Climate change impacts on New Zealand hydro catchment inflows & wind speeds

- **2020-2050 adjustments to wind and hydro records for electricity modelling purposes**
- **a report to MBIE**

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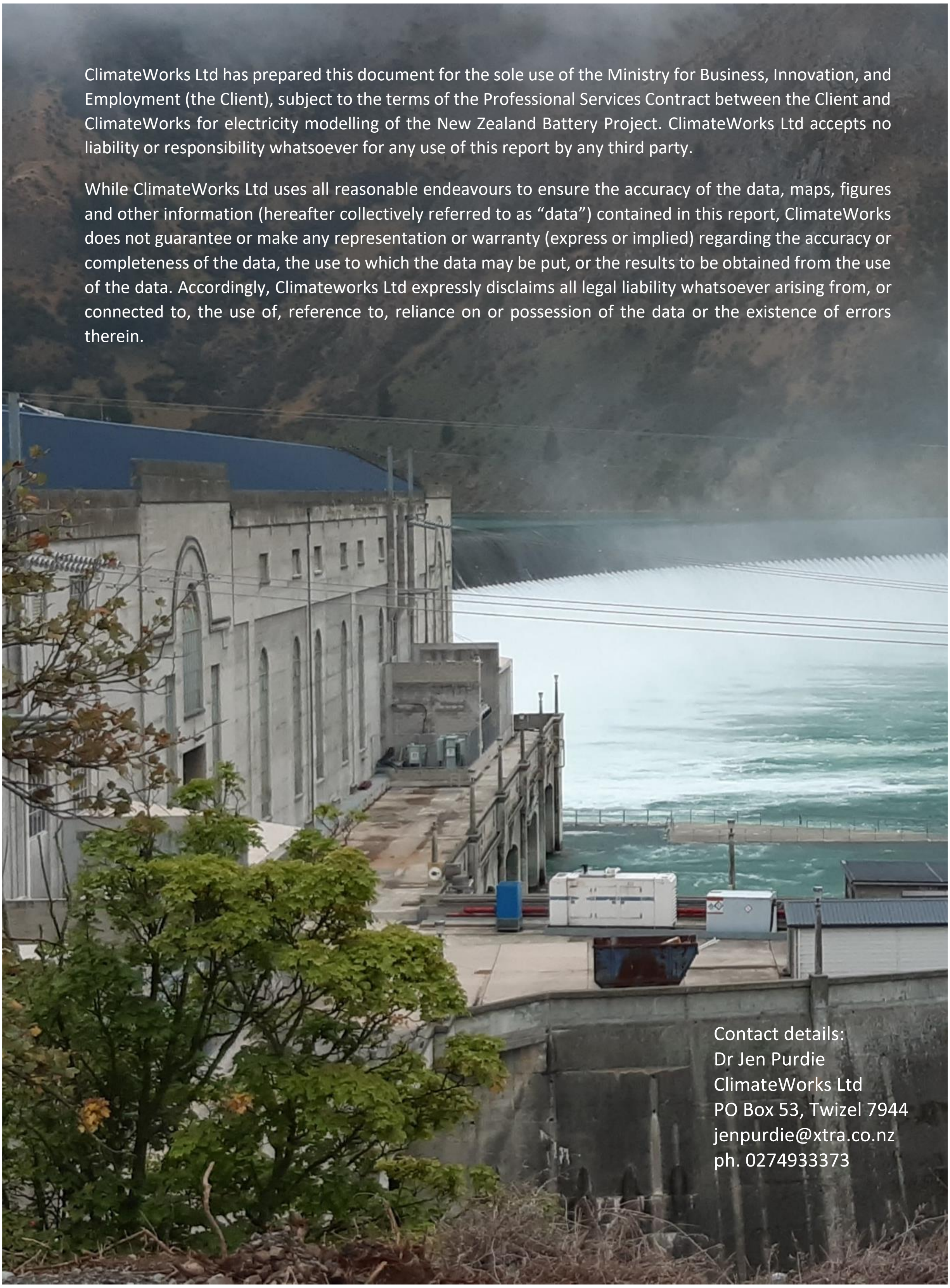

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Executive summary

Climate change is affecting water resources internationally, and the decarbonisation imperative is resulting in increasing levels of intermittent renewable electricity globally. Electricity demand is also predicted to increase as electrification of transport and industry increases. These factors will have significant impacts on the management of renewable electricity generation. Incorporating knowledge of future changes to wind speeds and water resources under climate change into electricity systems modelling is important as we transition to a 100% renewable electricity future.

In New Zealand, where 55% of electricity currently comes from hydro generation, rainfall in the major South Island hydro lakes is expected to increase in coming decades. The seasonality and volatility of that rainfall is also expected to change. Wind speeds over New Zealand are also expected to increase as atmospheric circulation changes occur over time.

This report outlines research which uses a change factor methodology linked to a model cascade to estimate changes to hydro catchment inflows in 12 regions of New Zealand where electricity is generated from river and lake inflows. A similar methodology is employed to estimate changes to wind resource over time in 12 different regions of New Zealand where wind farms are likely to be located in coming decades.

This report was written for MBIE’s New Zealand Battery Project, to assist in their electricity system modelling by providing change factors to historical hydro lake inflows and wind capacity records to represent changes that are likely to occur between current conditions and 2050 conditions. These change factors can be found in Tables 2 and 3.

The results of this modelling, when applied to long term river flow records, show an overall 2% increase in annual hydro catchment inflows over New Zealand between 2020 and 2050. Seasonal impacts are projected to be larger, with total New Zealand hydro catchment inflows projected to be 10% higher in winter and 6% lower in summer by 2050. These seasonal changes are larger in the snow-fed catchments in the South Island, where significant reductions to snow storage are predicted in coming decades. Winter inflows in these catchments are expected to increase by 15 to 26% by mid-century. Summer inflows are expected to decrease by 1 to 10% over this period, with a 4-6% increase in annual flows. These changes are commensurate with other similar studies in the region.

Nationally, annual average wind speeds are predicted to increase in the south of the South Island by mid-century, with the largest annual average change being in Otago (4.2%). In the north of the North Island they are expected to decrease over time, with the biggest annual average reduction in wind speed by mid-century predicted to occur in Auckland (-2.8%). Winter and spring wind speeds in New Zealand are predicted to increase by mid-century, with Summer and Autumn wind speeds expected to decrease.

For both hydro and wind changes out to 2050, the greatest projected impacts are not in annual volume changes, (all of which remain below 5%) but in changes to the seasonal distribution of the arrival of renewable energy “fuel”. These changes are generally in a beneficial direction, moving “fuel” from summer arrival now, when it is less needed for generation, to winter arrival in future, when it is more needed. This has significant implications for electricity generation, where the current hydro inflows are anti-correlated with demand.

Contents

1. Introduction

1.1 Climate change

Projected changes to temperatures and rainfall as a result of climate change have been well documented globally (IPCC 2021), and in New Zealand (Ackerly et al 2012, MfE 2018). The impacts of climate change on water resources are highly spatially varied globally, with some areas expected to receive less rainfall and others more in future (Shu et al 2018). Generally, New Zealand is expected to get wetter in the West and South over time, and drier in the North and East (MfE 2018). Temperatures are expected to increase between 0.7 and 1 degree Celsius by mid-century, relative to 1986-2005 (MfE 2018).

Seasonal changes to runoff regimes will be particularly noticeable in future in mountainous regions with significant glacier and snow cover, as changes to both temperature and precipitation are predicted to impact snow cover extent, and therefore melt regimes (Bombelli et al 2018, Soncini et al 2016). Climate change in snow fed catchments is likely to influence both the timing and magnitude of runoff. Many rivers in New Zealand are significantly impacted by snow melt, and in particular the large hydro catchments in the South Island. Snow cover extent in these catchments is projected to reduce by approximately 20% by the 2040s, and 40% to 80% by the 2090s (Hendrikx et al 2012).

A phenomenon of reducing wind speeds internationally called “global stilling” has been observed since the 1980s, but has been noted to have changed direction about a decade ago, and projections are generally for increased wind speeds in future (Kim & Paik 2015, Zeng et al 2019). The impacts of climate change on wind speeds are still an area of active research, and changes to wind speeds are expected to be spatially diverse (Moemken et al 2018, Chang et al 2015). Potential changes to wind speeds, combined with the expected large growth in wind capacity globally, results in a growing need to understand likely changes in wind resource. The error surrounding projections of wind from Global Circulation Models and downscaling from Regional Climate Models is higher than for rainfall or temperature projections (Solaun & Cerda 2019). Despite this, they are still the most trusted source for projections (Fant & Strzepek 2019). Less research has been published on wind projections in New Zealand than on rainfall and temperature projections.

1.2 Energy

Energy production in hydro catchments globally has been shown to decrease under climate change in parts of the world, due to decreases in rainfall, while other studies have projected increases to production (Bombelli et al 2018, Vliet et al 2016). Seasonal changes to energy generation due to seasonal changes in streamflow under climate change have also been projected (Vicuna et al 2011, Savelsberg et al 2018), and changes to wind energy capacity due to changes in wind speeds is projected (Carvalho et al 2017, Chang et al 2015, Moemken et al 2018, Tobin et al 2015).

This report conveys the results of research that has been conducted to quantify the expected changes to wind and hydro lake inflows in New Zealand between 2020 and 2050, for electricity modelling purposes. The report was commissioned by MBIE’s New Zealand Battery Project. The research outlined here was begun at Meridian Energy Ltd, and is being continued at the University of Otago, under the project: “Simulation of climate change impacts on the New Zealand energy system”, a Deep South Science Challenge funded project (MBIE contract number C01X19011).

2. Hydro lake inflow projections

In this study a modelling chain is applied, which is based on the combined use of Global Circulation Model (GCM) and Regional Climate Model (RCM) output of rainfall projections (Ackerley et al 2012), snow model output of melt estimates (Fitzharris & Garr 1995), projections of changes to snow water equivalent in the New Zealand mountains under climate change (Hendrikx et al 2012), and a Change Factor Model (CFM) to predict lake inflows. This chain of models is used to project changes to hydro catchment inflows in twelve hydrological regions around New Zealand, for each week, for the period 2020-2050.

2.1 Methodology

2.1.1 Study Area

LPCon (Meridian Energy owned electricity system model licensed to University of Otago for use) synthesises generation from forty different hydro electricity generation stations, but for modelling purposes each station is allotted to one of twelve distinct hydrological regions throughout New Zealand. The twelve hydrological regions can be seen in figure 1. The term "RoR" denotes "run of river", which generally denotes a region with run of river hydro stations, and little hydro storage.

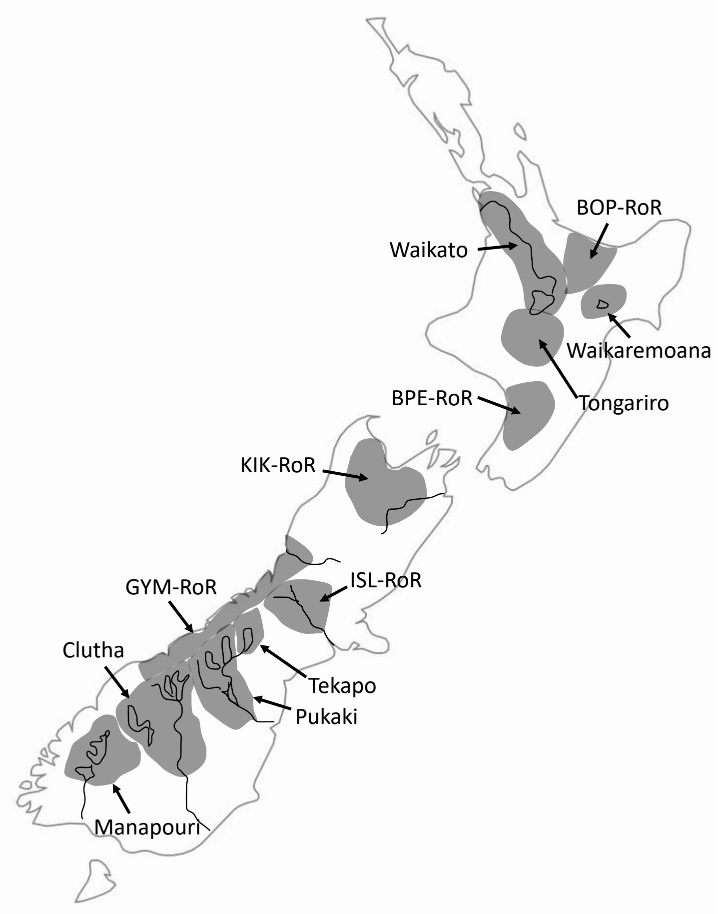


Figure 1: Locations of the 12 New Zealand hydro catchment regions used in this study

Some LPCon regions used projections from more than one National Institute of Water and Atmosphere (NIWA) region. In these cases NIWA projections from constituent regions are averaged to create LPCon region rainfall projections. This methodology acknowledges the spatial coherence of river flow records within regions, and also the regional nature of projected climate change impacts. Each of the 12 regions has an 87 year history of observed hydrological flows.

