Precipitation Trends for the Otago Region over the 21st century
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Front Cover – Photo Acknowledgements

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Executive summary

An analysis of historic trends and precipitation projections over the 21st century is presented for the Otago region. Nine annual precipitation metrics were used to assess the historical trends in precipitation for the Otago Region.

- The number of wet days.
- The total annual precipitation.
- The maximum consecutive number of wet days.
- The maximum precipitation over a 5-day period.
- The average daily precipitation.
- The number of days with very high or extreme precipitation (2 metrics).
- The proportion of the total annual rainfall coming from very high or extreme precipitation days (2 metrics).

For projected precipitation we have included two additional metrics which capture trends in dry conditions – the number of dry days, and the maximum consecutive number of dry days.

In this report we update the historic precipitation record for long-term Otago stations through to the end of 2015 (or 2014 if station data was unavailable). The historic precipitation record was updated using the methodology of Mojzisek (2006), resulting in an extended dataset from 2004-2014/15 for 16 Otago stations and for nine precipitation metrics. Trends were analysed for the historic data using a linear least squares regression approach, which included the contribution from the climate indices El Niño–Southern Oscillation (ENSO) and the Southern Annular Mode (SAM). This showed that sites to the east of the region have generally experienced a decrease in total annual precipitation, total number of rain days, and precipitation intensity over the 65-year period from 1951-2015. Localities in western and central regions have generally seen increased total precipitation and precipitation intensity over the period. Consistent relationships are displayed between high phases of both ENSO and SAM (i.e., generally drier conditions) and lower values of the precipitation metrics.

Extremes of high or low precipitation can be exceptionally damaging, as evidenced by the impacts of recent floods and droughts and it is important to assess changes in precipitation under various climate change scenarios. This study quantified the changes in precipitation metrics for the Otago region under two greenhouse gas emission scenarios (RCP2.6 and RCP 8.5) over the 21st century. Ensembles of precipitation metric projections were generated which emulated the expected range of model structural uncertainties using a statistical approach. This method allows probabilities to be assigned to the likelihood of changes in precipitation. Results indicate that much of the region is projected to receive increased total annual precipitation by the end of the 21st century, together with significant changes in many of the other precipitation metrics. However, the patterns are highly variable over both space and time.
Introduction

Otago Regional Council is seeking to better understand the likely impacts and implications of climate change on long-term rainfall at both a regional scale and for specific locations within the region. Such information has been useful for natural hazards assessments and regional planning.

A previous study (Mojzisek, 2006) identified historic trends in total precipitation in the South Island, as well as trends in eight other precipitation metrics that better represent the likelihood of changes in extreme events. This project expands on the Mojzisek (2006) study by updating the historical time series to the end of 2015 and by generating precipitation projections for the 21st century. These projections are based on Regional Climate Model (RCM) simulations for New Zealand, which are expanded to better account for uncertainties resulting from incomplete knowledge of how the climate system will respond to changes in greenhouse gas emissions.

This report provides the key results from the analyses of past and future trends in precipitation in the Otago Region, and describes the methods used to generate those results.

Historic precipitation trends are examined for 16 locations within the region, based on stations used by Mojzisek (2006), namely Duntroon, Oamaru Airport Aws, Earnslaw, Lake Hawea, Cardrona, Blackstone Hill, Naseby Forest 2, Trotters Creek, Middlemarch (Garthmyl), Ross Creek, Dunedin (Musselburgh Ews), Queenstown, Cromwell 2, Lauder Flat, Tuapeka Mouth, Nugget Point Aws.

Some time and effort was spent on developing an alternative method for estimating historic patterns in the metrics for any location in the region – using interpolation from all stations across both space and time. This would have provided maps for the region showing where significant trends in the metrics existed. However, some anomalies in the output data were discovered late in the process, and it was decided to only use the 16 stations mentioned above for the historic analysis. The Council may wish to revisit the value of further investigation into the interpolation approach for historic data at a later date.

For projected precipitation during the 21st century, trends are illustrated for thirteen towns/localities chosen to give a reasonable spatial coverage across the region, including Wanaka, Queenstown, Makarora, Glenorchy, Omarama, Kurow, Ranfurly, Alexandra, Dunedin, Mosgiel, Oamaru, Balclutha, Tapanui. Further sites of interest for the projected precipitation metrics can be further examined through analysis of the maps provided to ORC within and alongside this report.

In Section 1 previous work on precipitation trends and extremes across New Zealand is reviewed and summarised. Section 2 explains how historic precipitation data and annual metrics were updated to the present day and examines trends in the historic time series. Section 3 describes the calculation of projected precipitation, and outlines patterns which could emerge toward the end of the 21st century.

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1 We use a 20-year rolling average, which leads to the 2090 value covering the last two decades of the century (i.e. 2080-2100)
1. Precipitation trends in New Zealand

Otago experiences a wide range of total annual precipitation, with areas of very high annual median rainfall near the Southern Alps (e.g., average of 2400mm at Makarora between 1967-2010 (Otago Regional Council, 2011)), and areas of very low annual rainfall (e.g., average of 360mm at Alexandra between 1971-2000 (NIWA, 2003)).

New Zealand rainfall variability and extremes are modulated by both the El Niño–Southern Oscillation (ENSO) and by the Southern Annular Mode (SAM) (Ummenhofer and England, 2007; Ummenhofer, 2009). Mojzisek (2006) found that the south-east of the South Island exhibits a strong relationship between total precipitation and ENSO on seasonal and annual time-scales, and with the Interdecadal Pacific Oscillation (IPO) at the decadal scale. Others have found that the effect of the SAM is more pronounced for the South Island, while in the southwest of the South Island the two climate indices (ENSO and SAM) are found to act in opposition to one another, with the SAM dominating during the summer months (Ummenhofer, 2009). Mojzisek (2006) found that precipitation variability in the South Island is governed largely by the local atmospheric circulation; principally the strength and position of the westerly flow. Given that both SAM and ENSO have an impact on the strength and position of the westerly flow, future trends in these phenomena are likely to be important in determining precipitation for the Otago region.

Recent analyses of the geographical distribution and intensity of precipitation over New Zealand during the 20th Century indicate increasingly drier summers and autumns, and increasingly wetter winter and springs, for much of the country (Ummenhofer, 2009; Caloiero, 2015).

There is little evidence to date of significant increases in high-intensity, short-duration rainfall in New Zealand (Sansom and Renwick, 2007) and at the national scale, heavy rainfall (4–32 mm/day) has been found to be decreasing while lighter rainfall (0–4 mm/day) is increasing over time (Caloiero, 2015). Research in the Waikato region (Dravitzki and McGregor, 2011) found no evidence of significant variations in total annual precipitation or extreme precipitation since 1900 and no correlation between extreme rainfall events and climate indices for that region. Heavy rainfall events in the Waikato were associated with either mid-latitude cyclones or the presence of a blocking high to the east of New Zealand.

The trend towards wetter conditions, particularly in the winter and spring, is consistent with simulated patterns of change over the 21st century derived from climate models (MfE, 2008). Expected changes in the Otago Region are outlined in Box 1:
While the magnitude of extreme precipitation events is likely to increase in the future over most, if not all, of New Zealand, such changes will not be geographically uniformly distributed (Carey-Smith et al., 2010). Sansom and Renwick (2007) find that changes in the risk of extreme rainfall events (both floods and droughts) with climate change are particularly difficult to estimate for New Zealand, due to its small and mountainous nature. However, climate change was found to cause increasing precipitation at the three sites investigated by Sansom and Renwick (2007) mostly due to increased frequency of rainfall events rather than an increase in rainfall intensity. Sansom and Renwick (2007) suggest that for the coming few decades, rainfall distributions in New Zealand are likely to be primarily determined by changes in circulation.

An increasing body of work uses downscaling methods to estimate precipitation at the local level based on either global or regional climate model simulation output. Studies carried out in the Clutha catchment (Hashmi et al, 2009; Hashmi et al, 2013) found that catchment scale precipitation downscaling is challenging and more prone to uncertainty than for other climate variables (such as temperature). For this reason, an ensemble strategy which combines results from multiple downscaling methods is recommended. Hashmi et al. (2013) indicated that average annual rainfall in the Clutha catchment (the watershed upstream of Balclutha) is projected to increase by 12-24 mm by the end of the century. A separate study (Schwertheim and Bodeker, 2014) found no evidence for a trend in rainfall in the upper Manuherikia Catchment over the same time period. Given spatial differences across the catchment there is a clear need to assess projected precipitation in a framework that incorporates uncertainty in models.

Box 1: Projected changes in rainfall and impacts in the Otago Region (MfE, 2008).

