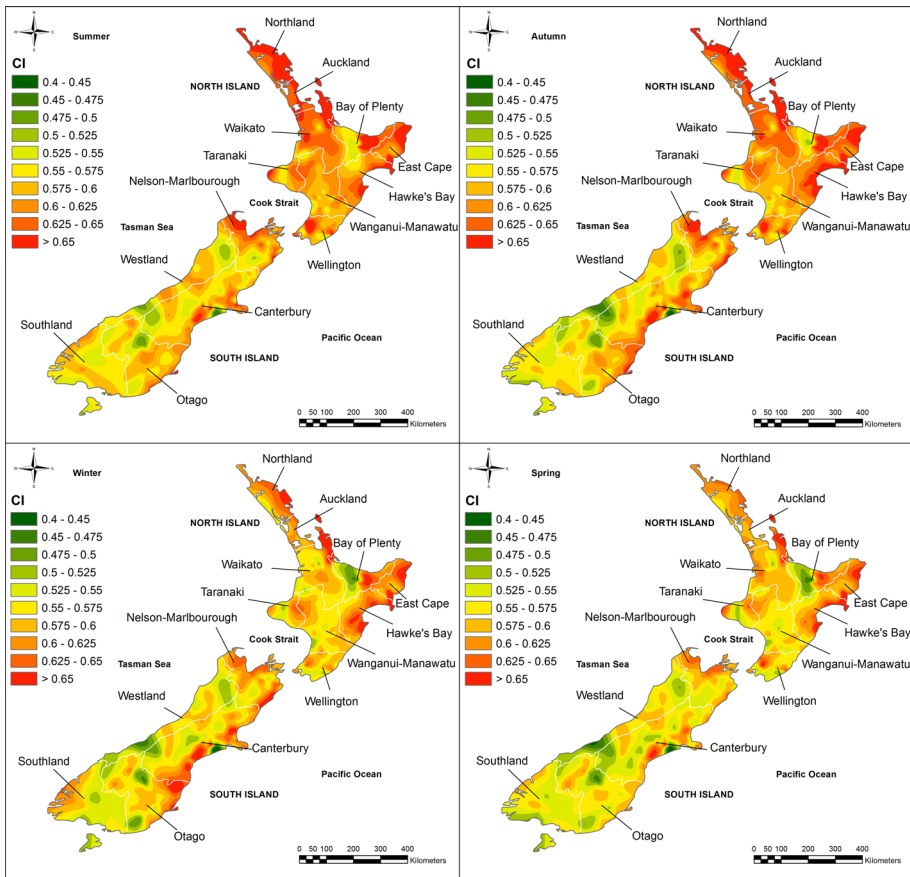


Fig. 6 Spatial distribution of the CI on the investigated area evaluated for the four seasons

in the eastern part of the Bay of Plenty, at East Cape, at Hawke’s Bay and in Canterbury areas, with the lowest values of yearly rainfall and number of rainy days (Fig. 2). Such a different behavior in the spatial distribution of CI can be explained by the particular orography of New Zealand, which influences the rainfall amount and its distribution over the area. In fact, the interaction between atmospheric circulation patterns and the orography leads to a precipitation gradient between the eastern and the western part of South Island (Griffiths 2011; Jiang et al. 2013). In particular, the Southern Alps, which trends southwest to northeast, provides a significant barrier to the mean west to southwest airflow (Tomlinson 1976). The country’s other mountain ranges, as well as North Island volcanic peaks, act as similar obstacles to the prevailing airflow. As a result, there are marked rain-shadow and orographic enhancement effects on precipitation (Salinger 1988; Tait and Fitzharris 1998).