2.1.2 Rainfall changes

The International Panel on Climate Change (IPCC) uses five Shared Socioeconomic Pathways (SSPs 1-5) to represent the impact on the climate from low (1) to high (5) emissions pathways. The Sixth Assessment Report (AR6) (IPCC 2021) scientific literature denotes SSP2 as the most likely scenario. This pathway has a radiative forcing of 4.5 Wm^{-2} (equivalent to Representation Concentration Pathway (RCP) 4.5 from IPCC (2013) and IPCC (2014)) and a projected temperature range by end of century of 2.5-2.7 degC above pre-industrial levels. This study uses this “most likely” middle of the road scenario as the basis for river flow projections, and refers to it in this document as “RCP4.5”.

To estimate the impact of climate change on New Zealand, NIWA derives data from six GCMs, for the four RCPs, as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (IPCC 2013). The global models have a resolution of approximately 100-300km, and GCM output variables are downscaled initially with the HadRM3P regional atmosphere model (resolution ~27km) (Ackerley et at 2012, Sood and Mullan 2020). This process produces projections of such variables as rainfall and temperature out to 2100, to enable the closer examination of the regional impacts of climate change (MfE 2018, NIWA 2022).

2.1.3 Snow melt changes

Snow accumulation and melt is modelled using Snowsim, a model that calculates seasonal snow accumulation and ablation in the Southern Alps, New Zealand (Fitzharris and Garr 1995). The model is based on daily temperature and precipitation data from long-established climate stations proximal to the Southern Alps. Output is given as a daily specific net balance of Snow Water Equivalent (SWE) stored at five elevation bands from 1000 to >2200 metres over several major river catchments. Daily decreases to modelled storage of snow water equivalent are used as daily melt estimates for this study for the snow-fed catchments of the Waitaki, Clutha, and Waiau rivers.

Recent estimates (1998-2018) of daily melt (in GWh) from Snowsim at different times of the year for the Waitaki catchment are used as the baseline measure of snow melt in the catchment. Under climate change, some of the water that would historically have melted from the snowpack in summer will appear as throughflow in winter instead. Using the average estimate of a 25% reduction in snow water equivalent (SWE) by 2050 (from Hendrik et al 2012), 25% of modelled melt water is redistributed from summer melt water to winter throughflow in the projected 2050 inflow record. The water is subtracted from the historical inflow record proportionate to the rate it would have melted (in summer), and redistributed to the 2050 projected inflows proportionate to the rate it would have accumulated in the recent past (in winter).

South Island glacial ice melt input to hydro lake inflows is predicted to remain fairly constant in coming decades (Anderson et al 2021), so is not explicitly accounted for here.

2.1.4 Floods

Flood volumes in New Zealand's Southern Alps are expected to increase in coming decades, but significant uncertainty exists around the magnitude of these changes (MfE 2018). An increase of 1 degC of a parcel of air results in an 8% increase in moisture carrying ability of that air (MfE 2008). In addition to this thermal forcing, dynamic forcing is likely with increased wind speeds, projected in coming decades (MfE 2018), expected to enhance orographic uplift and spillover over the Southern Alps (Sinclair et al 1997).

The combined result of the above climate change forcing is that larger extreme rain volumes are expected in the headwaters of the South Island hydro catchments in future, and therefore bigger floods are expected in the Waitaki catchment in coming decades (MfE 2008, Collins 2020). A recommended conservative estimate for modelling purposes (MfE 2010) is that most rain events are likely to be 8% larger under a 1 degree warming from current temperatures, which is expected by mid-century (MfE 2010). This methodology is adopted for this study, and the historical inflow records are adapted for 2050 conditions by increasing peaks and rising and falling limbs of flood hydrographs by 8%, as a 1 degree temperature increase over recent antecedent conditions is expected by 2050 (MfE 2018).

Generally, little change in drought depth or duration is expected in New Zealand's largest hydro catchments over the next 3 decades (MfE 2018) (although drier conditions ARE projected in parts of the East Coast and Northland in the future). Therefore low flows in the hydro catchments are not particularly adjusted for, except for the mean flow adjustments already discussed.

2.1.5 Model cascade methodology

A model cascade is employed to encapsulate climate change impacts in the 2050 projected inflow record for each regional dataset. This process is outlined in figure 2.

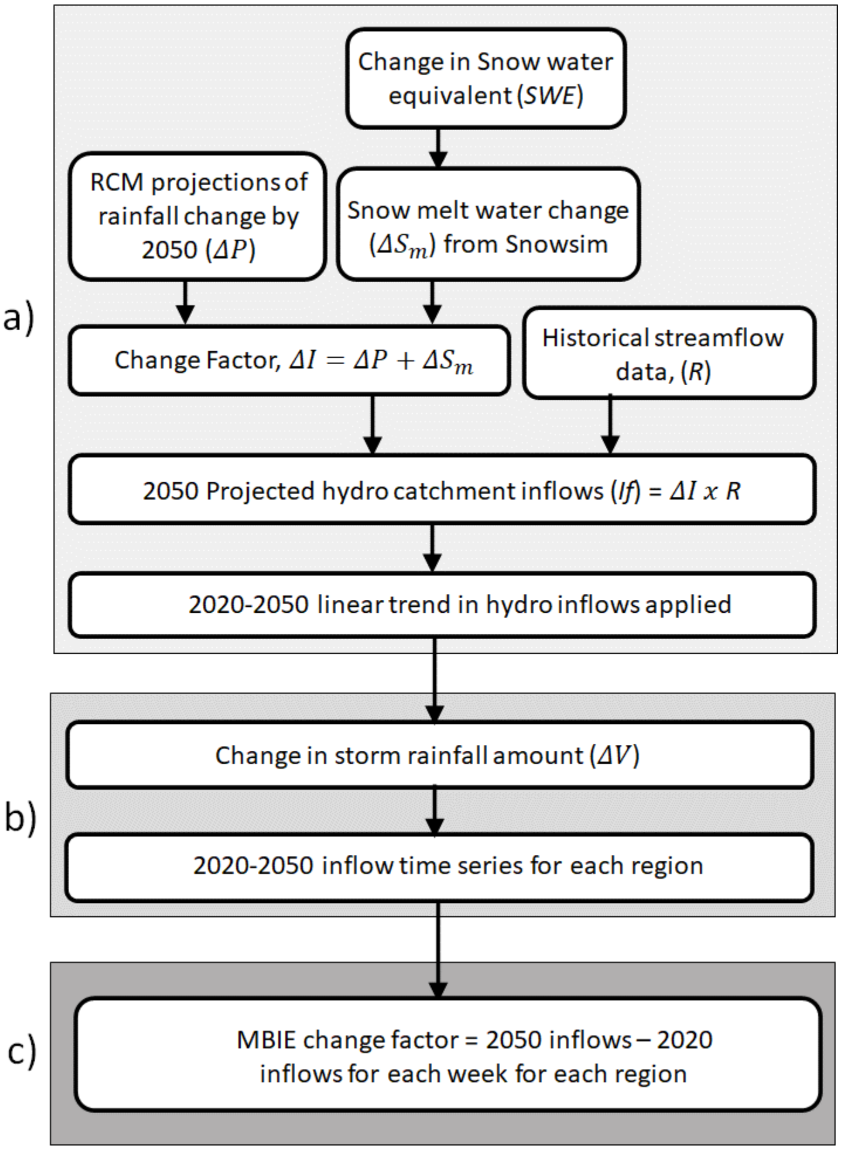


Figure 2: the model cascade for determining projected 2050 hydro catchment inflows for input to the LPCon, and the electricity system inputs and outputs, for each hydro catchment region, for each week of the year. a) is the process to capture seasonal and annual changes to inflows, b) is the process to capture increased short term rainfall amounts, and c) is the conversion from a 30 year hydro catchment inflow time series to a change factor that MBIE can apply to their own river flow records.

a) seasonal and annual changes to inflows from rainfall and snow melt:

Firstly, multiplicative change factors are used to encapsulate the seasonal and annual changes to inflows from projected changes to rainfall and snow melt. These are calculated using the following general equations, for each region and each week of the 2050 year (relative to recent history):

$$CF(\Delta I)_i = \frac{Future_i}{Base_i} \qquad \text{(Eq. 1)}$$

$$If_i = CF(\Delta I)_i \times R_i \qquad \text{(Eq. 2)}$$

where $CF(\Delta I)_i$ is the multiplicative change factor (in this case change in inflows, ΔI), for the ith time step (week) in the future time period, which is a ratio calculated from the difference between the future value and the base value for each constituent variable (in this case, seasonal rainfall (ΔP) and snow melt (ΔS_m), summed). If_i is future (2050) inflow for the ith time step (week), and R_i is the recent historical average inflow (adapted from Hansen 2017).

b) increased rainfall amounts:

Secondly, increased volatility is incorporated to represent projected increases to rainfall events. A representation of projected changes to flood peaks is important to assess the ability of the hydro storage lake to capture and store inflows, and to optimise generation and minimise spill in future. However, adjustments to annual and seasonal changes to rainfall and snow melt have already been addressed in step a). Therefore when 2050 inflow events are increased by 8% relative to the historical record, a corresponding amount is taken out of the inflow "troughs", so that seasonal and annual totals are not changed again. An example of a one year period (2020-2021) of the weekly Lake Pukaki inflow record with adjustments applied can be seen in figure 3.

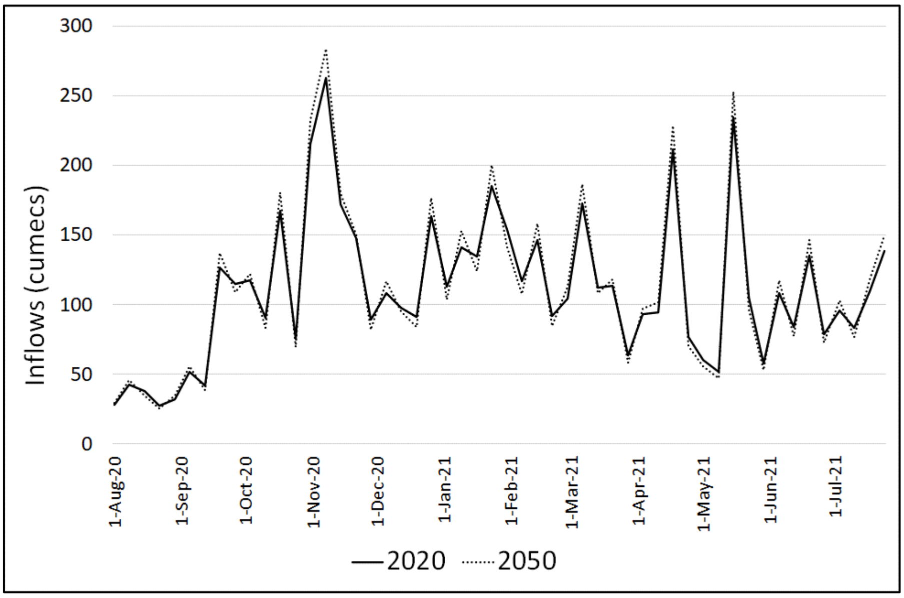


Figure 3: Lake Pukaki weekly mean inflows (cumecs) Aug 2020 to July 2021, and inflows adjusted to make inflow peaks 8% larger (and troughs 8% smaller)

These 8% changes are applied to the 2050 weekly record. A linear trend is applied to adapt the 2020-2050 record, from 0% change in volatility in 2020, to 8% change by 2050, for each region.