- Rainfall in Dunedin is expected to increase by 4 per cent by 2090
- Queenstown is expected to have 12 per cent more rainfall by 2090
- Very heavy rainfall events are likely to become more frequent in Otago
- Increased rainfall in the main divide of the Southern Alps could increase river flows in the Clutha and Waitaki rivers
- Increased risk of flooding and landslides, particularly in western Otago
- Lakeside communities such as those around Lakes Wakatipu and Wanaka, as well as those further downstream alongside the Clutha River, could face greater risk from floodwaters
- By 2090, the time spent in drought ranges from minimal change through to more than double, depending upon the climate model and emissions scenario considered
- Reduced snowfalls may also affect water availability (since snow acts as a storage mechanism until the water is required in summer).
2. Historic data

One of the goals of this study is to extend the historical record of precipitation and calculated precipitation metrics for the period 2004-2014/15 (data was incomplete for some stations for 2015). We use the methods employed by Mojzisek (2006) to complete this record for the Otago region as it is well suited to an individual location or station level. We then examine trends for the full time-series from 1951-2015.

2.1. Methodology

2.1.1. Station data

Daily precipitation records for all 16 of the Otago stations over the period 2004-2014/15 were extracted from the National Climate Database (NCDB). For each of these stations, homogeneity tests were performed using the software package AnClim following the approach used by Mojzisek (2006), which required nearby stations to be used to calculate proxy values where gaps existed in the target station record. Using Mojzisek’s method metric calculations are completed by aggregating daily data where years with more than 10% of the daily data missing are not included in the analysis.

![Image](image-url)

**Figure 2.1:** Historic station precipitation measurement sites across the region.

2.1.2. Precipitation indices

Nine precipitation indices are calculated based on those used by Mojzisek (2006), which in turn are sourced from the Expert Team on Climate Change Detection and Indices (ETCCDI²). The indices are:

- Total Precipitation (mm)
- Number of Wet (rain) Days: days where precipitation of >= 1mm occurs (days)
- Simple Daily Intensity Index (SDII): total precipitation / number of rain-days (mm/day)
- Highest 5-day precipitation amount: maximum rainfall over a consecutive 5-day period (mm)
- Consecutive Wet Days (CWD): maximum number of consecutive rain-days (days)

² [http://etccdi.pacificclimate.org/indices.shtml](http://etccdi.pacificclimate.org/indices.shtml) - within the World Climate Research Programme
• Number of Very Wet Days: total number of days above 95\textsuperscript{th} percentile\(^3\) (days)
• Precipitation fraction due to Very Wet Days: proportion of total rain from very wet days (%)
• Number of Extremely Wet Days: total number of days above 99\textsuperscript{th} percentile (days)
• Precipitation fraction due to Extremely Wet Days: proportion of total rain from extremely wet days (%)

2.1.3. Climate indices

Two key climate indices – namely El Niño-Southern Oscillation (ENSO) and The Southern Annular Mode (SAM), together with the Standardized Precipitation Index (SPI) were used to examine their contribution to precipitation patterns in the Otago region.

\textit{El Niño-Southern Oscillation (ENSO)}

During El Niño conditions (negative phase of ENSO) New Zealand typically experiences stronger south-westerly winds, lower temperatures and drier conditions to the north-east of the country. During the La Niña (positive phase of ENSO), the country is generally subject to more frequent winds from the north-east, above average temperatures, and greater likelihood of drought in the South Island.

\textit{The Southern Annular Mode (SAM)}

SAM controls the position of the belt of westerly winds surrounding Antarctica, which moves north or south depending on the phase of SAM (positive towards the pole, negative away from the pole). In its positive phase, the SAM is associated with relatively light winds and more settled weather over New Zealand, together with enhanced westerly winds over the southern oceans. In the negative phase, the westerlies increase over New Zealand, with more unsettled weather. Alternate modes (positive/negative) of the westerlies are observed roughly every month.

\textit{The Standardized Precipitation Index (SPI)}

The SPI is described as:

“\textit{comparing total cumulative precipitation over a particular time interval (e.g. the last 3 months, the last 12 months) for a specific station with the average cumulative precipitation total for the same time interval over the entire length of record. Because the SPI is normally distributed and standardized, it can be used to monitor both dry and wet periods for any location with different climatological or hydrological regime and any time scale.\(^4\)}”

In this report we examine trends for the 12 month SPI over the period 1951-2015 for the sixteen station locations across the Otago Region.

2.1.4. Trend analysis

As part of the trend analysis of historic precipitation, we have quantitatively established the relationships between precipitation at each site and indices of ENSO and SAM. A multivariate linear least-squares regression analysis was used to determine the relationships between these indices and annual precipitation metrics for a given location. This analysis can quantify the influence of both SAM and ENSO on each metric, which, in turn, allows for variability in ENSO and SAM to be accounted for when determining a trend. Historic trends for SAM and ENSO are shown in Figure 2.2 below.

\(^3\) With percentiles calculated over a 30-year base period
\(^4\) Mojzisek, 2006
Analysis was performed for each of the sixteen Otago locations and for each of the precipitation metrics. Each analysis provided regression coefficients for the relationships to ENSO and SAM, as well as any long-term linear trend, along with uncertainty associated with each. These coefficients are then used to determine whether the historical precipitation metrics indicate statistically significant trends at the 90% confidence level over the period 1951-2015. A description of the steps in this regression analysis process is included in Appendix 1.

2.2. Results

2.2.1. Homogeneity

Out of the sixteen Otago stations, only one station – Earnslaw – was found to have an inhomogeneity occurring in the period 2003 to 2014. For Earnslaw, this commenced in January 2006 following a modification to the immediate surroundings of the raingauge. We have corrected for this by adjusting the daily precipitation values downward from that date forward (in this case by a factor of 1.115 calculated using the AnClim package).

2.2.2. Historic trends

In this section we examine trends in each of the precipitation metrics as well as the relationship of each to ENSO\(^5\) and SAM\(^6\). For each metric we have mapped the sign (positive or negative) and significance (assessed at the 90% confidence level) of the precipitation metric trend for each of the sixteen Otago stations over the period 1951-2015 following the approach of Mojzisek (2006). However, our approach differs in that we do not use two confidence levels in the mapping – instead a trend is significant if it is non-zero at the 90% confidence level, it is not significant if it is non-zero below the 90% confidence level, and it shows ‘no-trend’ if the slope of the trend-line is equal to zero. In the tables that follow,

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\(^5\) We use the basic Southern Oscillation Index (SOI) as used by Mojzisek (2006), available from NOAA here: http://www.cpc.ncep.noaa.gov/data/indices/soi

\(^6\) We use the annualized SAM, available via the British Antarctic Survey website here: http://www.nerc-bas.ac.uk/public/icd/gjma/newsam.1957.2007.seas.txt
we only show locations that have a statistically significant trend or statistically significant relationship to ENSO or SAM (significance is determined at the 90% confidence level and is indicated by shading of the box and an asterisk). Locations with either no statistically significant trend or relationship to ENSO or SAM are not shown in the tables.

**Total Annual Precipitation**

Significant decreases in total precipitation have been seen for parts of the region over the last 65 years (Figure 2.1 and Table 2.1), most notably in eastern areas (e.g. Duntroon, Ross Creek, Musselburgh and Nugget Point), while increased annual precipitation has been seen in some western and inland areas (Lake Hawea, Cromwell and Tuapeka Mouth).

A number of significant relationships are observed between total precipitation, ENSO and SAM (Table 2.1). These can be interpreted as the sensitivity of the metric (in this case total annual precipitation) to the climate indices (SAM or ENSO). For example, when SAM is one standard deviation above its long-term mean (i.e., moving toward the positive phase featuring a more poleward belt of westerlies) Musselburgh would be expected to receive around 31mm less precipitation per annum. Similarly, when ENSO is one standard deviation higher than its mean (i.e., moving toward La Niña conditions) Musselburgh would be expected to receive around 23mm less precipitation per annum.

Five of the sixteen localities (Oamaru, Ross Creek, Musselburgh, Tuapeka Mouth, and Nugget Point) show significant relationships between total precipitation and SAM – all showing reduced precipitation with the positive phase of the SAM.

Eight localities (Earnslaw, Cardrona, Blackstone Hill, Ross Creek, Musselburgh, Queenstown, Tuapeka Mouth, Nugget Point) show significant relationships between total precipitation and ENSO – all showing reduced precipitation with the positive (La Niña) phase of the ENSO.

*Figure 2.1 Trends in total annual precipitation over the period 1953-2015*
Table 2.1 Locations with either a significant trend in total annual precipitation (mm/annum) or with a significant relationship between the metric and SAM or ENSO over the period 1953-2015. Significant values are indicated by an asterisk and a shaded box.