The range of CI values (0.47–0.70) found in New Zealand is similar to the one (0.51–0.72) obtained in Europe (Cortesi et al. 2012), but it is different in the minimum value to the one (0.59–0.73) obtained in Iran (Alijani et al. 2008), and it is clearly lower

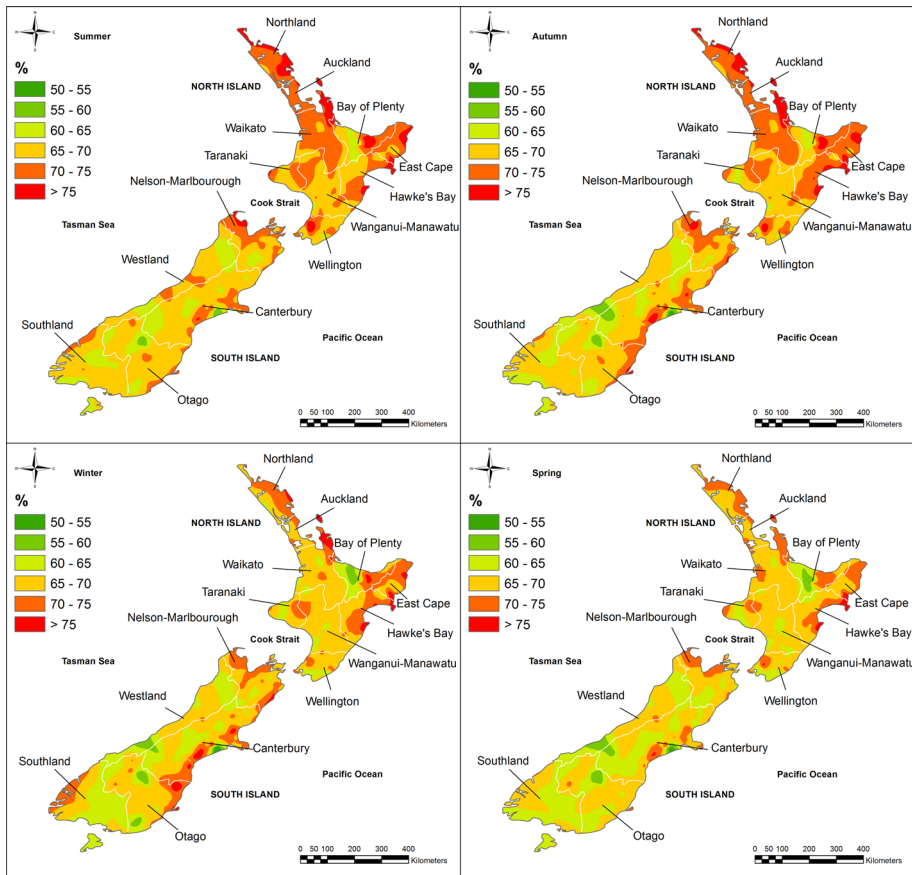


Fig. 7 Spatial distribution of the percentage of precipitation contributed by 25 % of the rainiest days evaluated for the four seasons

than that presented in China (0.74–0.80) by Zhang et al. (2009). This difference can be explained on the basis of the different climate systems and precipitation mechanisms responsible for rainfall in China (such as a typhoon).

Figure 5 reports the spatial distribution of the percentages of precipitation amount, provided by the highest quartile of rainy days calculated with Eq. (3), which range from 59 % (corresponding to the minimum value of CI) to 78 % (corresponding to the maximum value of CI) with a variation of about 20 %, which shows a very different behavior between the area with the most concentrated rainfall and the one with a more regular distribution. The higher percentages confirm the results obtained by Sansom and Thompson (2008) who, analyzing the daily New Zealand dataset, showed that most rainfall events consist of a single shower (i.e., circumscribed and short-lived rainfall).

On a seasonal scale (Figs. 6, 7), the spatial gradients for summer and autumn are similar to the annual one, showing a stronger contrast among the different areas of New Zealand and in particular between North and South Islands and, in the latter, between the eastern and the western sides. The spatial differences between summer–autumn and winter–spring are particularly clear in North Island. In particular, in summer, CI values range between a