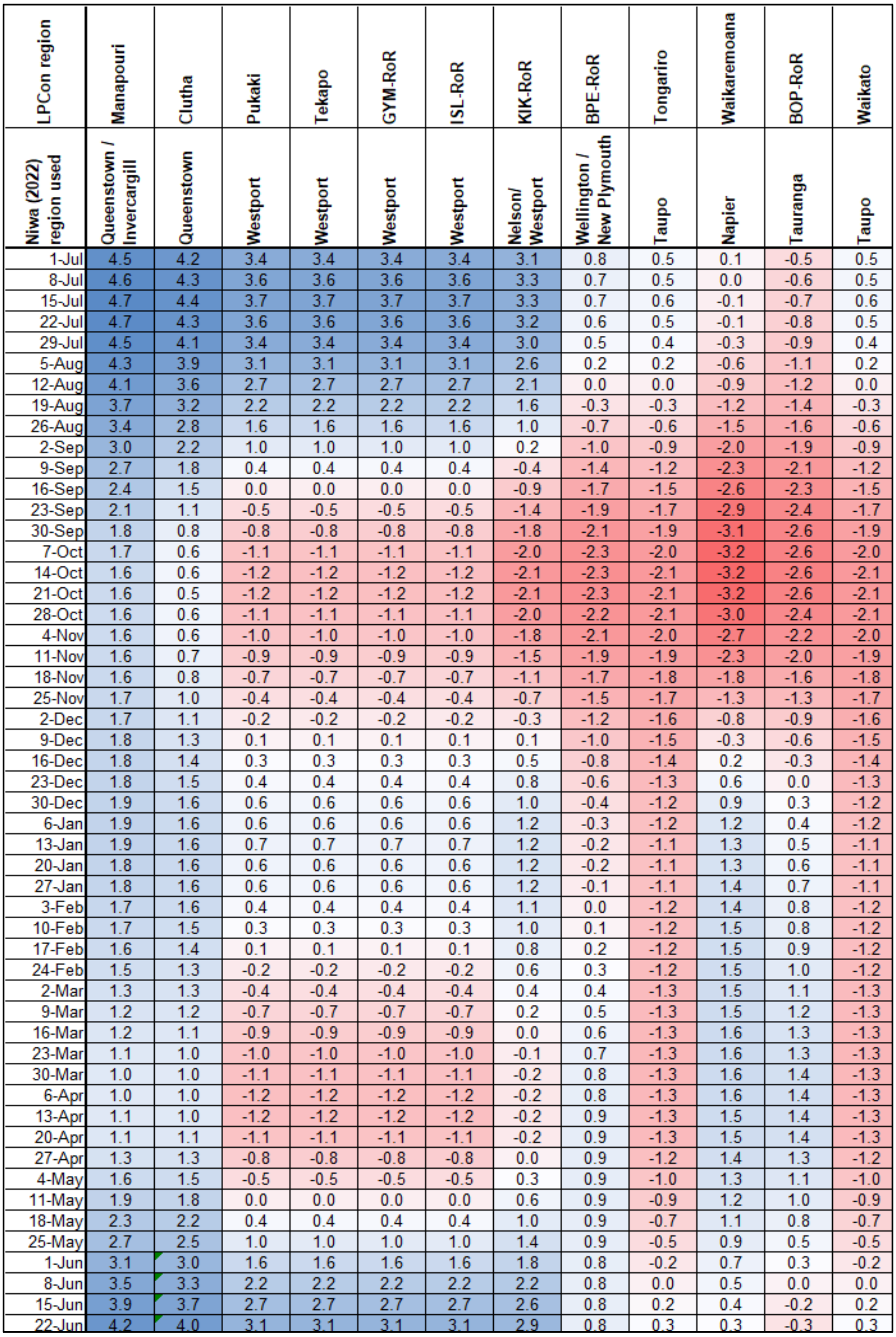
It should be noted that the only change to annual volume of water into catchments is precipitation changes from RCM projections. Changes to volatility and snow melt simply redistribute catchment inflows in time. However, this redistribution in time is particularly important in relation to electricity generation modelling, as hydro storage capacity is limited, flood events are optimally captured in storage rather than spilled, and seasonal hydro inflows are currently anti-correlated with demand, with peak inflows occurring in summer and peak demand occurring in winter.

2.2 Results

2.2.1 Rainfall projections

Rainfall changes for each region, for each week of 2050 relative to 2020, can be seen in Table 1.

Table 1: Change in rainfall (%) in each of the LPCon regions 2020 – 2050, and their constituent rainfall projection region from NIWA 2022.



LPCon region	**Manapouri**	**Clutha**	**Pukaki**	**Tekapo**	**GYM-RoR**	**ISL-RoR**	**KIK-RoR**	**BPE-RoR**	**Tongariro**	**Waikaremoana**	**BOP-RoR**	**Waikato**
Niwa (2022) region used	**Queenstown / Invercargill**	**Queenstown**	**Westport**	**Westport**	**Westport**	**Westport**	**Nelson/ Westport**	**Wellington / New Plymouth**	**Taupo**	**Napier**	**Tauranga**	**Taupo**
1-Jul	4.5	4.2	3.4	3.4	3.4	3.4	3.1	0.8	0.5	0.1	-0.5	0.5
8-Jul	4.6	4.3	3.6	3.6	3.6	3.6	3.3	0.7	0.5	0.0	-0.6	0.5
15-Jul	4.7	4.4	3.7	3.7	3.7	3.7	3.3	0.7	0.6	-0.1	-0.7	0.6
22-Jul	4.7	4.3	3.6	3.6	3.6	3.6	3.2	0.6	0.5	-0.1	-0.8	0.5
29-Jul	4.5	4.1	3.4	3.4	3.4	3.4	3.0	0.5	0.4	-0.3	-0.9	0.4
5-Aug	4.3	3.9	3.1	3.1	3.1	3.1	2.6	0.2	0.2	-0.6	-1.1	0.2
12-Aug	4.1	3.6	2.7	2.7	2.7	2.7	2.1	0.0	0.0	-0.9	-1.2	0.0
19-Aug	3.7	3.2	2.2	2.2	2.2	2.2	1.6	-0.3	-0.3	-1.2	-1.4	-0.3
26-Aug	3.4	2.8	1.6	1.6	1.6	1.6	1.0	-0.7	-0.6	-1.5	-1.6	-0.6
2-Sep	3.0	2.2	1.0	1.0	1.0	1.0	0.2	-1.0	-0.9	-2.0	-1.9	-0.9
9-Sep	2.7	1.8	0.4	0.4	0.4	0.4	-0.4	-1.4	-1.2	-2.3	-2.1	-1.2
16-Sep	2.4	1.5	0.0	0.0	0.0	0.0	-0.9	-1.7	-1.5	-2.6	-2.3	-1.5
23-Sep	2.1	1.1	-0.5	-0.5	-0.5	-0.5	-1.4	-1.9	-1.7	-2.9	-2.4	-1.7
30-Sep	1.8	0.8	-0.8	-0.8	-0.8	-0.8	-1.8	-2.1	-1.9	-3.1	-2.6	-1.9
7-Oct	1.7	0.6	-1.1	-1.1	-1.1	-1.1	-2.0	-2.3	-2.0	-3.2	-2.6	-2.0
14-Oct	1.6	0.6	-1.2	-1.2	-1.2	-1.2	-2.1	-2.3	-2.1	-3.2	-2.6	-2.1
21-Oct	1.6	0.5	-1.2	-1.2	-1.2	-1.2	-2.1	-2.3	-2.1	-3.2	-2.6	-2.1
28-Oct	1.6	0.6	-1.1	-1.1	-1.1	-1.1	-2.0	-2.2	-2.1	-3.0	-2.4	-2.1
4-Nov	1.6	0.6	-1.0	-1.0	-1.0	-1.0	-1.8	-2.1	-2.0	-2.7	-2.2	-2.0
11-Nov	1.6	0.7	-0.9	-0.9	-0.9	-0.9	-1.5	-1.9	-1.9	-2.3	-2.0	-1.9
18-Nov	1.6	0.8	-0.7	-0.7	-0.7	-0.7	-1.1	-1.7	-1.8	-1.8	-1.6	-1.8
25-Nov	1.7	1.0	-0.4	-0.4	-0.4	-0.4	-0.7	-1.5	-1.7	-1.3	-1.3	-1.7
2-Dec	1.7	1.1	-0.2	-0.2	-0.2	-0.2	-0.3	-1.2	-1.6	-0.8	-0.9	-1.6
9-Dec	1.8	1.3	0.1	0.1	0.1	0.1	0.1	-1.0	-1.5	-0.3	-0.6	-1.5
16-Dec	1.8	1.4	0.3	0.3	0.3	0.3	0.5	-0.8	-1.4	0.2	-0.3	-1.4
23-Dec	1.8	1.5	0.4	0.4	0.4	0.4	0.8	-0.6	-1.3	0.6	0.0	-1.3
30-Dec	1.9	1.6	0.6	0.6	0.6	0.6	1.0	-0.4	-1.2	0.9	0.3	-1.2
6-Jan	1.9	1.6	0.6	0.6	0.6	0.6	1.2	-0.3	-1.2	1.2	0.4	-1.2
13-Jan	1.9	1.6	0.7	0.7	0.7	0.7	1.2	-0.2	-1.1	1.3	0.5	-1.1
20-Jan	1.8	1.6	0.6	0.6	0.6	0.6	1.2	-0.2	-1.1	1.3	0.6	-1.1
27-Jan	1.8	1.6	0.6	0.6	0.6	0.6	1.2	-0.1	-1.1	1.4	0.7	-1.1
3-Feb	1.7	1.6	0.4	0.4	0.4	0.4	1.1	0.0	-1.2	1.4	0.8	-1.2
10-Feb	1.7	1.5	0.3	0.3	0.3	0.3	1.0	0.1	-1.2	1.5	0.8	-1.2
17-Feb	1.6	1.4	0.1	0.1	0.1	0.1	0.8	0.2	-1.2	1.5	0.9	-1.2
24-Feb	1.5	1.3	-0.2	-0.2	-0.2	-0.2	0.6	0.3	-1.2	1.5	1.0	-1.2
2-Mar	1.3	1.3	-0.4	-0.4	-0.4	-0.4	0.4	0.4	-1.3	1.5	1.1	-1.3
9-Mar	1.2	1.2	-0.7	-0.7	-0.7	-0.7	0.2	0.5	-1.3	1.5	1.2	-1.3
16-Mar	1.2	1.1	-0.9	-0.9	-0.9	-0.9	0.0	0.6	-1.3	1.6	1.3	-1.3
23-Mar	1.1	1.0	-1.0	-1.0	-1.0	-1.0	-0.1	0.7	-1.3	1.6	1.3	-1.3
30-Mar	1.0	1.0	-1.1	-1.1	-1.1	-1.1	-0.2	0.8	-1.3	1.6	1.4	-1.3
6-Apr	1.0	1.0	-1.2	-1.2	-1.2	-1.2	-0.2	0.8	-1.3	1.6	1.4	-1.3
13-Apr	1.1	1.0	-1.2	-1.2	-1.2	-1.2	-0.2	0.9	-1.3	1.5	1.4	-1.3
20-Apr	1.1	1.1	-1.1	-1.1	-1.1	-1.1	-0.2	0.9	-1.3	1.5	1.4	-1.3
27-Apr	1.3	1.3	-0.8	-0.8	-0.8	-0.8	0.0	0.9	-1.2	1.4	1.3	-1.2
4-May	1.6	1.5	-0.5	-0.5	-0.5	-0.5	0.3	0.9	-1.0	1.3	1.1	-1.0
11-May	1.9	1.8	0.0	0.0	0.0	0.0	0.6	0.9	-0.9	1.2	1.0	-0.9
18-May	2.3	2.2	0.4	0.4	0.4	0.4	1.0	0.9	-0.7	1.1	0.8	-0.7
25-May	2.7	2.5	1.0	1.0	1.0	1.0	1.4	0.9	-0.5	0.9	0.5	-0.5
1-Jun	3.1	3.0	1.6	1.6	1.6	1.6	1.8	0.8	-0.2	0.7	0.3	-0.2
8-Jun	3.5	3.3	2.2	2.2	2.2	2.2	2.2	0.8	0.0	0.5	0.0	0.0
15-Jun	3.9	3.7	2.7	2.7	2.7	2.7	2.6	0.8	0.2	0.4	-0.2	0.2
22-Jun	4.2	4.0	3.1	3.1	3.1	3.1	2.9	0.8	0.3	0.3	-0.3	0.3

As the table generally moves from south (left of table) to north (right of table). It can be seen that rainfall generally gets wetter in the South and West over time, and drier in the North and East. The biggest seasonal shifts in rainfall occur in the Pukaki, Tekapo, GYM-RoR and ISL-RoR regions (drier in spring and autumn, and wetter in winter), as well as the Waikaremoana and BOP-RoR regions (drier in spring, wetter in autumn). The biggest absolute change is a 4.7% increase in July rainfall in the Manapouri catchment by 2050, and the biggest negative change is a move to 3.2% drier in Waikaremoana in spring.

2.2.2 Snow melt projections

Snow melt adjustments are needed for the Waitaki (Pukaki, Tekapo), Clutha, and Waiau regions, because these regions have a non-negligible portion of annual lake inflows derived from snow melt (McKerchar et al 1998, Kerr 2013). Other regions did not need adjustments for snow melt changes, as it is assumed there is negligible or no snow melt portion to inflows.

Figure 4 shows the average modelled snow accumulation and ablation rates from Snowsim for the Waitaki catchment. These rates of accumulation and ablation are used to redistribute the snow melt water in the modelling.