<table>
<thead>
<tr>
<th>Station</th>
<th>Trend</th>
<th>SAM</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duntroon</td>
<td>-1.76 ± 0.98</td>
<td>-13.29 ± 16.72</td>
<td>-20.55 ± 16.82</td>
</tr>
<tr>
<td>Oamaru_Airport_Aws</td>
<td>0.23 ± 0.68</td>
<td>-22.47* ± 13.47</td>
<td>4.64 ± 12.95</td>
</tr>
<tr>
<td>Earnslaw</td>
<td>1.98 ± 1.74</td>
<td>-51.98 ± 35.04</td>
<td>-56.96* ± 31.73</td>
</tr>
<tr>
<td>Lake_Hawea</td>
<td>2.34* ± 1.28</td>
<td>-22.4 ± 22.85</td>
<td>-15 ± 22.58</td>
</tr>
<tr>
<td>Cardrona</td>
<td>0.82 ± 0.9</td>
<td>-16.47 ± 18.38</td>
<td>-32.3* ± 16.3</td>
</tr>
<tr>
<td>Blackstone_Hill</td>
<td>0.88 ± 0.86</td>
<td>3.64 ± 14.19</td>
<td>-27.6* ± 14.45</td>
</tr>
<tr>
<td>Ross_Creek</td>
<td>-3.15* ± 1.2</td>
<td>-48.43* ± 21.08</td>
<td>-39.18* ± 21.24</td>
</tr>
<tr>
<td>Dunedin_Musselburgh_EWS</td>
<td>-1.86* ± 0.71</td>
<td>-31.11* ± 14.02</td>
<td>-22.64* ± 13.41</td>
</tr>
<tr>
<td>Queenstown</td>
<td>1.2 ± 0.99</td>
<td>-31.12 ± 19.07</td>
<td>-38.29* ± 18.09</td>
</tr>
<tr>
<td>Cromwell_2</td>
<td>1.04* ± 0.62</td>
<td>-4.96 ± 10.31</td>
<td>-6.43 ± 10.42</td>
</tr>
<tr>
<td>Tuapeka_Mouth</td>
<td>1.62* ± 0.92</td>
<td>-26.15* ± 13.0</td>
<td>-42.48* ± 13.26</td>
</tr>
<tr>
<td>Nugget_Point_Aws</td>
<td>-1.21* ± 0.68</td>
<td>-38.71* ± 13.02</td>
<td>-25.36* ± 12.67</td>
</tr>
</tbody>
</table>

Number of rain days

Figure 2.2 and Table 2.2 show that over the last 65 years that only one of the sixteen stations exhibits a significant upward trend in the number of rain days (at Earnslaw to the west of the region), increasing at a rate of 0.15 more rain days per annum over the period. Seven locations display a significant downward trend in the number of rain days (Duntroon, Naseby, Trotters Creek, Middlemarch, Ross Creek, Musselburgh, Lauder), reducing at rates ranging from 0.14-0.29 fewer rain days per annum.

A significant relationship between SAM or ENSO are shown for many sites. When either SAM or ENSO are one standard deviation above their long-term mean, Musselburgh (for example) would be expected to receive almost 3 fewer rain days per annum. Other locations showing similar patterns (i.e., an effect for both ENSO and SAM) include Queenstown, Tuapeka Mouth and Nugget Point. Several locations have significant relationships to ENSO only, where higher ENSO relates to decreased rain days (Earnslaw, Cardronna, Blackstone Hill, Middlemarch and Ross Creek), while only Lake Hawea has a significant relationship to the SAM where higher values relate to fewer rain days.

Figure 2.2 Trends in the number of rain days over the period 1951-2015
Table 2.2 Locations with either a significant trend in the number of rain days (days per annum) or with a significant relationship between the metric and SAM or ENSO over the period 1953-2015. Significant values are indicated by an asterisk and a shaded box.

<table>
<thead>
<tr>
<th>Station</th>
<th>Trend</th>
<th>SAM</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duntroon</td>
<td>-0.14* ± 0.08</td>
<td>0.18 ± 1.35</td>
<td>-1.17 ± 1.36</td>
</tr>
<tr>
<td>Oamaru_Airport_Aws</td>
<td>0.04 ± 0.06</td>
<td>-1.26 ± 1.22</td>
<td>-0.21 ± 1.19</td>
</tr>
<tr>
<td>Earnslaw</td>
<td>0.15* ± 0.09</td>
<td>-1.93 ± 1.75</td>
<td>-2.86* ± 1.6</td>
</tr>
<tr>
<td>Lake_Hawea</td>
<td>-0.08 ± 0.09</td>
<td>-2.92* ± 1.52</td>
<td>-1.42 ± 1.49</td>
</tr>
<tr>
<td>Cardrona</td>
<td>-0.07 ± 0.09</td>
<td>-0.93 ± 1.72</td>
<td>-3.04* ± 1.55</td>
</tr>
<tr>
<td>Blackstone_Hill</td>
<td>-0.01 ± 0.08</td>
<td>0.66 ± 1.33</td>
<td>-3.4* ± 1.37</td>
</tr>
<tr>
<td>Naseby_Forest_2</td>
<td>-0.16* ± 0.07</td>
<td>1.35 ± 1.32</td>
<td>-1.35 ± 1.32</td>
</tr>
<tr>
<td>Trotters_Creek</td>
<td>-0.26* ± 0.07</td>
<td>-0.81 ± 1.26</td>
<td>0.98 ± 1.19</td>
</tr>
<tr>
<td>Middlemarch_Garthmyl</td>
<td>-0.29* ± 0.06</td>
<td>-0.19 ± 1.23</td>
<td>-2.09* ± 1.27</td>
</tr>
<tr>
<td>Ross_Creek</td>
<td>-0.18* ± 0.1</td>
<td>-2.82 ± 1.78</td>
<td>-3.67* ± 1.75</td>
</tr>
<tr>
<td>Dunedin_Musselburgh_EWS</td>
<td>-0.26* ± 0.07</td>
<td>-2.96* ± 1.47</td>
<td>-2.71* ± 1.4</td>
</tr>
<tr>
<td>Queenstown</td>
<td>-0.03 ± 0.07</td>
<td>-3.12* ± 1.36</td>
<td>-3.37* ± 1.32</td>
</tr>
<tr>
<td>Lauder_Flat</td>
<td>-0.16* ± 0.07</td>
<td>1.1 ± 1.41</td>
<td>-1.88 ± 1.32</td>
</tr>
<tr>
<td>Tuapeka_Mouth</td>
<td>0.01 ± 0.08</td>
<td>-5.69* ± 1.17</td>
<td>-6.87* ± 1.19</td>
</tr>
<tr>
<td>Nugget_Point_Aws</td>
<td>-0.07 ± 0.08</td>
<td>-4.25* ± 1.57</td>
<td>-2.54* ± 1.51</td>
</tr>
</tbody>
</table>

Simple Daily Intensity Index (SDII)

Figure 2.3 and Table 2.3 show significant trends in precipitation intensity have occurred for some central and western parts of the region (Queenstown, Cardrona, Lake Hawea, Lauder, Naseby and Tuapeka Mouth). Two localities to the east experience decreases in intensity (Ross Creek and Nugget Point). No significant relationships are apparent between precipitation intensity and the climate indices SAM and ENSO.

Figure 2.3 Trends in the SDII over the period 1951-2015
Table 2.3 Locations with either a significant trend in the Simple Daily Intensity Index (mmd/day) or with a significant relationship between the metric and SAM or ENSO over the period 1953-2015. Significant values are indicated by an asterisk and a shaded box.

<table>
<thead>
<tr>
<th>Station</th>
<th>Trend</th>
<th>SAM</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake_Hawea</td>
<td>0.04*± 0.01</td>
<td>0.06± 0.17</td>
<td>0.02± 0.17</td>
</tr>
<tr>
<td>Cardrona</td>
<td>0.02*± 0.01</td>
<td>-0.1± 0.16</td>
<td>-0.09± 0.14</td>
</tr>
<tr>
<td>Naseby_Forest_2</td>
<td>0.01*± 0.01</td>
<td>-0.11± 0.13</td>
<td>0.09± 0.13</td>
</tr>
<tr>
<td>Ross_Creek</td>
<td>-0.01*± 0.01</td>
<td>-0.19± 0.14</td>
<td>-0.05± 0.14</td>
</tr>
<tr>
<td>Queenstown</td>
<td>0.02*± 0.01</td>
<td>-0.04± 0.14</td>
<td>-0.07± 0.13</td>
</tr>
<tr>
<td>Lauder_Flat</td>
<td>0.03*± 0.01</td>
<td>0.14± 0.2</td>
<td>0.23± 0.19</td>
</tr>
<tr>
<td>Tuapeka_Mouth</td>
<td>0.02*± 0.01</td>
<td>0.13± 0.11</td>
<td>0.05± 0.11</td>
</tr>
<tr>
<td>Nugget_Point_Aws</td>
<td>-0.01*± 0</td>
<td>-0.11± 0.07</td>
<td>-0.06± 0.06</td>
</tr>
</tbody>
</table>

Highest 5-day precipitation amount

Figure 2.4 and Table 2.4 shows significant downward trends in the maximum precipitation over a five-day period (in Cardrona, Lauder, Middlemarch and Musselburgh) of between 0.36-0.49 mm less over 5-days per annum.