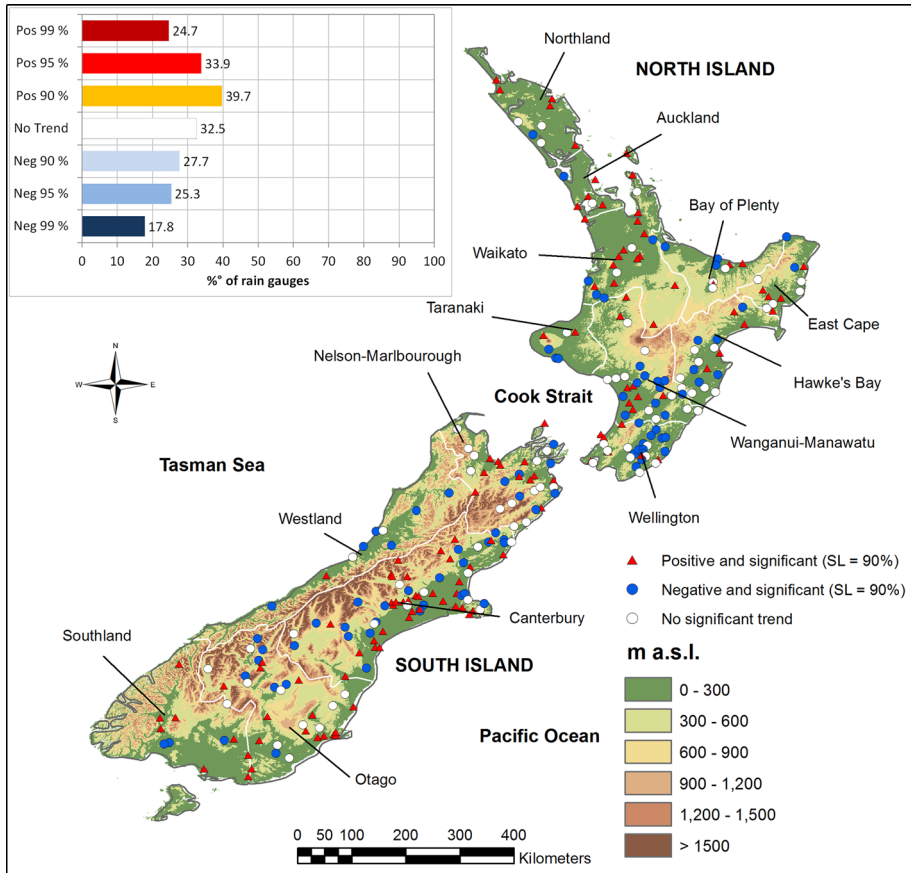


Fig. 8 Spatial distribution of the observed CI trends with summary of the results for different values of the significance level

minimum of 0.50 (in Westland) to a maximum of 0.71 (in Auckland) with a percentage of precipitation contributed by 25 % of the rainiest days, which ranges from 61 to 79 %, while in autumn, CI values range between a minimum of 0.47 (in Westland) to a maximum of 0.71 (in Auckland) with a percentage of precipitation amount, which ranges from 59 to 79 %. In winter and spring, CI values range between a minimum obtained in Westland (0.46 and 0.44 for winter and spring, respectively), to a maximum obtained in Auckland (0.70 in winter), and in Hawke’s Bay and Otago (0.68 in spring). The percentage of precipitation contributed by 25 % of the rainiest days ranges from 58 to 78 % in winter and from 57 to 76 % in spring.

Figure 8 shows the spatial distribution of the trend sign and summarizes the results showing the percentages of rain gauges, which present trends (positive and negative) for three different values of significance level. A unique trend cannot be detected; however, there are more rain gauges with positive trends (42.5 %) of CI than those with negative ones (30.3 %); 27.2 % of the rainfall series reveals no significant trend. In particular, a general negative trend has been detected in the eastern part of North Island (Wellington, Wanganui-Manawatu, and Hawke’s Bay areas), while a positive one occurred in the