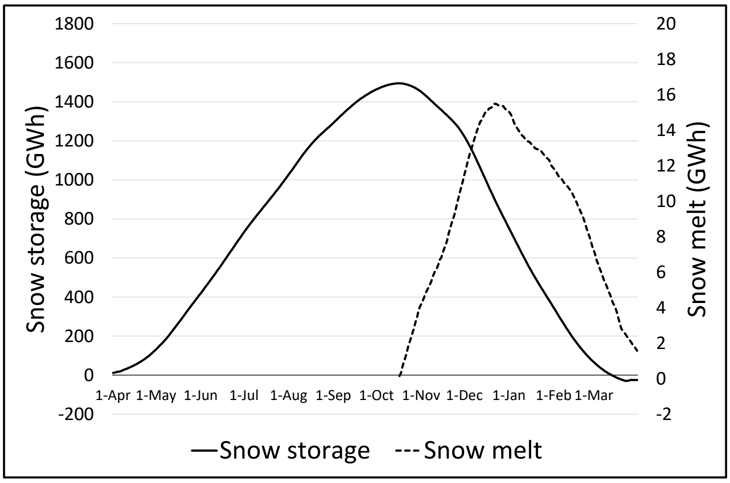


Figure 4: average modelled snow storage (solid line) and melt (dashed line) rates for the Waitaki catchment, 1998-2018, from Snowsim, in GWh.

Following Hendrikx et al (2012) projections of changes to snow pack over time, twenty-five percent of snow melt in the Waitaki, Clutha, and Waiau catchments is subtracted from the historical inflow record proportionate to the rate it would have melted, and redistributed to the 2050 projected inflows proportionate to the rate it would have accumulated in the recent past. This adjustment results in rain water flowing through into the hydro lakes in winter rather than in summer. The proportion of snow melt redistributed in each of the snow fed catchments is shown in figure 5.

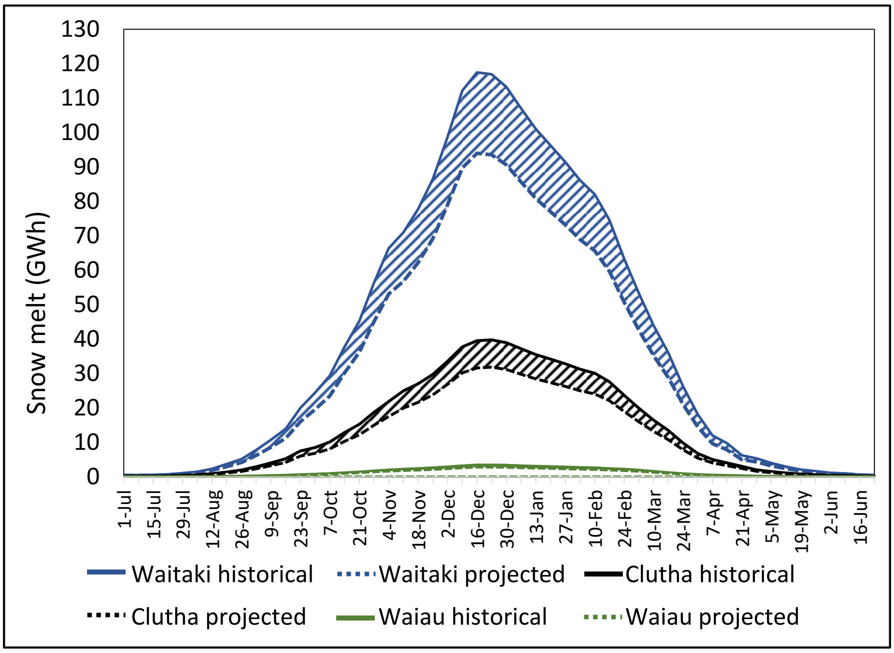


Figure 5: Historical modelled snow melt in the Waitaki, Clutha, and Waiau catchments (GWh) from Snowsim, and projected 2050 snow melt. Shaded areas show volume of water needing seasonal redistribution.

The reassigned snow melt water equated to 409 GWh of water in the Waitaki catchment, 146GWh in the Clutha catchment, and 13 GWh in the Waiau catchment. The 409 GWh that needed to be redistributed seasonally in the Waitaki catchment is assigned to the Tekapo and Pukaki catchments proportional to their average annual inflows, so 60% of the 409 GWh of melt water (245 GWh) is redistributed in the Pukaki catchment, and 40% of the 409 GWh (164 GWh) is redistributed in the Tekapo catchment.

Water is expressed as GWh of potential energy in this study to align with the use of the electricity system model. A GWh of water in a given catchment is the amount of water that results in 1GWh being generated when the water is routed through the generation turbines in that catchment.

2.2.3 Inflow projections

Following the Change Factor Methodology outlined in the methods section, change factors for each week of each of the twelve LPCon regions are calculated. These can be seen in Table 2. These change factors are applied to each of the 87 historical hydro sequences for 2050. A linear trend is then applied between each hydro sequence in 2020 and that hydro sequence in 2050.

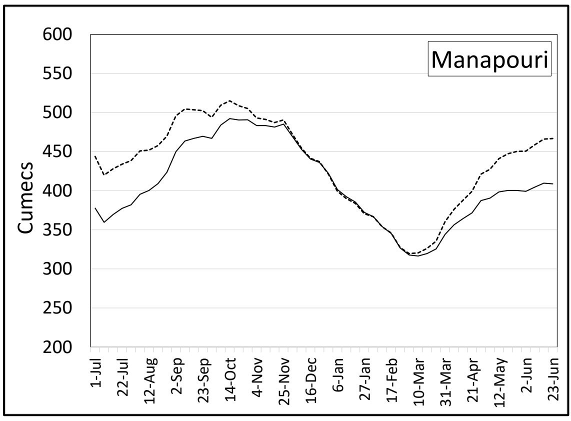
The biggest changes between 2020 and 2050 inflows are seen in the seasonal adjustments to inflows in the snow fed catchments of Manapouri, Clutha, Pukaki, and Tekapo. Although all regions showed reductions in inflows in spring and summer and increases in winter, the timing and magnitude of these changes varied from region to region.

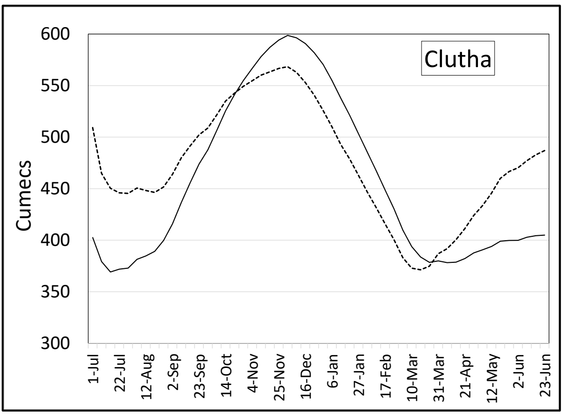
Table 2: Inflow change factors for each LPCon catchment and week of the year (% change)

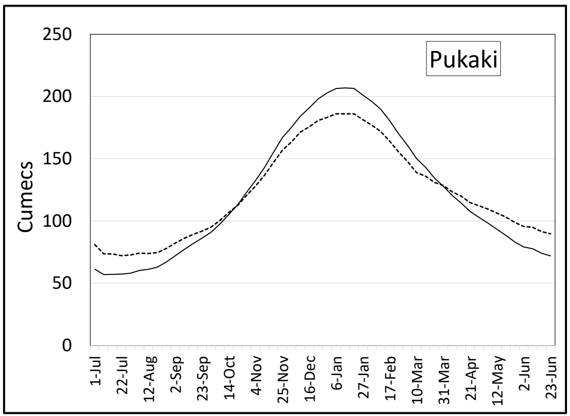
Week	**Manapouri**	**Clutha**	**Pukaki**	**Tekapo**	**GYM-RoR**	**ISL-RoR**	**KIK-RoR**	**BPE-RoR**	**Tongariro**	**Waikaremoana**	**BOP-RoR**	**Waikato**
1-Jul	18%	27%	32%	32%	4%	3%	3%	2%	1%	3%	-1%	2%
8-Jul	17%	23%	29%	29%	4%	3%	3%	2%	1%	3%	-1%	2%
15-Jul	16%	22%	29%	28%	4%	3%	3%	2%	1%	3%	-1%	2%
22-Jul	16%	21%	27%	27%	4%	3%	3%	2%	1%	2%	-2%	1%
29-Jul	15%	19%	25%	24%	4%	3%	3%	2%	0%	2%	-2%	1%
5-Aug	14%	17%	23%	22%	3%	2%	2%	2%	0%	2%	-2%	1%
12-Aug	14%	17%	22%	22%	3%	2%	2%	2%	0%	1%	-2%	0%
19-Aug	13%	16%	21%	20%	3%	2%	2%	2%	0%	1%	-2%	0%
26-Aug	12%	15%	19%	18%	3%	2%	2%	1%	-1%	0%	-2%	0%
2-Sep	11%	13%	16%	15%	2%	1%	1%	1%	-1%	0%	-3%	-1%
9-Sep	9%	11%	13%	12%	2%	1%	1%	1%	-1%	0%	-3%	-1%
16-Sep	8%	10%	11%	10%	2%	1%	0%	0%	-2%	-1%	-3%	-1%
23-Sep	7%	8%	9%	9%	1%	1%	0%	0%	-2%	-1%	-3%	-2%
30-Sep	6%	6%	6%	5%	1%	0%	0%	0%	-2%	-1%	-3%	-2%
7-Oct	5%	3%	3%	3%	1%	0%	-1%	0%	-2%	-1%	-4%	-2%
14-Oct	3%	1%	1%	0%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
21-Oct	3%	0%	-1%	-1%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
28-Oct	2%	-2%	-2%	-3%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
4-Nov	2%	-3%	-4%	-4%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
11-Nov	1%	-4%	-5%	-6%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
18-Nov	1%	-5%	-6%	-7%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
25-Nov	0%	-5%	-7%	-8%	1%	0%	-1%	0%	-2%	0%	-3%	-2%
2-Dec	1%	-6%	-7%	-8%	1%	0%	-1%	1%	-2%	0%	-3%	-2%
9-Dec	0%	-6%	-7%	-8%	1%	0%	-1%	1%	-2%	1%	-3%	-2%
16-Dec	0%	-6%	-8%	-9%	1%	0%	0%	1%	-2%	1%	-2%	-2%
23-Dec	0%	-6%	-8%	-9%	1%	0%	0%	1%	-2%	2%	-2%	-1%
30-Dec	0%	-6%	-8%	-9%	1%	0%	0%	2%	-2%	2%	-2%	-1%
6-Jan	0%	-7%	-9%	-10%	1%	0%	0%	2%	-1%	3%	-2%	-1%
13-Jan	0%	-8%	-10%	-11%	1%	0%	0%	2%	-1%	3%	-1%	-1%
20-Jan	-1%	-9%	-11%	-12%	1%	0%	0%	2%	-1%	4%	-1%	-1%
27-Jan	-1%	-10%	-12%	-12%	1%	-1%	0%	2%	-1%	5%	-1%	-1%
3-Feb	-2%	-10%	-12%	-12%	1%	-1%	1%	3%	-1%	5%	-1%	-1%
10-Feb	-1%	-11%	-12%	-12%	1%	-1%	0%	3%	-1%	6%	-1%	-1%
17-Feb	-1%	-10%	-12%	-12%	1%	-1%	0%	3%	-1%	7%	-1%	0%
24-Feb	0%	-8%	-10%	-10%	1%	-1%	0%	3%	-1%	7%	0%	0%
2-Mar	0%	-6%	-8%	-8%	0%	-1%	0%	4%	-1%	7%	0%	0%
9-Mar	2%	-4%	-5%	-5%	0%	-1%	0%	4%	-1%	7%	0%	0%
16-Mar	2%	-2%	-4%	-4%	0%	-1%	0%	4%	-1%	7%	0%	0%
23-Mar	3%	-1%	-2%	-2%	1%	0%	0%	4%	-1%	7%	0%	0%
30-Mar	3%	1%	0%	0%	1%	0%	0%	4%	0%	7%	0%	0%
6-Apr	5%	2%	2%	3%	1%	0%	0%	4%	0%	7%	0%	0%
13-Apr	5%	4%	5%	5%	1%	0%	1%	4%	0%	6%	0%	0%
20-Apr	7%	7%	8%	8%	1%	1%	1%	4%	0%	6%	0%	1%
27-Apr	8%	9%	11%	10%	2%	1%	2%	4%	1%	6%	0%	1%
4-May	9%	11%	14%	13%	2%	2%	2%	4%	1%	5%	0%	1%
11-May	10%	14%	16%	15%	2%	2%	2%	3%	1%	5%	0%	1%
18-May	12%	15%	19%	18%	3%	2%	2%	3%	1%	5%	0%	1%
25-May	13%	17%	21%	20%	3%	3%	2%	3%	1%	4%	0%	2%
1-Jun	14%	19%	23%	23%	3%	3%	3%	3%	1%	4%	0%	2%
8-Jun	15%	21%	26%	26%	3%	3%	3%	3%	1%	4%	0%	2%
15-Jun	15%	22%	27%	28%	3%	3%	3%	3%	1%	4%	0%	2%
22-Jun	16%	22%	28%	28%	4%	3%	3%	2%	1%	4%	-1%	2%

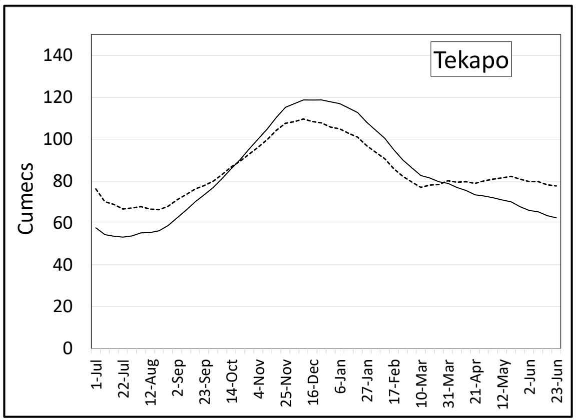
Increased volatility is then applied to the daily time series, enhancing inflow peaks and reducing inflow troughs by a commensurate amount. The resulting inflow records are formed for 12 hydrological regions, for 87 hydrological scenarios, on a weekly time resolution, for the period 2020-2050.