When SAM is one standard deviation above its long-term mean, several locations would be expected to have a significant reduction in maximum precipitation over a five-day period (Cardrona, Trotters Creek, Ross Creek, Musselburgh and Nugget Point). Two localities show a decrease in maximum five-day precipitation with increasing ENSO (Cardrona and Tuapeka Mouth).

Figure 2.4 Trends in the maximum 5-day precipitation over the period 1951-2015.
Table 2.4 Locations with either a significant trend in the maximum 5-day precipitation (mm per annum) or with a significant relationship between the metric and SAM or ENSO over the period 1953-2015. Significant values are indicated by an asterisk and a shaded box.

<table>
<thead>
<tr>
<th>Station</th>
<th>Trend</th>
<th>SAM</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardrona</td>
<td>-0.4* ± 0.2</td>
<td>-7.29* ± 4</td>
<td>-10.21* ± 3.62</td>
</tr>
<tr>
<td>Trotters_Creek</td>
<td>0.22 ± 0.29</td>
<td>-7.5* ± 4.15</td>
<td>1.76 ± 4.26</td>
</tr>
<tr>
<td>Middlemarch_Garthmyl</td>
<td>-0.36* ± 0.16</td>
<td>0.45 ± 2.9</td>
<td>-2.37 ± 2.98</td>
</tr>
<tr>
<td>Ross_Creek</td>
<td>-0.43 ± 0.37</td>
<td>-13.91* ± 6.27</td>
<td>-9.55 ± 6.12</td>
</tr>
<tr>
<td>Dunedin_Musselburgh_EWS</td>
<td>-0.37* ± 0.2</td>
<td>-9.39* ± 3.98</td>
<td>-0.71 ± 3.75</td>
</tr>
<tr>
<td>Lauder_Flat</td>
<td>-0.49* ± 0.15</td>
<td>2.94 ± 2.86</td>
<td>-1.53 ± 2.91</td>
</tr>
<tr>
<td>Tuapeka_Mouth</td>
<td>-0.03 ± 0.18</td>
<td>-1.59 ± 2.49</td>
<td>-8.77* ± 2.55</td>
</tr>
<tr>
<td>Nugget_Point_Aws</td>
<td>-0.15 ± 0.12</td>
<td>-5.79* ± 2.27</td>
<td>-3.07 ± 2.15</td>
</tr>
</tbody>
</table>

Consecutive Wet Days (CWD)

Figure 2.5 and Table 2.5 shows significantly fewer consecutive wet days in Naseby, Middlemarch and Nugget Point (ranging from 0.01-0.03 days per annum). The positive SAM is correlated with fewer consecutive wet days for many locations (Lake Hawea, Ross Creek, Queenstown, Tuapeka Mouth and Nugget Point). Blackstone Hill exhibits an opposite trend, with an increase in the number of consecutive wet days with more positive SAM. Several locations show a significant reduction in the number of consecutive wet days with increased positive ENSO (Cardrona, Ross Creek, Tuapeka and Nugget Point).

Figure 2.5 Trends in Consecutive Wet Days over the period 1951-2015.
Table 2.5 Locations with either a significant trend in Consecutive Wet Days (number of days per annum) or with a significant relationship between the metric and SAM or ENSO over the period 1953-2015. Significant values are indicated by an asterisk and a shaded box.

<table>
<thead>
<tr>
<th>Station</th>
<th>Trend</th>
<th>SAM</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake_Hawea</td>
<td>-0.01 ± 0.01</td>
<td>-0.4* ± 0.18</td>
<td>0.07 ± 0.18</td>
</tr>
<tr>
<td>Cardrona</td>
<td>-0.02 ± 0.01</td>
<td>-0.32 ± 0.22</td>
<td>-0.33* ± 0.2</td>
</tr>
<tr>
<td>Blackstone_Hill</td>
<td>0 ± 0.01</td>
<td>0.55* ± 0.2</td>
<td>-0.32 ± 0.2</td>
</tr>
<tr>
<td>Naseby_Forest_2</td>
<td>-0.01* ± 0.01</td>
<td>0.13 ± 0.16</td>
<td>-0.25 ± 0.15</td>
</tr>
<tr>
<td>Middlemarch_Garthmyl</td>
<td>-0.02* ± 0.01</td>
<td>-0.13 ± 0.16</td>
<td>0.01 ± 0.16</td>
</tr>
<tr>
<td>Ross_Creek</td>
<td>-0.01 ± 0.01</td>
<td>-0.49* ± 0.25</td>
<td>-0.55* ± 0.25</td>
</tr>
<tr>
<td>Queenstown</td>
<td>0 ± 0.01</td>
<td>-0.88* ± 0.21</td>
<td>0.11 ± 0.2</td>
</tr>
<tr>
<td>Tuapeka_Mouth</td>
<td>0.02 ± 0.02</td>
<td>-0.46* ± 0.22</td>
<td>-0.6* ± 0.22</td>
</tr>
<tr>
<td>Nugget_Point_Aws</td>
<td>-0.03* ± 0.01</td>
<td>-0.57* ± 0.29</td>
<td>-0.52* ± 0.27</td>
</tr>
</tbody>
</table>

Very wet and extremely wet days
The following table indicates the daily thresholds above which a precipitation day is counted as either very wet (95th percentile) or extremely wet (99th percentile) at each of the Otago stations. The values are calculated from all rain days over the period 1961-1990.

<table>
<thead>
<tr>
<th>Station</th>
<th>Precipitation threshold for very wet days (mm)</th>
<th>Precipitation threshold for extremely wet days (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duntroon</td>
<td>22.3</td>
<td>45.8</td>
</tr>
<tr>
<td>Oamaru Airport Aws</td>
<td>20.1</td>
<td>42.9</td>
</tr>
<tr>
<td>Earnslaw</td>
<td>40.6</td>
<td>64.9</td>
</tr>
<tr>
<td>Lake Hawea</td>
<td>27.2</td>
<td>47.8</td>
</tr>
<tr>
<td>Cardrona</td>
<td>24.1</td>
<td>44.9</td>
</tr>
<tr>
<td>Blackstone Hill</td>
<td>22.5</td>
<td>37.8</td>
</tr>
<tr>
<td>Naseby Forest 2</td>
<td>22.5</td>
<td>39.0</td>
</tr>
<tr>
<td>Trotters Creek</td>
<td>21.4</td>
<td>46.8</td>
</tr>
<tr>
<td>Middlemarch, Garthmyl</td>
<td>20.3</td>
<td>36.0</td>
</tr>
<tr>
<td>Ross Creek</td>
<td>23.5</td>
<td>52.8</td>
</tr>
<tr>
<td>Dunedin, Musselburgh Ews</td>
<td>20.3</td>
<td>38.6</td>
</tr>
<tr>
<td>Queenstown</td>
<td>26.7</td>
<td>46.1</td>
</tr>
<tr>
<td>Cromwell 2</td>
<td>17.5</td>
<td>31.9</td>
</tr>
<tr>
<td>Lauder Flat</td>
<td>23.6</td>
<td>36.7</td>
</tr>
<tr>
<td>Tuapeka Mouth</td>
<td>19.5</td>
<td>31.8</td>
</tr>
<tr>
<td>Nugget Point Aws</td>
<td>16.9</td>
<td>28.4</td>
</tr>
</tbody>
</table>

Number of Very Wet Days
Figure 2.6 and Table 2.6 shows that significantly more very wet days have occurred at Lake Hawea and Lauder. Only Nugget Point shows a relationship with the climate indices, where an increase of 1 standard deviation in the SAM is associated with a decrease of around 0.6 very wet days per annum.
**Figure 2.6** Trends in the number of very wet days over the period 1951-2015.

Table 2.6 Locations with either a significant trend in the number of very wet days (number of days per annum) or with a significant relationship between the metric and SAM or ENSO over the period 1953-2015. Significant values are indicated by an asterisk and a shaded box.

<table>
<thead>
<tr>
<th>Station</th>
<th>Trend</th>
<th>SAM</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake_Hawea</td>
<td>0.03* ± 0.02</td>
<td>0.02 ± 0.33</td>
<td>-0.17 ± 0.32</td>
</tr>
<tr>
<td>Lauder_Flat</td>
<td>0.03* ± 0.01</td>
<td>0.07 ± 0.26</td>
<td>0.25 ± 0.24</td>
</tr>
<tr>
<td>Nugget_Point_Aws</td>
<td>-0.03 ± 0.02</td>
<td>-0.59* ± 0.31</td>
<td>-0.16 ± 0.29</td>
</tr>
</tbody>
</table>

**Precipitation fraction due to Very Wet Days**

Figure 2.7 and Table 2.7 shows that three localities experience a greater proportion of their total annual precipitation from very wet days (Lauder, Naseby and Trotters Creek), with significant upward trends ranging from 0.13 to 0.3% per annum. Cardrona and Trotters Creek both have around 2.8% less of their total precipitation per annum from very wet days when SAM is one standard deviation above its mean. Meanwhile Lauder has about 2.3% more of its total annual precipitation from very wet days when ENSO is more positive than average.