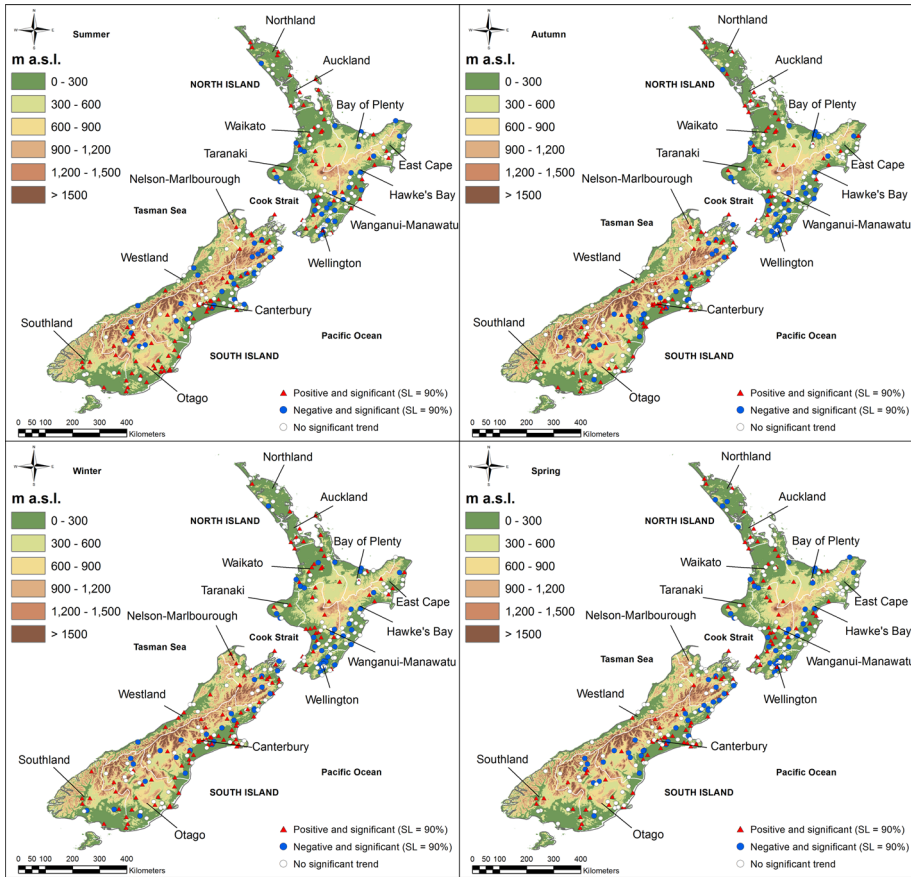


Fig. 9 Spatial distribution of the observed CI trends evaluated for the four seasons

eastern part of South Island (Canterbury and Otago areas), in which west/east difference trend emerged, as Salinger and Griffiths (2001) also highlighted. The seasonal analysis (Fig. 9) confirms the annual pattern with a general negative trend detected in the eastern part of North Island, in particular, in winter and autumn, and a west/east difference trend in South Island, in particular, in winter and summer.

These results are particularly important for South Island because the difference between the western (with lowest values of CI) and the eastern sides (with higher CI values) is expected to increase. In fact, NIWA scientists, following a downscaling approach to prepare New Zealand climate change scenarios for 2040 and 2090 (Ministry for the Environment 2008), showed that the difference in average rainfall between the western and the eastern parts of New Zealand is expected to become stronger, with rainfall likely to increase in the west of the country and to decrease in the east. At the same time, heavy rainfall events will occur more frequently in New Zealand, but the likely size of this change remains uncertain (Ministry for the Environment 2008). A decrease in total precipitation and an increase in the frequency of intense daily precipitation in the eastern area of South Island may lead to an increase in precipitation concentration.

5 Conclusion

In this paper, a study of rainfall distribution in New Zealand has been carried out using a daily rainfall database and applying the CI. CI values were estimated for all the stations, ranging from a minimum of 0.47 to a maximum of 0.70 with a correspondence percentage of precipitation contributed by 25 % of the rainiest days ranging from 59 to 78 %, with a variation of about 20 %, which shows a very different rainfall distribution between the areas. In particular, a different behavior emerged between North Island and South Island and, in the latter, among the eastern and the western sides. In fact, while North Island presents the greatest daily rainfall contrast and the most critical rainfall concentration, South Island can be divided into two parts: the western side of the island with lowest CI values and the eastern side with CI values comparable to those of North Island. On a seasonal scale, results for summer and autumn are similar to the annual one. The results of the trend analysis do not show a univocal trend of CI, even though there are more rain gauges with positive trends than those with negative ones. These results also show a tendency in the reduction of the daily rainfall concentration in North Island, while, in South Island, the differences between the western and the eastern sides are expected to increase. The seasonal analysis confirms the annual pattern with a general negative trend detected in the eastern part of North Island, in particular, in winter and autumn, and a west/east difference trend in South Island, in particular, in winter and summer.

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