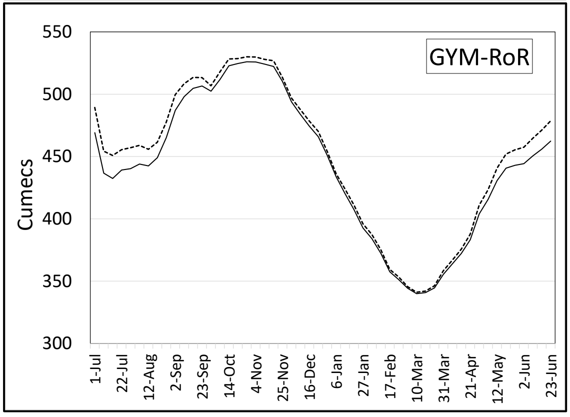
Summary graphs of the inflows for each region in 2020 and 2050 can be seen in figure 6.

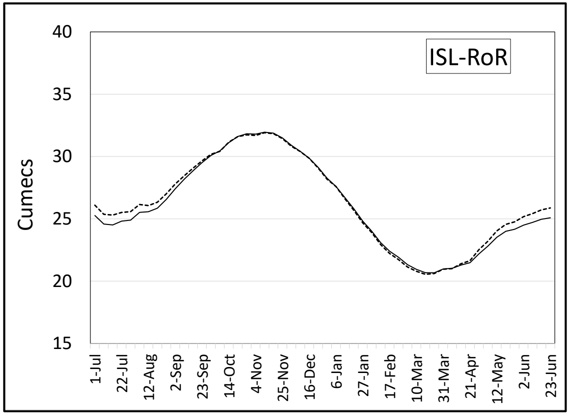












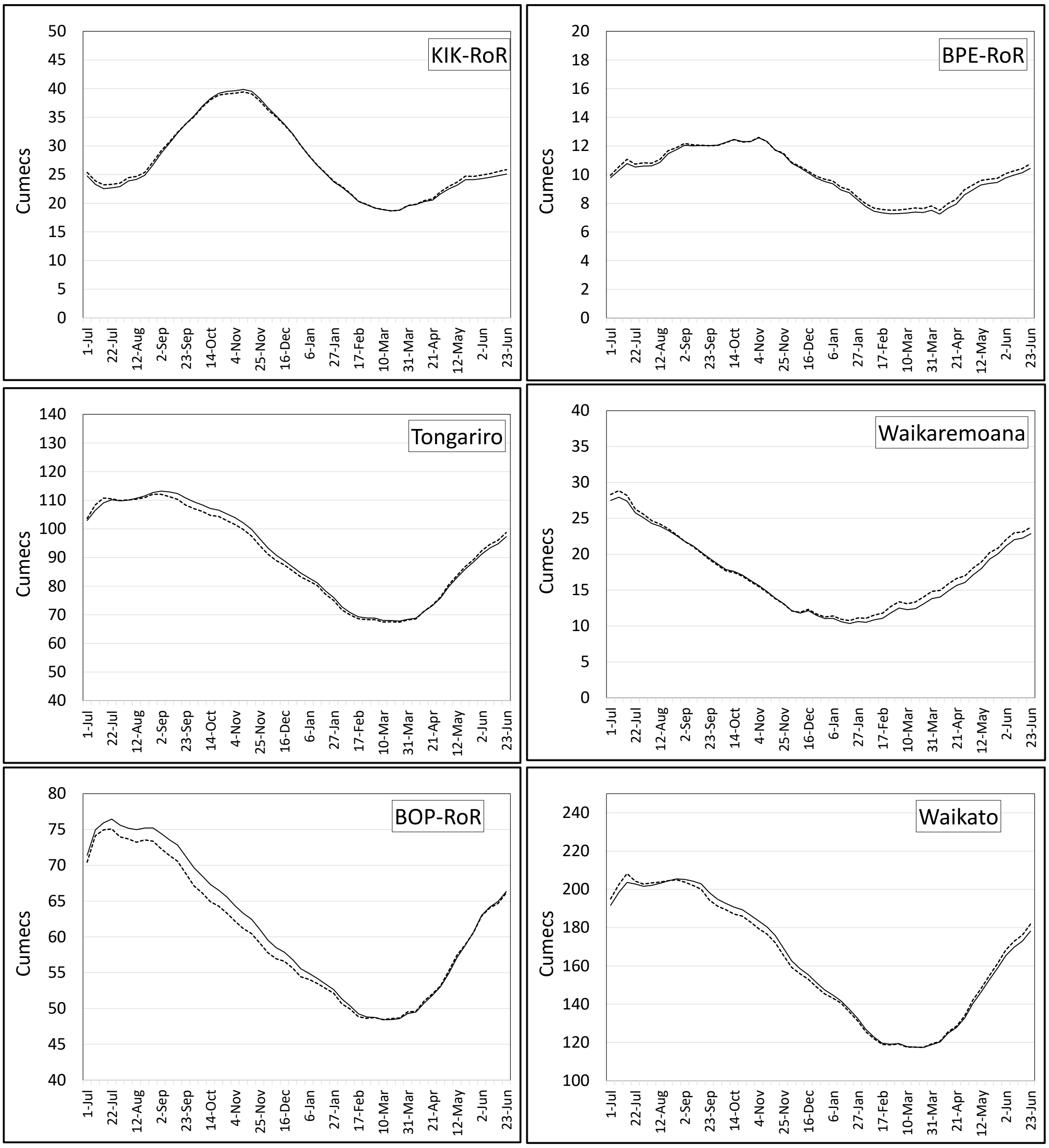


Figure 6: Current (solid line) and 2050 (dotted line) smoothed average weekly hydro lake inflows for 12 hydrological regions, in cumecs. Note different x-axis scales.

Using regionalised k-factors for each hydrological region (calculated from known k-factors for each constituent hydro scheme within the region), cumec values are converted to GWh of potential energy for input into LPCon.

The total change, in GWh, of New Zealand hydro inflows between 2020 and 2050 is shown in figure 7.

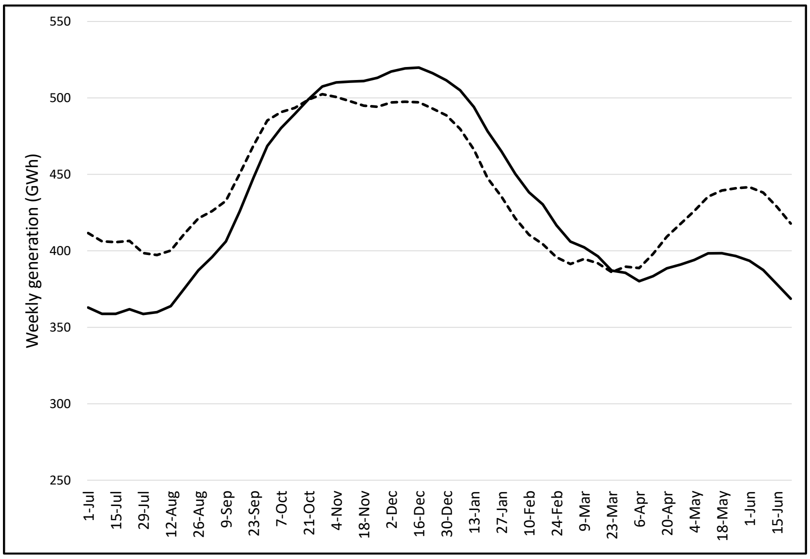


Figure 7: Total weekly New Zealand hydro inflows (smoothed), averaged over all 87 hydrological scenarios, 2020 (solid line) vs 2050 (dashed line).

Annual New Zealand total hydro catchment inflows (approx. 23,000 GWh) are projected to increase by 2% by 2050 (to 23,500), which equates to an increase of 500 GWh. This is significant when compared with the total annual generation in 2020 of 43,000 GWh.

However, it is projected that seasonal impacts will be larger, with total New Zealand hydro catchment inflows projected to be 10% higher in winter and 6% lower in summer (see figure 8).

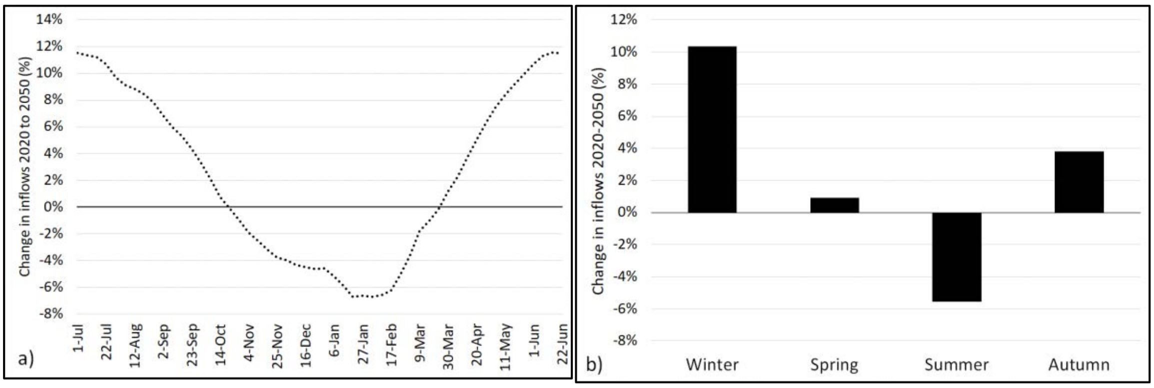


Figure 8: Difference between total weekly New Zealand hydro inflows in 2020 and in modelled 2050 inflows, with a) weekly smoothed differences, and b) seasonal total differences.

3. Wind capacity projections

The methodology applied by NIWA to project changes to wind speeds is the same applied to projecting temperature and rainfall changes, and involves downscaling GCM outputs with an RCM, as outlined in the previous section.

Projected changes to wind speeds over New Zealand in the next few decades are closely linked to changes to atmospheric circulation as a result of climate change. Mean sea level pressure (MSLP) is projected to increase in summer, especially to the south-east of New Zealand, leading to more north-easterly airflow in summer (MfE 2018). In winter, MSLP is projected to decrease in future, especially over and south of the South Island, resulting in stronger westerlies, particularly over central New Zealand. These increased westerlies are linked to increased precipitation on the West Coast, and will also impact wind generation over New Zealand in future.

Nationally, wind speeds are expected to increase in the South Island and lower North Island, and decrease in the north half of the North Island over coming decades. A 5-10% increase in New Zealand annual mean East-West winds is expected by 2040, with no change to the annual average Southerly-Northerly component (MfE 2008). Figure 9 shows projections of high (99th%ile) wind speeds in the 2040s and 2090s, relative to a 1986-2005 base period. This study focussed on the most likely, RCP4.5, outcomes.

Strong winds are expected to be 1-4% higher by the 2040s (relative to the base period) in the South Island, and 1-3% lower by the 2040s in Northland, as is shown in figure 9 (MfE 2016).