**Figure 2.7** Trends in the proportion of total precipitation from very wet days over the period 1951-2015.
**Table 2.7** Locations with either a significant trend in the proportion of total precipitation (percentage per annum) or with a significant relationship between the metric and SAM or ENSO over the period 1953-2015. Significant values are indicated by an asterisk and a shaded box.

<table>
<thead>
<tr>
<th>Station</th>
<th>Trend</th>
<th>SAM</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardrona</td>
<td>-0.01 ± 0.07</td>
<td>-2.83* ± 1.36</td>
<td>-0.64 ± 1.19</td>
</tr>
<tr>
<td>Naseby_Forest_2</td>
<td>0.13* ± 0.07</td>
<td>-1.22 ± 1.31</td>
<td>1.2 ± 1.3</td>
</tr>
<tr>
<td>Trotters_Creek</td>
<td>0.2* ± 0.08</td>
<td>-2.77* ± 1.55</td>
<td>0.41 ± 1.48</td>
</tr>
<tr>
<td>Lauder_Flat</td>
<td>0.13* ± 0.07</td>
<td>-0.25 ± 1.45</td>
<td>2.26* ± 1.37</td>
</tr>
</tbody>
</table>

**Number of Extremely Wet Days**

Figure 2.8 and Table 2.8 shows that there is a small but significant increasing trend in the number of extremely wet days that have occurred at Lauder and Naseby (equating to about 1 day more in 2015 than experienced 65 years ago). Several sites show relationships with the SAM and ENSO, where significantly fewer extremely wet days are associated with more positive SAM/ENSO values.

**Figure 2.8** Trends in the number of extremely wet days over the period 1951-2015.

![Number of Extremely Wet Days](image)

**Table 2.8** Locations with either a significant trend in the number of extremely wet days (number of days per annum) or with a significant relationship between the metric and SAM or ENSO over the period 1953-2015. Significant values are indicated by an asterisk and a shaded box.

<table>
<thead>
<tr>
<th>Station</th>
<th>Trend</th>
<th>SAM</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duntroon</td>
<td>0 ± 0.01</td>
<td>-0.03 ± 0.13</td>
<td>-0.25* ± 0.14</td>
</tr>
<tr>
<td>Oamaru_Airport_Aws</td>
<td>0 ± 0.01</td>
<td>-0.21* ± 0.1</td>
<td>0.03 ± 0.09</td>
</tr>
<tr>
<td>Earnslaw</td>
<td>0.01 ± 0.01</td>
<td>-0.13 ± 0.15</td>
<td>-0.26* ± 0.13</td>
</tr>
<tr>
<td>Lake_Hawea</td>
<td>0.01 ± 0.01</td>
<td>-0.26* ± 0.16</td>
<td>0.07 ± 0.15</td>
</tr>
<tr>
<td>Cardrona</td>
<td>0 ± 0.01</td>
<td>-0.25* ± 0.12</td>
<td>-0.25* ± 0.11</td>
</tr>
<tr>
<td>Naseby_Forest_2</td>
<td>0.02* ± 0.01</td>
<td>-0.07 ± 0.12</td>
<td>0.13 ± 0.12</td>
</tr>
<tr>
<td>Trotters_Creek</td>
<td>0 ± 0.01</td>
<td>-0.37* ± 0.12</td>
<td>-0.1 ± 0.12</td>
</tr>
<tr>
<td>Ross_Creek</td>
<td>-0.01 ± 0.01</td>
<td>-0.45* ± 0.18</td>
<td>0.03 ± 0.18</td>
</tr>
<tr>
<td>Lauder_Flat</td>
<td>0.02* ± 0.01</td>
<td>0.18 ± 0.12</td>
<td>0.13 ± 0.12</td>
</tr>
<tr>
<td>Nugget_Point_Aws</td>
<td>0 ± 0.01</td>
<td>-0.3* ± 0.14</td>
<td>-0.2 ± 0.13</td>
</tr>
</tbody>
</table>
Precipitation fraction due to Extremely Wet Days

Figure 2.9 and Table 2.9 shows that both Lauder and Naseby display a trend toward a greater proportion of their total annual precipitation from extremely wet days, ranging from 0.12-0.14% more per annum. Several stations have between 1.4-3.0% less of their total annual precipitation from extremely wet days when SAM is one standard deviation above its mean. Meanwhile two stations have 1.7-2.3% less of their total annual precipitation from extremely wet days when ENSO is higher than average.

**Figure 2.9** Trends in the proportion of total precipitation (percentage per annum) from extremely wet days over the period 1951-2015.

Table 2.9 Locations with either a significant trend in the proportion of total precipitation (percentage per annum) or with a significant relationship between the metric and SAM or ENSO over the period 1953-2015. Significant values are indicated by an asterisk and a shaded box.

<table>
<thead>
<tr>
<th>Station</th>
<th>Trend</th>
<th>SAM</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duntroon</td>
<td>-0.01 ± 0.07</td>
<td>-0.56 ± 1.23</td>
<td>-2.33* ± 1.23</td>
</tr>
<tr>
<td>Oamaru_Airport_Aws</td>
<td>0.01 ± 0.05</td>
<td>-2* ± 0.96</td>
<td>0.62 ± 0.91</td>
</tr>
<tr>
<td>Cardrona</td>
<td>-0.02 ± 0.05</td>
<td>-1.97* ± 0.98</td>
<td>-1.73* ± 0.85</td>
</tr>
<tr>
<td>Naseby_Forest_2</td>
<td>0.14* ± 0.04</td>
<td>-0.35 ± 0.9</td>
<td>1.34 ± 0.9</td>
</tr>
<tr>
<td>Trotters_Creek</td>
<td>0.07 ± 0.06</td>
<td>-3.01* ± 1.12</td>
<td>-0.41 ± 1.08</td>
</tr>
<tr>
<td>Ross_Creek</td>
<td>-0.01 ± 0.06</td>
<td>-2.96* ± 1.01</td>
<td>0.09 ± 1.01</td>
</tr>
<tr>
<td>Lauder_Flat</td>
<td>0.12* ± 0.05</td>
<td>1.22 ± 1.03</td>
<td>1.14 ± 0.98</td>
</tr>
<tr>
<td>Nugget_Point_Aws</td>
<td>0.04 ± 0.03</td>
<td>-1.38* ± 0.67</td>
<td>-0.56 ± 0.64</td>
</tr>
</tbody>
</table>

Standardized Precipitation Index (SPI)

The 12 month SPI represents the difference between each annual precipitation distribution and the long-term average distribution. Positive SPI values indicate greater than median precipitation, while negative values indicate less than median precipitation. Table 2.12 confirms what we found above (Figure 2.1 and Table 2.1), that over the last 65 years, locations which are central or to the west of the region show an increasing trend in the SPI (more precipitation) while other areas in the east show a significant decreasing trend. Also as seen above, significant increases in both the SAM and ENSO are associated with reduced precipitation for much of the region.
**Figure 2.12** Trends in the SPI over the period 1951-2015.

**Table 2.12** Locations with either a significant trend in the SPI or with a significant relationship between the metric and SAM or ENSO over the period 1953-2015. Significant values are indicated by an asterisk and a shaded box.

<table>
<thead>
<tr>
<th>Station</th>
<th>Trend</th>
<th>SAM</th>
<th>SOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duntroon</td>
<td>-0.01* ± 0</td>
<td>-0.07* ± 0.04</td>
<td>-0.17* ± 0.04</td>
</tr>
<tr>
<td>Oamaru_Airport_Aws</td>
<td>0 ± 0</td>
<td>-0.12* ± 0.04</td>
<td>-0.05 ± 0.04</td>
</tr>
<tr>
<td>Lake_Hawea</td>
<td>0.01* ± 0</td>
<td>-0.06 ± 0.04</td>
<td>0 ± 0.04</td>
</tr>
<tr>
<td>Cardrona</td>
<td>0 ± 0</td>
<td>-0.04 ± 0.04</td>
<td>-0.06* ± 0.04</td>
</tr>
<tr>
<td>Blackstone_Hill</td>
<td>0.01* ± 0</td>
<td>-0.05 ± 0.04</td>
<td>-0.18* ± 0.04</td>
</tr>
<tr>
<td>Naseby_Forest_2</td>
<td>0 ± 0</td>
<td>-0.07* ± 0.04</td>
<td>-0.12* ± 0.03</td>
</tr>
<tr>
<td>Trotters_Creek</td>
<td>0 ± 0</td>
<td>-0.1* ± 0.04</td>
<td>-0.07* ± 0.04</td>
</tr>
<tr>
<td>Middlemarch_Garthmyl</td>
<td>-0.01* ± 0</td>
<td>-0.08* ± 0.04</td>
<td>-0.14* ± 0.04</td>
</tr>
<tr>
<td>Ross_Creek</td>
<td>-0.01* ± 0</td>
<td>-0.11* ± 0.04</td>
<td>-0.22* ± 0.04</td>
</tr>
<tr>
<td>Dunedin_Musselburgh_EWS</td>
<td>-0.01* ± 0</td>
<td>-0.08* ± 0.03</td>
<td>-0.17* ± 0.03</td>
</tr>
<tr>
<td>Queenstown</td>
<td>0.01* ± 0</td>
<td>-0.05 ± 0.04</td>
<td>-0.09* ± 0.04</td>
</tr>
<tr>
<td>Cromwell_2</td>
<td>0.01* ± 0</td>
<td>-0.07* ± 0.04</td>
<td>-0.04 ± 0.04</td>
</tr>
<tr>
<td>Lauder_Flat</td>
<td>0.01* ± 0</td>
<td>-0.06* ± 0.04</td>
<td>0.02 ± 0.04</td>
</tr>
<tr>
<td>Tuapeka_Mouth</td>
<td>0.01* ± 0</td>
<td>0.01 ± 0.04</td>
<td>-0.19* ± 0.04</td>
</tr>
<tr>
<td>Nugget_Point_Aws</td>
<td>-0.01* ± 0</td>
<td>-0.03 ± 0.03</td>
<td>-0.17* ± 0.03</td>
</tr>
</tbody>
</table>
3. Precipitation projections for the Otago region

Climate projections for the 21st century are calculated based on Regional Climate Models (RCMs) extended to cover a full ensemble of different global models and model biases. Large ensembles are generated using a statistical approach based on the precipitation data obtained from RCM model runs, to provide a data product with high spatial resolution (5km grid across New Zealand). The use of a statistical approach allows for the estimation of how the probability density function changes over time. This provides a full data set of historic and projected precipitation for sites across the Otago region where the projections include information about the likelihood of changes being different to the modelled median.

3.1. Methodology

Resolving changes in regional scale extreme weather events requires projections which have a high spatial and temporal resolution. Due to the computational burden of generating high resolution projections of climate variables, it is prohibitively expensive to run every climate model under all potential climate change scenarios. Typically, a subset of possible models is run which exposes the users of these data to a selection bias whereby the projections may not be representative of the population of models. In addition, performing analysis on output from a small number of simulations may limit the statistical significance of the results.

We have developed a method for generating an ensemble of projections for precipitation metrics which explores the range of structural uncertainties (i.e. model bias) between models. This method emulates several thousand model runs across 190 global climate models to provide a distribution of potential future trajectories in a computationally efficient manner. The projection methodology uses the lowest (2.6) and highest (8.5) representative concentration pathways (RCP) in order to investigate the possible spread of projected precipitation. RCPs provide a means for creating consistent climate projections, based on possible paths that atmospheric concentrations of greenhouse gases may take over the course of the 21st century. It should be noted that, in order to achieve lower concentrations by the end of the 21st century, RCP2.6 assumes that greenhouse gas emissions peak mid-century and decline thereafter. RCP8.5 assumes that emissions continue to increase throughout the 21st century.

Generating daily time series of precipitation is more difficult than other climate variables such as surface temperature which are continuous. Instead, we generate projections of annual precipitation metrics which aggregate a large number of daily precipitation values to provide an indicator for the likelihood of the frequency and intensity of precipitation.

A detailed description of the approach to generating precipitation projections is included at Appendix 3.

In order to calculate some of the rainfall metrics of interest to ORC (those which are compared to long-term patterns), a 30 year ‘climate normal’ base-period is used to compare extremes against. In our approach we have used the 1980-2010 period as the base-period, as we did not have good spatial coverage over the country prior to this time. This means that our precipitation metrics will differ slightly from those of Mojzisek (2006), who used a base period of 1961-1990. The different base period does not affect the ability to compare trends at a specific location over time.

In our mapping we have used boundaries for the Otago region which include the Waitaki District.
3.2. Results

3.2.1. Precipitation metric projections at selected locations in Otago

Figure 3.1 provides the sites used to investigate temporal trends across the Otago region.

![Figure 3.1: Site locations where projected metrics are examined](image)

This report focuses on the forced change in precipitation due to climate change, therefore twenty-year rolling average was used for calculating the precipitation metrics. This aggregation smooths out the inter-annual variability of the time series, hence it is expected that precipitation metrics for a given year may occur outside of the limits shown by the percentiles used here. This report does not provide the range of extreme annual precipitation metrics at the end of the century as this is out of scope. Instead the figures below identify locations where there will likely be a change over the 21st century. In addition to the nine indices used for completion of the historic record, for projections we have included two indices which capture dry years as follows:

- Number of dry (no-rain) Days: days where no rain (or <1mm) occurs (days)\(^8\)
- Consecutive Dry Days (CDD): maximum number of consecutive dry-days (<1mm) (days)

A summary table of the median change for the 21st century, together with charts showing projections in each of the metrics at each of the Otago localities is included at Appendix 4. Here we look at several examples which demonstrate projected patterns of interest at specific locations (Alexandra, Dunedin, Makarora, Omarama, Queenstown) based on the change in the median values of the metrics.

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\(^8\) Note that this is the ‘inverse’ of the number of rain days – i.e., any day that is not a rain day is a dry day
Alexandra
This locality is projected to have up to 44mm more precipitation per year by the end of the century, with around 4 more rain days each year (4 fewer dry days), of slightly greater intensity. However, around 10mm less precipitation is expected over a 5-day period, while 2-3% more of the total annual precipitation is projected to come from very wet days, and up to 5% from extremely wet days. The maximum number of consecutive dry days is projected to decrease by up to 6 days.

Dunedin
Around 40-80mm more precipitation per year is projected for Dunedin (a 5-10% increase, which compares to the projected change calculated by MfE (2008) of a 4% increase – see Box 1 above). Precipitation is projected to come from 1-2 more rain days, and slightly more intense rainfall on average. Between 20-40mm less precipitation is expected over a 5-day period, while 2-3% more of the total annual precipitation is projected to come from very wet days, and up to 2% more from extremely wet days. The maximum number of consecutive dry days is projected to decrease by up to 5 days.

Makarora
Annual precipitation here is projected to increase by 100-450mm, with average intensity increasing by up to 2.5mm per rain day. The maximum number of consecutive wet days is projected to increase by 2-3 days, while the number of very wet days could increase by up to 6 days. Up to 8% more of the total annual precipitation is projected to come from very wet days, and up to 5% from extremely wet days.

Omarama
In Omarama, the projections indicate a drop in the number of wet days of up to 9 days. Up to 5% of the annual precipitation is projected to come from very wet days, and up to 7% from extremely wet days.

Queenstown
This locality is projected to have up to 100mm more precipitation per year by the end of the century (an 11% increase, which compares favourably to the projected change calculated by MfE (2008) of a 12% increase – see Box 1 above). Up to 5 more very wet days are projected per annum, and with slightly greater precipitation intensity (up to 1mm more). Up to 7% of the annual precipitation is projected to come from very wet days, and up to 4% from extremely wet days.
3.2.2. Projected changes in precipitation metrics across Otago

For each of the eleven precipitation metrics we have plotted the average (median) change between the base period (2000-2010) and the last two decades of the century (i.e. the twenty years centred on 2090) for each RCP. This can be interpreted as the change in the metric anomaly over the course of the 21st century. Areas of significant changes (above 90% level of confidence) are indicated by hashed shading. In this section we provide an overview of the results calculated for each of the metrics, with a focus on areas where significant changes are apparent for the average (median) results. Maps for the 5th and 95th percentiles of change as projected by the model runs give further detail on the range of projected change, and are found in Appendix 5.

**Total Annual Precipitation**

Significantly wetter conditions are projected in alpine areas to the west (more than 400 mm increase) and parts of the east coast (up to 70mm increase) for both RCPs (Figure 3.1). RCP8.5 shows a much greater area with significant change to wetter conditions, with a typical increase of 60mm total annual precipitation. An increase of up to 200mm is shown for parts of South Otago. Some inland areas show decreases in total annual precipitation, but this change is not consistent across model runs and is therefore, not statistically significant.

![Figure 3.3: Average change in total precipitation over the 21st century for RCP2.6 and RCP8.5. Hashed areas indicate statistically significant anomalies (90% of model runs agree on the sign of change).](image)

**Annual number of rain days**

Most areas show no significant change in annual number of rain days, under both RCP2.6 and RCP8.5 (Figure 3.2). Under RCP2.6, significant increases of 3-7 rain days per annum are seen in pockets along the east coast and to the North and West of Lake Wanaka.
**Figure 3.4:** Average change in the number of rain days over the 21st century for RCP2.6 and RCP8.5. Hashed areas indicate statistically significant anomalies (90% of model runs agree on the sign of change).