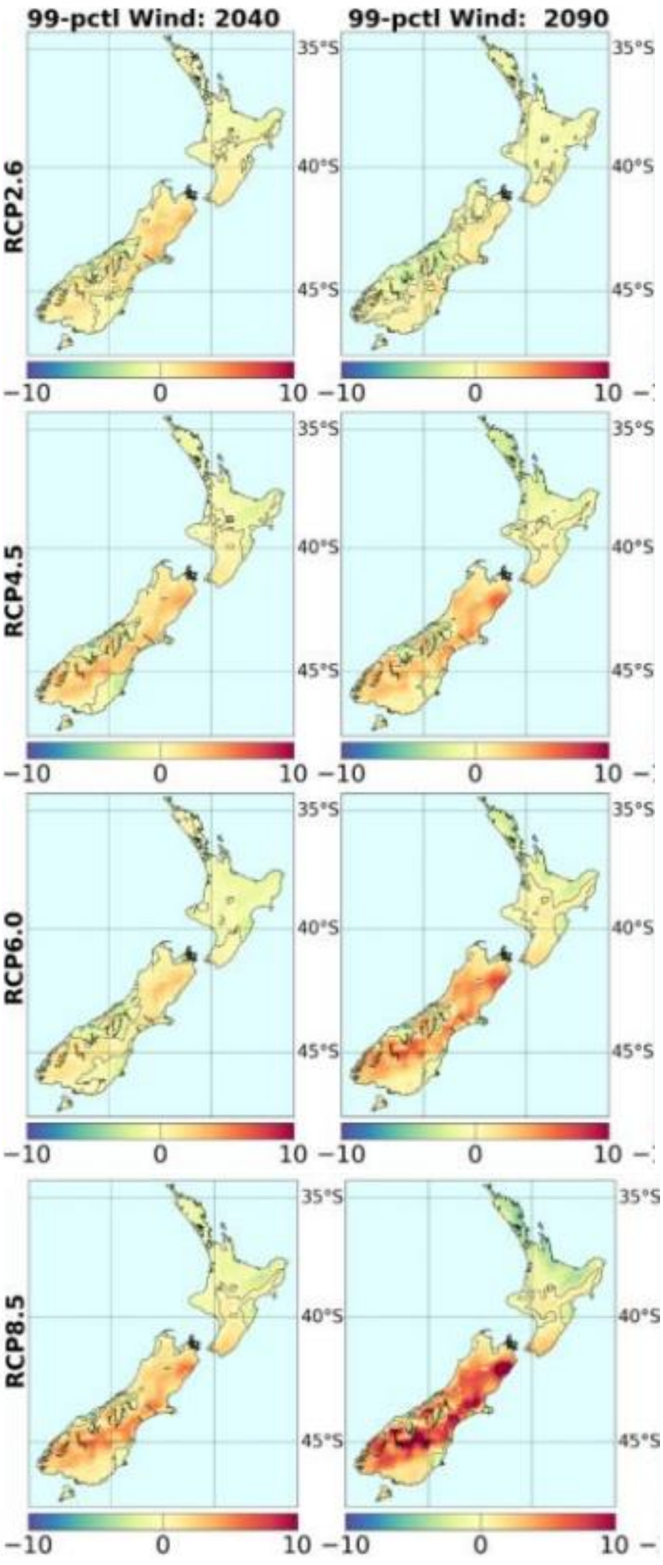


Figure 9: Change in the magnitude of the 99th percentile of daily-mean wind speed, for RCPs 2.6 (low emissions), 4.5 (mid-range-low) and 6.0 (mid-range-high) and RCP8.5 (high emissions), for the 2040s and 2090s, relative to the daily 99th percentile in the baseline 1986–2005 period (MfE 2016).

Winds over New Zealand are expected to increase the most in winter, and decrease in summer and autumn, in coming decades. Figure 10 shows long term average wind speeds over New Zealand (in metres per second) and the projected changes to those wind speeds by the 2040s for each season and annually.

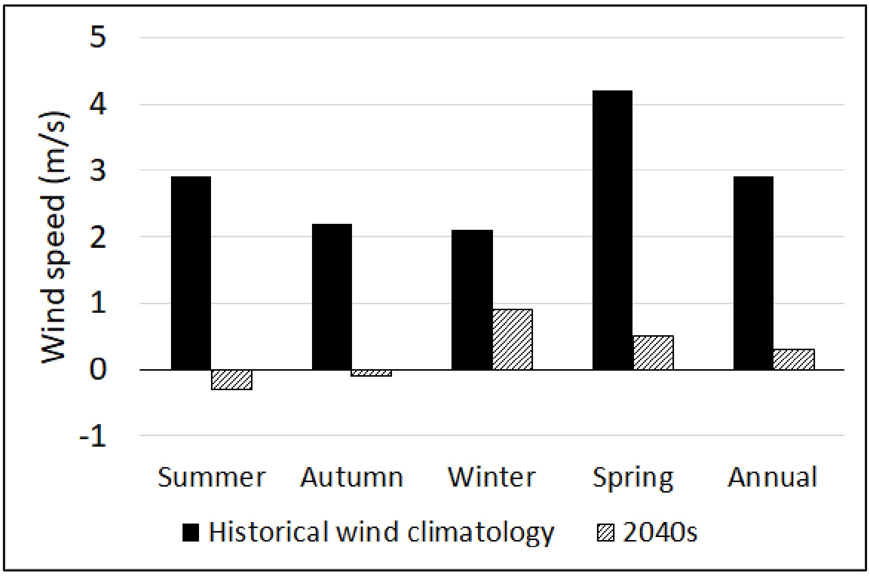


Figure 10: New Zealand historical average wind speeds for each season and annually compared to projected 2040s wind speeds (data from MfE 2008).

3.1 Methodology

The electricity model (LPCon) models wind generation in 12 separate regions (different to the hydrological regions), with individual wind farms in the model located in these regions utilising the same historical wind dataset to inform wind distribution and variability at the wind farm site.

The regions are Southland, Otago, Canterbury, Wellington, Wairarapa, Manawatu, Hawkes Bay, Taranaki, Central North Island, Waikato, Auckland, and Northland. These regions can be seen in figure 11.

Although all regions of New Zealand are not covered in this dataset, it covers all current, consented, and anticipated wind farm sites currently in LPCon modelling.

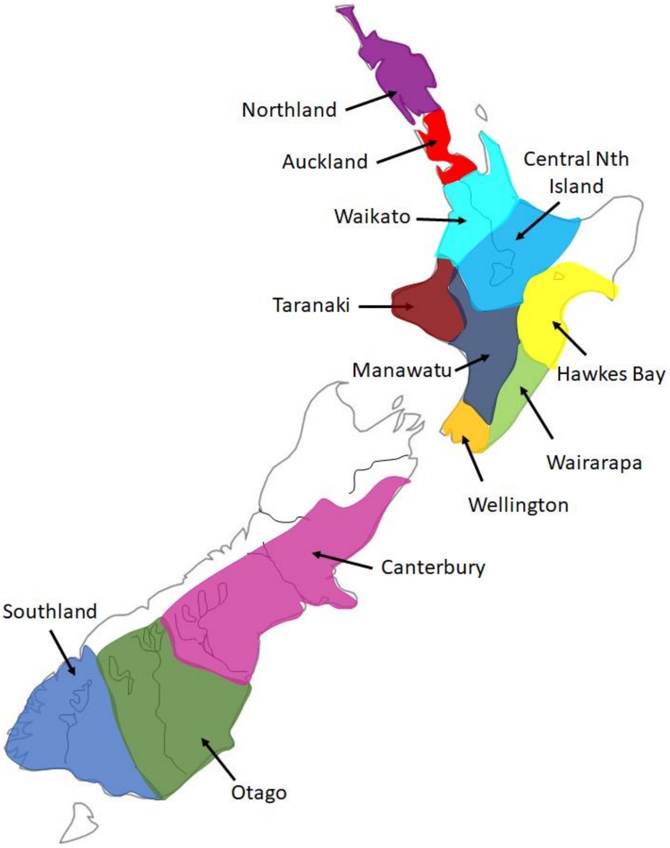


Figure 11: Locations of the 12 New Zealand wind energy regions used in this study

Each region has a distinct historical weekly wind record from 1932 to 2020 in LPCon. This wind data is compiled from historical datasets from the region from various sources (NIWA Clidb, actual wind mast data, Renewable Ninja). Historical wind speed data from these regions is used to represent wind variability in future years in electricity system modelling. However, the 2020-2050 record is adjusted to represent projected changes due to climate change.

There is limited research on detailed regional, seasonal wind projections in New Zealand. This study amalgamated wind projections from various studies (MfE 2008, MfE 2010, MfE 2016, MfE 2018, Pearce et al 2017, Macara et al 2019, NIWA 2020) and used New Zealand annual and seasonal wind speed projections for RCP4.5 for mid-century from MfE 2008, and apportioned those changes regionally following MfE (2016) and other studies (MfE 2010, MfE 2018, Pearce et al 2017, Macara et al 2019, NIWA 2020).

Weekly regional changes in windiness are projected as change factors. These are designed to be utilised to adjust historical wind records for 2050 conditions, and do not account for mast height, wind direction, elevation, or topography. It is intended that these adjustment factors are applied to an already existing wind record in the region, and will therefore encompass the variance, range, etc of the existing dataset. An assumption is made that the shape of the distribution will not change into the future.

Once the wind record has been adjusted using the change factors to relect a 2050 wind record, a linear trend is then applied between the 2020 record and the 2050 record.

3.2 Results

Annual average wind speeds are predicted to increase in the south of the South Island, with the largest change being in Otago (4.2%). In the northern half of the North Island they are expected to decrease, with the biggest reduction in annual average wind speed predicted to occur in Auckland (-2.8%). Changes to annual average wind speeds between 2020 and 2050 for each modelled region can be seen in figure 12.

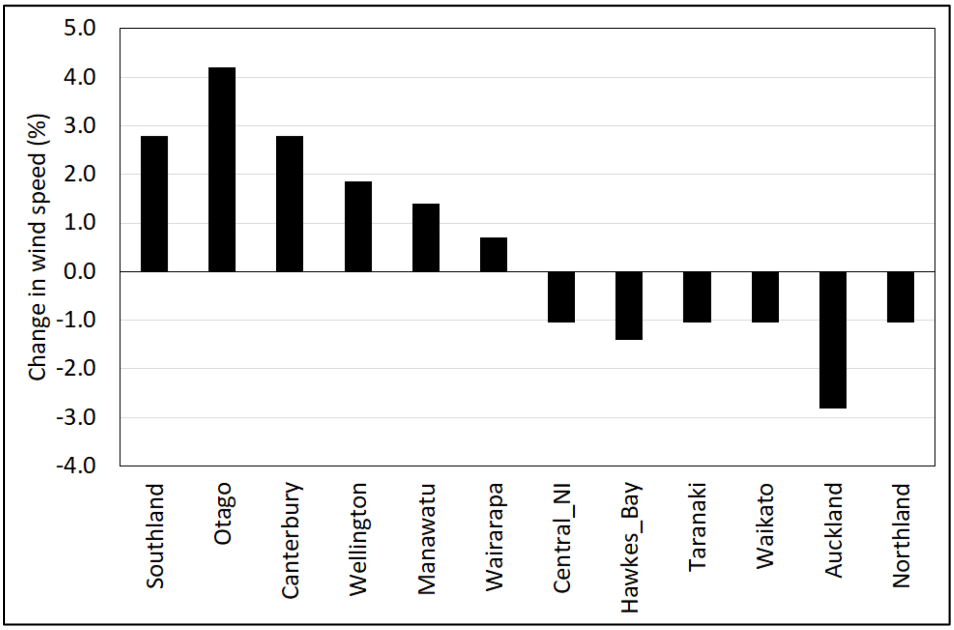
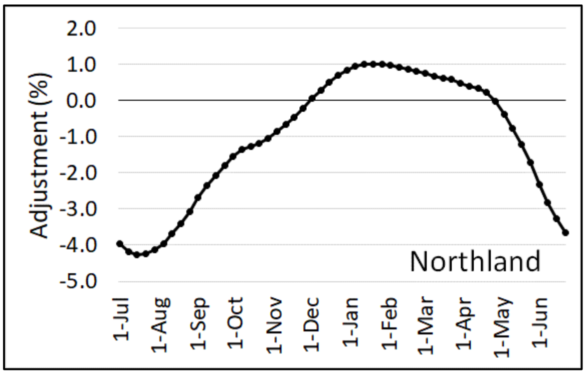
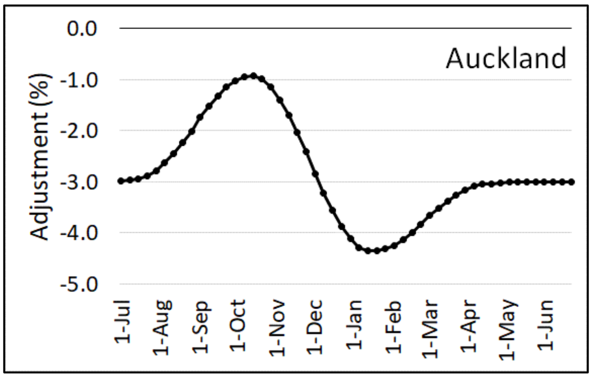
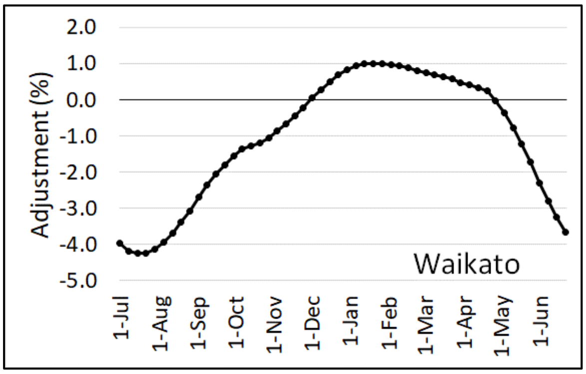


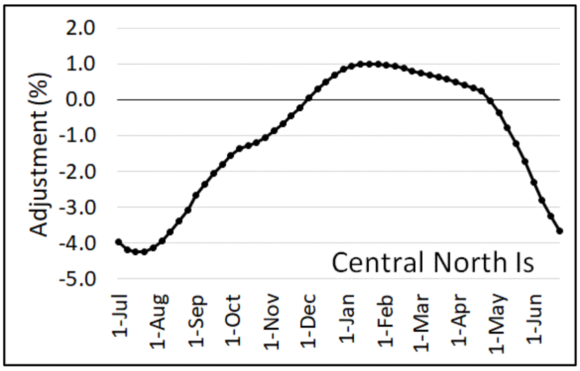
Figure 12: Modelled change (%) in annual average wind speed between 2020 and 2050.