**Simple Daily Intensity Index (SDII)**

SDII is calculated as total annual precipitation divided by the number of rain days – giving a metric for the average daily intensity of rainfall. No significant trends are apparent for RCP8.5, however the general pattern for both RCPs is suggestive of an increased SDII across the region of around 0.5mm per rain-day. Under RCP2.6, small areas on the main divide and around Dunedin show small but significant increases in SDII of up to 2mm more per rain day.

**Figure 3.5:** Average change in the simple day intensity index (SDII) over the 21st century for RCP2.6 and RCP8.5. Hashed areas indicate statistically significant anomalies (90% of model runs agree on the sign of change).
Maximum consecutive wet days

Few areas show a significant change in the maximum number of consecutive wet days. The general pattern for the region is of moderately fewer consecutive wet days, but this change is not consistent between model runs, and should be treated with caution.

![Map of maximum consecutive wet days](image)

**Figure 3.6:** Average change in consecutive wet days over the 21st century for RCP2.6 and RCP8.5. Hashed areas indicate statistically significant anomalies (90% of model runs agree on the sign of change).

Maximum consecutive 5-day precipitation

Under both RCP’s there is little significant change in the annual maximum 5-day consecutive precipitation across most of the region. The exception is the Dunedin area, where a significant decrease of up to around 80mm is seen under both RCPs.
Number of very wet days

RCP 8.5 shows a significant increase of 2-3 very wet days (i.e. those exceeding the 95th percentile of the 30-year average) for much of the region. The far west and south of the region are projected to experience higher numbers of very wet days (increase of 7-10 per annum). A moderate but non-significant decrease in very wet days is indicated for the inland north Otago area. Under RCP2.6, significant increases in the number of very wet days only occur for areas around Lake Wakatipu.

Figure 3.7: Average change in annual maximum 5-day precipitation over the 21st century for RCP2.6 and RCP8.5. Hashed areas indicate statistically significant anomalies (90% of model runs agree on the sign of change).

Figure 3.8: Average change in number of very wet days over the 21st century for RCP2.6 and RCP8.5. Hashed areas indicate statistically significant anomalies (90% of model runs agree on the sign of change).
Percentage of annual precipitation due to very wet days

Under RCP8.5, a greater percentage of annual precipitation is projected to come from very wet days (Figure 3.7). The change is less pronounced and not significant for inland north Otago. Changes under RCP2.6 are more varied and for the most part not significant.

Figure 3.9: Average change in percentage of annual precipitation due to very wet days over the 21st century for RCP2.6 and RCP8.5. Hashed areas indicate statistically significant anomalies (90% of model runs agree on the sign of change).

Number of extremely wet days

The pattern here is consistent with the previous two metrics, where RCP 8.5 shows a significant increase of 1-2 extremely wet days (i.e. those exceeding the 99th percentile of the 30-year average) for much of the region. The far west and south of the region are projected to experience a greater increase in number of extremely wet days (3-4 per annum). No significant change in extremely wet days is indicated for the whole of the north Otago area and eastern areas of Central Otago. There is no consistent and significant trend in any area under RCP2.6.
Figure 3.10: Average change in number of extremely wet days over the 21st century for RCP2.6 and RCP8.5. Hashed areas indicate statistically significant anomalies (90% of model runs agree on the sign of change).

Percentage of annual precipitation due to extremely wet days
Under RCP8.5, the number of extremely wet days is projected to increase (Figure 3.9). The trend is less pronounced and not significant for inland north Otago. However, for RCP2.6 a significant increase in the number of extremely wet days is projected for North Otago, while for other areas no significant change is projected.

Figure 3.11: Average change in percentage of annual precipitation from extremely wet days over the 21st century for RCP2.6 and RCP8.5. Hashed areas indicate statistically significant anomalies (90% of model runs agree on the sign of change).
**Number of dry days**

The anomaly in the number of dry days reflects the change in the total number of rain days per annum (see above). The 50th percentile indicates a moderate but significant decrease of 5-10 dry days per annum in the east of the region for RCP2.6. Similar decreases are seen to the north and west of lake Wanaka. No significant trends are apparent for RCP8.5, however the RCP2.6 maps suggest that these same areas could either get 30-40 fewer dry days (5th percentile) or up to around 5 fewer or 5 more dry days per annum (95th percentile).

![Map showing changes in number of dry days](image_url)

**Figure 3.12**: Average change in number of dry days over the 21st century for RCP2.6 and RCP8.5. Hashed areas indicate statistically significant anomalies (90% of model runs agree on the sign of change).

**Maximum consecutive dry days**

The general pattern for the region is of around 6-12 fewer consecutive dry days per annum. Significant change in the maximum number of consecutive dry days under RCP8.5 is apparent across much of the region to the east of Queenstown and Wanaka (Figure 3.11).
Figure 3.13: Average change in maximum consecutive dry days over the 21st century for RCP2.6 and RCP8.5. Hashed areas indicate statistically significant anomalies (90% of model runs agree on the sign of change).
4. Summary

Precipitation metrics

Nine metrics indicating components of annual precipitation were analysed for updated historic data. The metrics included – total annual precipitation, the number of wet days, the maximum consecutive number of wet days, the maximum precipitation over a 5-day period, the average daily precipitation, the number of days with very high or extreme precipitation, and the proportion of the total annual rainfall coming from very high or extreme precipitation days. An additional two metrics were added to the analysis of projections to capture changes in dryness – these were the number of dry days and the maximum consecutive number of dry days.

Historic precipitation

In this report we update the historic record of the nine metrics between 2004 and 2014/15, following the approach of Mojzisek (2006) to continue his time-series of the data. Results indicate that sites to the east of the region have generally experienced a decrease in total annual precipitation, total number or rain days, and precipitation intensity over the 65-year period from 1951-2015. Localities in western and central regions have generally seen increased total precipitation and precipitation intensity over the period. Consistent relationships are displayed between high phases of both ENSO and SAM (i.e., generally drier conditions) and lower values of the precipitation metrics.

Projected precipitation

This report quantifies the changes and uncertainties in each precipitation metric over the 21st century. Ensembles of precipitation metric projections were generated which emulated the expected range of structural uncertainties in climate models using a statistical approach. Results indicate that much of the region is projected to receive increased total annual precipitation by the end of the 21st century, together with significant changes in many of the other precipitation metrics. However, the patterns are highly variable over both space and time.
Appendix 1: Calculating historic precipitation trends

This section describes the analysis of historic precipitation trends using linear least-squares regression. This method is chosen as it provides a standard, robust and proven statistical method for analyzing multivariate time series data. The resultant fit coefficients obtained from this method allows for analysis of trends and corresponding uncertainties in the time series. We have taken the following approach to analysing the precipitation data.

**Step 1: Detrend and normalize the SAM and ENSO time series**

To detrend each time series (ENSO and SAM), a least-squares regression fit is applied and any resulting linear trend and offset is subtracted from each data point in the time series. This results in a time series with a mean of zero and no linear trend. To normalize the time series, each annual value is divided by the standard deviation of the full time-series – thus giving a value which represents the number of standard deviations that each point is away from the mean. Using a detrended and normalized time series for ENSO and SAM indices means that the trends estimated for each of the metrics (step 2 below) are not influenced by any linear trends which may exist in the underlying ENSO and SAM indices – thus providing a more robust estimation of the trend in the metric.

**Step 2: Carry out multivariate least-squares regression analysis**

To ascertain any linear trend and the influence of SAM and ENSO in each precipitation metric, a least squares regression was carried out of the form:

\[
P_{\text{metric}} = \alpha + \beta \times t + \gamma \times \text{ENSO}' + \delta \times \text{SAM}'
\]

Where:

- \( P_{\text{metric}} \) = calculated annual value in the precipitation metric
- \( \alpha \) = y-intercept
- \( \beta \) = the total trend in the time-series irrespective of its origin
- \( t \) = time in years
- \( \gamma \) = the sensitivity of precipitation to ENSO'
- \( \delta \) = the sensitivity of precipitation to SAM'
- \( \text{ENSO}' \) = the detrended and normalized ENSO/SOI data set
- \( \text{SAM}' \) = the detrended and normalized SAM data set

**Step 3: Estimate uncertainty**

A Monte-Carlo approach was used to estimate the uncertainty in the regression co-efficients, where the residuals from the initial fit are resampled and applied to the regression fit. The same equation is used to calculate a new set of regression coefficients from the resampled time series. By repeating this a number of times (10,000 in this case) we can establish the variability of the regression coefficients (Bodeker and Kremser, 2015).

The regression coefficients and their uncertainty allow for calculation of significance using a two-tailed z-test at the required confidence level for each of the key trend terms above (namely \( \beta \), \( \gamma \) and \( \delta \)). Following the approach of Ummenhofer (2009) we have used a 90% confidence level for our analysis.