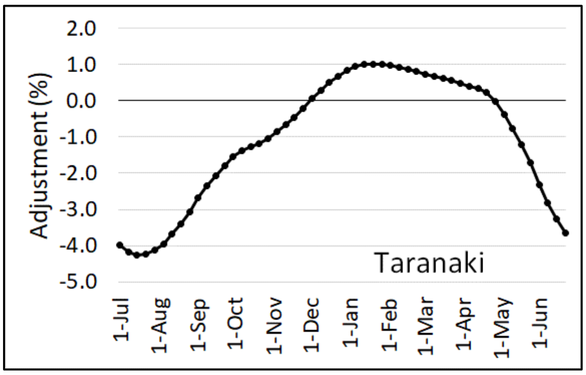
However, the seasonal changes are expected to be larger than the annual changes. The weekly change factors that are needed to adjust 2020 wind capacity records to reflect 2050 conditions can be seen in the graphs in figure 13. Regions that are north of the middle of the North Island show the general pattern of windier summers and less windy winters, although Auckland is less windy all year. Auckland shows a slightly different pattern to other northern regions, and this is because data for this region comes from a specific higher resolution study conducted for Auckland council by NIWA (Pearce et al 2017). Projections for other sites come from other studies. From Manawatu south, including the South Island, regions show predictions of windier winters and less windy summers. Note the different y-axis scales in figure 13. The largest changes are expected to occur in Southland, Otago, and Canterbury.

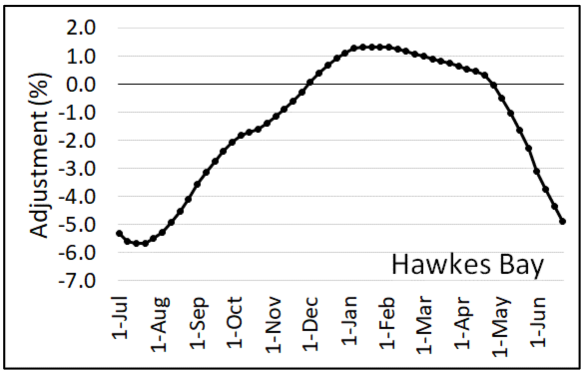

Northland
Adjustment (%)
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun

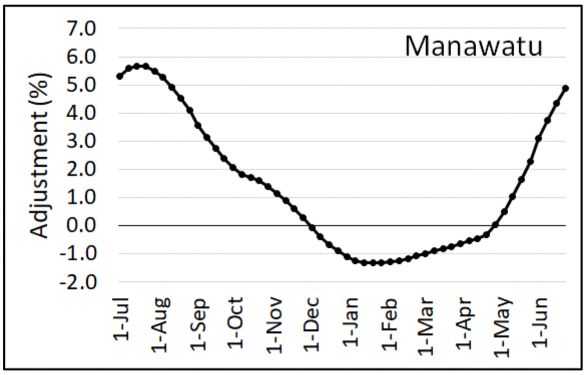

Auckland
Adjustment (%)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun

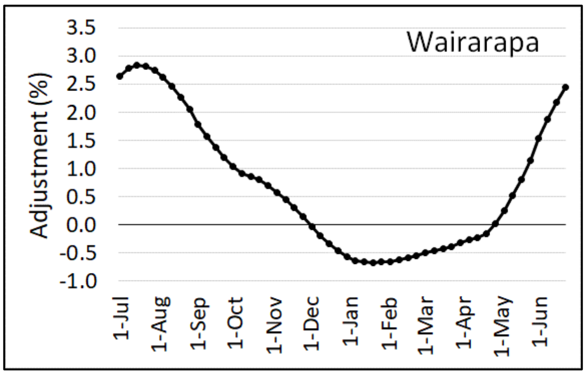

Waikato
Adjustment (%)
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun


Central North Is
Adjustment (%)
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun


Taranaki
Adjustment (%)
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun


Hawkes Bay
Adjustment (%)
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun


Manawatu
Adjustment (%)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun


Wairarapa
Adjustment (%)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun

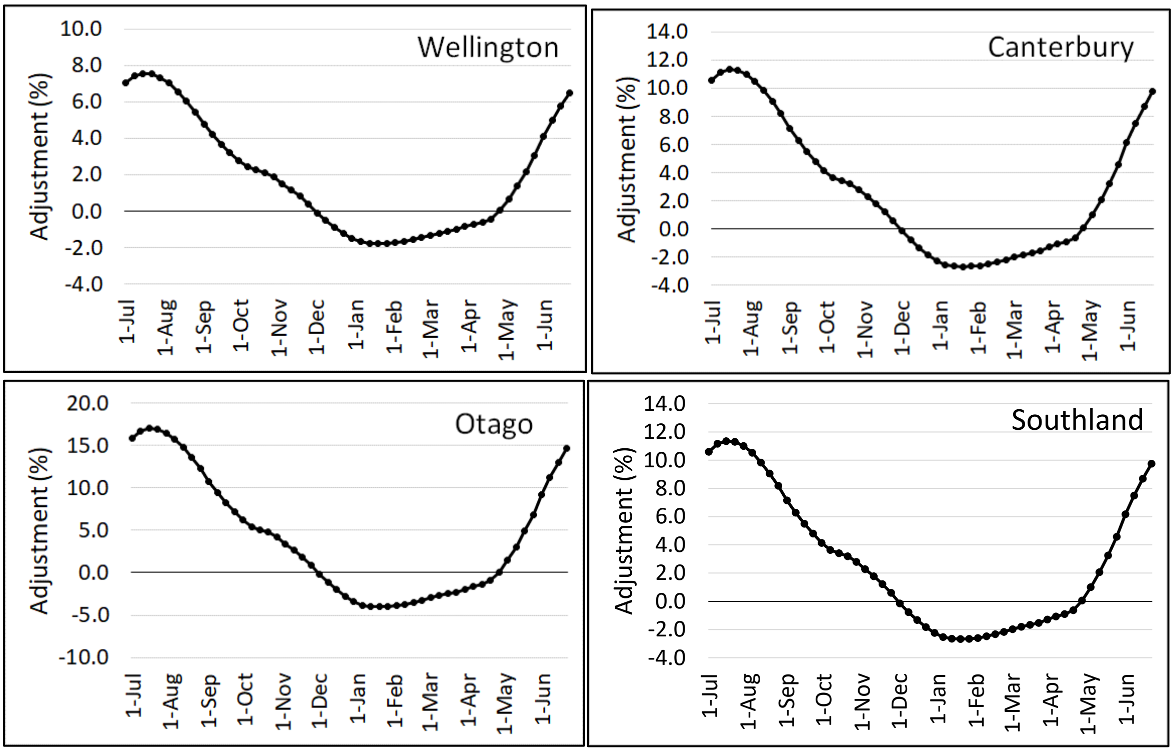
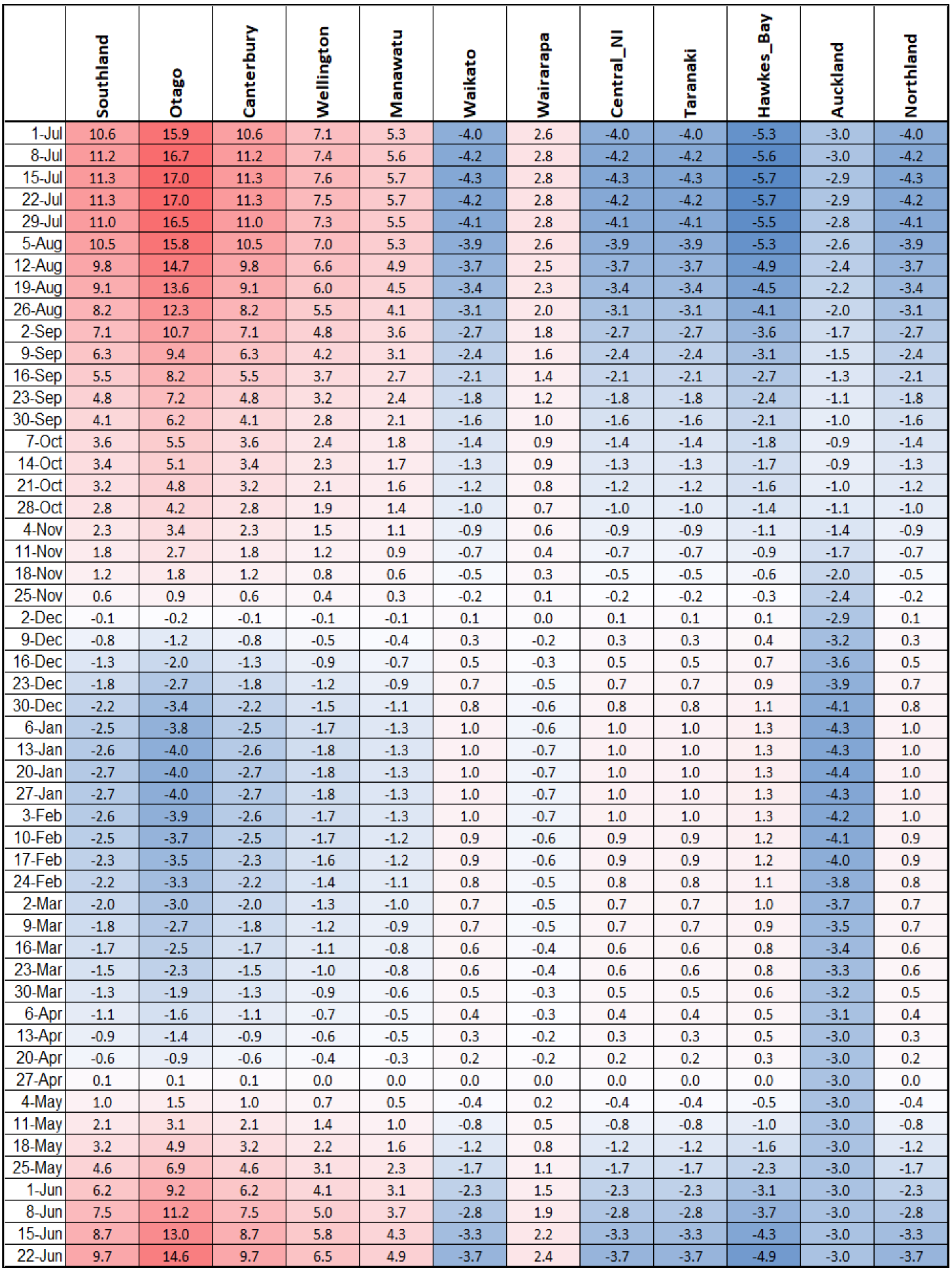


Figure 13: Weekly wind speed change factors for 12 regions representing change between 2020 and 2050, to adjust for climate change.

These change factors are listed in Table 3. It can be seen that the biggest increases in projected wind speeds are in winter in Southland, Otago and Canterbury. The biggest decreases in projected wind speeds are in the north of the North Island.

Table 3: Change factors (%) to convert 2020 wind capacity records to 2050 predicted values to adjust for climate change.