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9 A separate regression is carried out for each metric using the SPI only.
Appendix 2: Generating precipitation projections

There are two phases to the generation of these precipitation metrics. First, the quantitative relationship between the change in annual mean global mean surface temperature ($T'_{\text{global}}$) and the change in the chosen precipitation metric is established for a given location. This process forms the “training” phase of the algorithm. This relationship is then applied to emulate a larger number of models using a method based upon climate pattern-scaling in the “application” phase. These processes are described in more detail below.

**Training Phase**

Previous studies of projected precipitation used precipitation which were statistically downscaled to 5 km resolution over New Zealand. Precipitation projections from General Circulation Models (GCM) with a grid spacing of between 1.125° to 3.75° in longitude, and 0.56° to 2.5° in latitude in combination with observations were downscaled to a 0.05° grid (MFE, 2008). Regional Climate Models (RCMs) use a nested grid to provide a finer resolution over a subset of the globe in order to reduce the computational requirement of the model. This RCM is constrained by the global scale changes in climate and chemistry simulated in the GCM, but features the resolution to be able to model orography and land use which impacts the local weather.

This study uses RCM output generated as part of the Climate Change Impacts and Implications programme ([http://ccii.org.nz/](http://ccii.org.nz/)). The RCM uses the Hadley Centre regional climate model (HadRM3-PRECIS) on a 0.27° grid, but is then downscaled to a 0.05° grid (~5km). The model was constrained by specifying sea surface temperatures as boundary conditions. These sea surface temperatures were calculated from 6 different GCMs for 4 different greenhouse gas emissions scenarios giving a total of 24 simulations.

To establish the relationship between the annual mean global mean surface temperature and the change in precipitation metrics under a selected greenhouse gas emissions scenario, a linear least squares regression model is used. This regression model minimises the sum of the squares of the residuals in equation A2.1:

\[
M(y) = \alpha \times T'_{\text{global}}(y) + \beta
\]

Where $M$ is the time series of a metric calculated from an RCM simulation and $T'_{\text{global}}$ is the annual mean global mean surface temperature obtained from the GCM which provided the boundary conditions for the RCM model. This fit is repeated for each of the RCM simulations available for the selected greenhouse gas emissions scenario.

In order to estimate the uncertainty for each of the fit coefficients obtained above, a bootstrapping approach is used (Bodeker and Kremser, 2015) whereby the residuals from the regression fit are rearranged randomly and added to the initial fit to create a new time series. This time series has the same underlying structure, but with different random noise. The regression model is now rerun to obtain a new set of regression coefficients. This is performed a number of times to estimate the uncertainty of the regression coefficients.

**Application Phase**

With the relationship between $T'_{\text{global}}$ and the precipitation metric of choice established, climate pattern scaling can be used to provide a computationally efficient mechanism for emulating different model responses. Climate pattern scaling is a methodology to generate projections...
of possible climates that have not been simulated by full GCMs, but can be quickly simulated by simpler (and computationally faster to run) climate models. Simple climate models, such as MAGICC (Model for Assessment of Greenhouse-gas Induced Climate Change (Meinshausen et al 2011a, and Meinshausen et al 2011b) can be used to generate T′
global_MAGICC time series. MAGICC can be calibrated to emulate the behaviour of 19 different AOGCMs (Meehl et al 2007) and 10 carbon cycle models (Friedlingstein et al 2006). The resultant 190 different ‘tunings’ for MAGICC can be used to generate 190 equally probable T′
global_MAGICC time series that provide some representation of the spread in T глоб_Magicc that can result from running 190 different configurations of GCMs.

Residuals and autocorrelation

A projection of the metric of interest, X, can be established using the following equation:

\[(A2.2) \quad X(y) = \alpha \times T_{global\_MAGICC}(y, tune) + \beta_{2000-2010} + R\]

Where \(\alpha\) is chosen randomly from the values calculated in the “training” phase, \(T_{global\_MAGICC}\) is chosen randomly from the 190 time series generated using MAGICC, \(\beta_{2000-2010}\) is the mean of the precipitation metric between 2000-2010 obtained from the reconstructed historic precipitation data set for the location of interest. \(R\) is a synthetic set of residuals for the time series which has the same mean, standard deviation and autocorrelation (similarity between observations as a function of the time lag between them) as a random set of residuals from the first fit to equation A2.1 from the training of the model (i.e., so the synthetic time series emulates the same properties (variance or noise) as the original data).

RCM simulations may have different biases compared to the historical data set. RCMs can model the change in precipitation well, but may not accurately model the absolute value of precipitation well as each RCM simulation has a different offset compared to the historical metrics. Therefore, a fixed offset obtained from historical values was used instead of \(\beta\) values (equation A2.1) to model the divergence of the precipitation from the historical mean, predicted by the climate models.
Appendix 3: Projected precipitation by location

**Table A4.1:** Summary of the differences in the median values (50th percentile) for each metric for each RCP for selected Otago locations between the start and end of the 21st century.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Scenario</th>
<th>Alexandra</th>
<th>Balclutha</th>
<th>Dunedin</th>
<th>Gore</th>
<th>Invercargill</th>
<th>Kakanui</th>
<th>Lakeside</th>
<th>Luggate</th>
<th>Mataura</th>
<th>Mosgiel</th>
<th>Oamaru</th>
<th>Omarama</th>
<th>Queenstown</th>
<th>Ranfurly</th>
<th>Taiaroa</th>
<th>Taieri Mouth</th>
<th>Wanaka</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Annual Precipitation</td>
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<td>8.3</td>
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This represents the difference between the average for the first 20-year period of the century (centred on 2010) and the last 20-year period of the century (centred on 2090).
**Charts for each location**

The following charts show the projected trend in each metric for RCP 2.6 (upper, blue) and RCP 8.5 (lower, red) for each location. Each panel shows the median (solid green line), the 25-75th percentile range (dark shading) and the 5-95th percentile range (light shading) of the projection. An estimated 10-year rolling average for indicative historic values (blue line) is included for the 2000-2015 period.

For each location the projections are organised alphabetically according to the short name for each metric as shown below.

- CDD – Consecutive Dry Days
- CWD – Consecutive Wet Days
- DD1 – Number of Dry Days
- PRCPTOT – Total Annual Precipitation
- R95p – Number of Wet days
- R95pTOT – Precipitation Fraction Due to Wet Days
- R99p – Number of Extremely Wet Days
- R99pTOT – Precipitation Fraction Due to Extremely Wet Days
- RR1 – Number of Wet Days
- Rx5day – Highest 5-day Precipitation Amount
- SDII – Simple Daily Intensity Index

**Alexandra**

![Charts for Alexandra](image-url)
Makarora
Oamaru

Projections of annual CDD for Oamaru

Projections of annual CWD for Oamaru

Projections of annual DD1 for Oamaru

Projections of annual PREPTOT for Oamaru

Projections of annual R95p for Oamaru

Projections of annual R95p/TOT for Oamaru
Ranfurly

Projections of annual CDD for Ranfurly

Projections of annual CWD for Ranfurly

Projections of annual DD1 for Ranfurly

Projections of annual PRCPTOT for Ranfurly

Projections of annual R95p for Ranfurly

Projections of annual R95pTOT for Ranfurly
Wanaka

Projections of annual CDD for Wanaka

Projections of annual CWD for Wanaka

Projections of annual DO1 for Wanaka

Projections of annual PRCTOT for Wanaka

Projections of annual P95p for Wanaka

Projections of annual P95pTOT for Wanaka
Appendix 4: Precipitation projections for the Otago region

The maps below show the values of the 5th, 50th and 95th percentiles of the projected change in each metric between the base period (2000-2010) to the period covering 2080-2100 (centered on 2090) for each RCP. The scale indicates the lower band of the contour range (i.e, for total precipitation, the lowest band captures -825 to -120mm).

The hashed areas are the same percentiles within each RCP and indicate where a significant average anomaly exists for that RCP. A significant trend is where at least 90% of projected anomalies (generated through the RCM – MAGICC process) have the same sign. Seen another way, a trend is not significant if more than 10% of the anomalies have the opposite sign to the average anomaly.
Number of Very Wet Days

RCP2.6

RCP8.5

5%

Queenstown
Alexandra
Oamaru
Dunedin
Balclutha

10%

Wanaka
Queenstown
Alexandra
Oamaru
Dunedin
Balclutha

95%

Wanaka
Queenstown
Alexandra
Oamaru
Dunedin
Balclutha
Precipitation Fraction from Very Wet Days (95th percentile)

RCP2.6

RCP8.5

Significant
Percent

-21.01
-8.56
-5.35
-1.96
0.49
1.78
2.82
3.67
4.63
6.16
7.51
8.46
9.43
10.68
12.51
15.26
References