	Southland	Otago	Canterbury	Wellington	Manawatu	Waikato	Wairarapa	Central_NI	Taranaki	Hawkes_Bay	Auckland	Northland
1-Jul	10.6	15.9	10.6	7.1	5.3	-4.0	2.6	-4.0	-4.0	-5.3	-3.0	-4.0
8-Jul	11.2	16.7	11.2	7.4	5.6	-4.2	2.8	-4.2	-4.2	-5.6	-3.0	-4.2
15-Jul	11.3	17.0	11.3	7.6	5.7	-4.3	2.8	-4.3	-4.3	-5.7	-2.9	-4.3
22-Jul	11.3	17.0	11.3	7.5	5.7	-4.2	2.8	-4.2	-4.2	-5.7	-2.9	-4.2
29-Jul	11.0	16.5	11.0	7.3	5.5	-4.1	2.8	-4.1	-4.1	-5.5	-2.8	-4.1
5-Aug	10.5	15.8	10.5	7.0	5.3	-3.9	2.6	-3.9	-3.9	-5.3	-2.6	-3.9
12-Aug	9.8	14.7	9.8	6.6	4.9	-3.7	2.5	-3.7	-3.7	-4.9	-2.4	-3.7
19-Aug	9.1	13.6	9.1	6.0	4.5	-3.4	2.3	-3.4	-3.4	-4.5	-2.2	-3.4
26-Aug	8.2	12.3	8.2	5.5	4.1	-3.1	2.0	-3.1	-3.1	-4.1	-2.0	-3.1
2-Sep	7.1	10.7	7.1	4.8	3.6	-2.7	1.8	-2.7	-2.7	-3.6	-1.7	-2.7
9-Sep	6.3	9.4	6.3	4.2	3.1	-2.4	1.6	-2.4	-2.4	-3.1	-1.5	-2.4
16-Sep	5.5	8.2	5.5	3.7	2.7	-2.1	1.4	-2.1	-2.1	-2.7	-1.3	-2.1
23-Sep	4.8	7.2	4.8	3.2	2.4	-1.8	1.2	-1.8	-1.8	-2.4	-1.1	-1.8
30-Sep	4.1	6.2	4.1	2.8	2.1	-1.6	1.0	-1.6	-1.6	-2.1	-1.0	-1.6
7-Oct	3.6	5.5	3.6	2.4	1.8	-1.4	0.9	-1.4	-1.4	-1.8	-0.9	-1.4
14-Oct	3.4	5.1	3.4	2.3	1.7	-1.3	0.9	-1.3	-1.3	-1.7	-0.9	-1.3
21-Oct	3.2	4.8	3.2	2.1	1.6	-1.2	0.8	-1.2	-1.2	-1.6	-1.0	-1.2
28-Oct	2.8	4.2	2.8	1.9	1.4	-1.0	0.7	-1.0	-1.0	-1.4	-1.1	-1.0
4-Nov	2.3	3.4	2.3	1.5	1.1	-0.9	0.6	-0.9	-0.9	-1.1	-1.4	-0.9
11-Nov	1.8	2.7	1.8	1.2	0.9	-0.7	0.4	-0.7	-0.7	-0.9	-1.7	-0.7
18-Nov	1.2	1.8	1.2	0.8	0.6	-0.5	0.3	-0.5	-0.5	-0.6	-2.0	-0.5
25-Nov	0.6	0.9	0.6	0.4	0.3	-0.2	0.1	-0.2	-0.2	-0.3	-2.4	-0.2
2-Dec	-0.1	-0.2	-0.1	-0.1	-0.1	0.1	0.0	0.1	0.1	0.1	-2.9	0.1
9-Dec	-0.8	-1.2	-0.8	-0.5	-0.4	0.3	-0.2	0.3	0.3	0.4	-3.2	0.3
16-Dec	-1.3	-2.0	-1.3	-0.9	-0.7	0.5	-0.3	0.5	0.5	0.7	-3.6	0.5
23-Dec	-1.8	-2.7	-1.8	-1.2	-0.9	0.7	-0.5	0.7	0.7	0.9	-3.9	0.7
30-Dec	-2.2	-3.4	-2.2	-1.5	-1.1	0.8	-0.6	0.8	0.8	1.1	-4.1	0.8
6-Jan	-2.5	-3.8	-2.5	-1.7	-1.3	1.0	-0.6	1.0	1.0	1.3	-4.3	1.0
13-Jan	-2.6	-4.0	-2.6	-1.8	-1.3	1.0	-0.7	1.0	1.0	1.3	-4.3	1.0
20-Jan	-2.7	-4.0	-2.7	-1.8	-1.3	1.0	-0.7	1.0	1.0	1.3	-4.4	1.0
27-Jan	-2.7	-4.0	-2.7	-1.8	-1.3	1.0	-0.7	1.0	1.0	1.3	-4.3	1.0
3-Feb	-2.6	-3.9	-2.6	-1.7	-1.3	1.0	-0.7	1.0	1.0	1.3	-4.2	1.0
10-Feb	-2.5	-3.7	-2.5	-1.7	-1.2	0.9	-0.6	0.9	0.9	1.2	-4.1	0.9
17-Feb	-2.3	-3.5	-2.3	-1.6	-1.2	0.9	-0.6	0.9	0.9	1.2	-4.0	0.9
24-Feb	-2.2	-3.3	-2.2	-1.4	-1.1	0.8	-0.5	0.8	0.8	1.1	-3.8	0.8
2-Mar	-2.0	-3.0	-2.0	-1.3	-1.0	0.7	-0.5	0.7	0.7	1.0	-3.7	0.7
9-Mar	-1.8	-2.7	-1.8	-1.2	-0.9	0.7	-0.5	0.7	0.7	0.9	-3.5	0.7
16-Mar	-1.7	-2.5	-1.7	-1.1	-0.8	0.6	-0.4	0.6	0.6	0.8	-3.4	0.6
23-Mar	-1.5	-2.3	-1.5	-1.0	-0.8	0.6	-0.4	0.6	0.6	0.8	-3.3	0.6
30-Mar	-1.3	-1.9	-1.3	-0.9	-0.6	0.5	-0.3	0.5	0.5	0.6	-3.2	0.5
6-Apr	-1.1	-1.6	-1.1	-0.7	-0.5	0.4	-0.3	0.4	0.4	0.5	-3.1	0.4
13-Apr	-0.9	-1.4	-0.9	-0.6	-0.5	0.3	-0.2	0.3	0.3	0.5	-3.0	0.3
20-Apr	-0.6	-0.9	-0.6	-0.4	-0.3	0.2	-0.2	0.2	0.2	0.3	-3.0	0.2
27-Apr	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-3.0	0.0
4-May	1.0	1.5	1.0	0.7	0.5	-0.4	0.2	-0.4	-0.4	-0.5	-3.0	-0.4
11-May	2.1	3.1	2.1	1.4	1.0	-0.8	0.5	-0.8	-0.8	-1.0	-3.0	-0.8
18-May	3.2	4.9	3.2	2.2	1.6	-1.2	0.8	-1.2	-1.2	-1.6	-3.0	-1.2
25-May	4.6	6.9	4.6	3.1	2.3	-1.7	1.1	-1.7	-1.7	-2.3	-3.0	-1.7
1-Jun	6.2	9.2	6.2	4.1	3.1	-2.3	1.5	-2.3	-2.3	-3.1	-3.0	-2.3
8-Jun	7.5	11.2	7.5	5.0	3.7	-2.8	1.9	-2.8	-2.8	-3.7	-3.0	-2.8
15-Jun	8.7	13.0	8.7	5.8	4.3	-3.3	2.2	-3.3	-3.3	-4.3	-3.0	-3.3
22-Jun	9.7	14.6	9.7	6.5	4.9	-3.7	2.4	-3.7	-3.7	-4.9	-3.0	-3.7

The biggest seasonal increase to wind speeds is expected to be faster wind speeds in winter, and the biggest decrease is expected with lower wind speeds in summer (see figure 14).

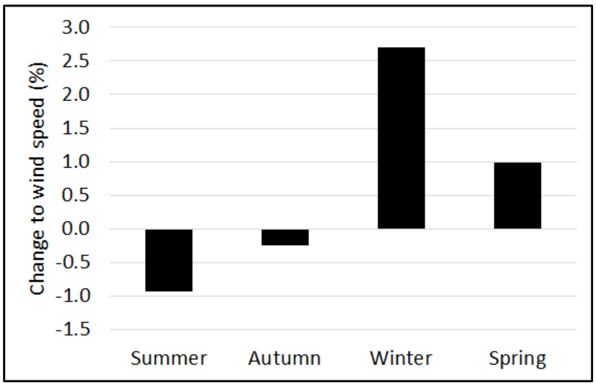


Figure 14: Seasonal average New Zealand changes to predicted wind speeds between 2020 and 2050.

Annual average changes are projected to be small (-2.8% to +4.2%) (figure 12), but the seasonal changes are significant, with the largest weekly change to wind speeds expected for July in Otago (17% stronger by mid-century).

4. Discussion

Climate change impacts on inflows to forty New Zealand hydro generation stations, encompassed in twelve regions, are modelled using a model cascade. A similar methodology is employed to estimate changes to wind resource over time in 12 different regions of New Zealand where wind farms are likely to be located in coming decades. These changes are designed to be included in electricity system modelling in New Zealand.

4.1 Hydro inflows

Results show an overall 2% increase in annual hydro catchment inflows over the whole of New Zealand between 2020 and 2050, which equates to an increase of 520 GWh. This increase in generation is significant when compared with the total annual generation in 2020 of 43,000 GWh, but less so when projected increases to electricity demand over this time (14,000-29,000 GWh) are considered.

Seasonal impacts are projected to be larger, with total New Zealand hydro catchment inflows projected to be 10% higher in winter and 6% lower in summer by 2050, and this is an important and beneficial shift, with New Zealand electricity demand currently anti-correlated with inflows.

South Island hydro storage catchment inflows are particularly affected, as in addition to expected rainfall changes, they receive a significant proportion of their inflows from snowmelt, resulting in large seasonal changes to inflows as temperatures warm in coming decades. The two Waitaki catchments modelled are predicted to get higher inflows in winter (+26%), and lower inflows in summer (-10%), with a 6% increase in annual flows. The Clutha catchment has a smaller proportion of inflows from snowmelt, and it is modelled to get higher inflows in winter (+19%) and lower inflows in summer (-9%), with a small increase in annual inflows over this time (+4%). Manapouri catchment is also expected to receive higher winter inflows by 2050 (+15%) and lower summer inflows (-1%), with 6% higher annual inflows.

These projected changes are compared to other recent studies projecting changes to South Island river flows, in Figure 15.

	Period	Emissions scenario	Catchment
Poyck et al (2011)	2040s	mid-range	Clutha
Jobst et al (2018)	2050	mid-range	Clutha
Collins (2020)	2050	RCP4.5 (mid-range)	Southern Alps
Zammit & Woods (2011)	2040	mid-range	Waimakariri
Caruso (2017b)	2040s	mid-range	Waitaki
This study	2050s	RCP4.5 (mid-range)	Waitaki, Clutha,

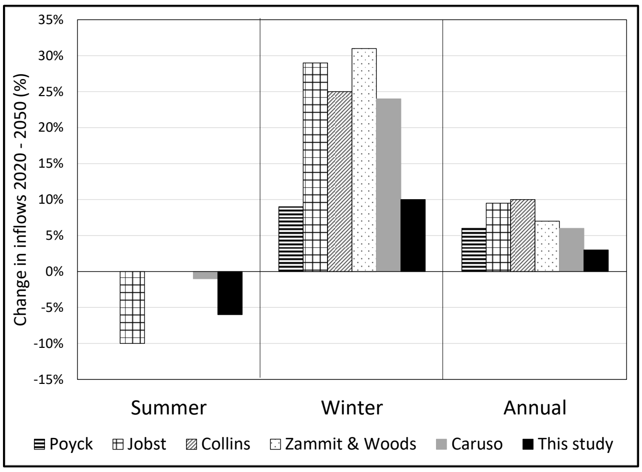


Figure 15: Comparison of seasonal and annual changes to catchment inflows by 2040s or 2050 – various New Zealand studies

Although the studies differ in catchments, periods of projections, and methodologies, it can be seen that all studies project catchment streamflows in large, eastward flowing rivers sourced in the Southern Alps with some snow component changing in the same direction. That is, increasing flows in winter and decreasing or static flows in summer, and small increases (3-10%) in annual flows.

4.2 Wind speed

Annual average wind speeds are predicted to increase in the south of the South Island, with the largest change being in Otago (4.2%). In the north half of the North Island they are expected to decrease, with the biggest reduction in wind speed predicted to occur in Auckland (-2.8%).

Weekly changes are greater, with 17% stronger winds expected in Otago in July by 2050, and 5.7% weaker winds in Hawkes Bay in July.

It should be noted, but is out of the scope of this study, that increasing wind speeds may actually lead to less generation as wind turbines may be forced into cutoff speeds more often, resulting in turbine shut down and less generation.

For both hydro and wind changes out to 2050, the greatest projected impacts are not in annual volume changes (all of which remain below 5%) but in changes to the seasonal distribution of the arrival of renewable energy “fuel”. These changes are generally in a beneficial direction, moving “fuel” from summer arrival, when it is less needed for generation, to winter arrival, when it is more needed. This has significant implications for electricity generation, where the current hydro inflows are anti-correlated with demand.

5. Acknowledgements & Future work

This research was able to be completed by the support of Meridian Energy Ltd. The work was partly undertaken while the author was employed at Meridian Energy, and finished while employed as a research fellow at the University of Otago, funded by a Deep South Science Challenge Domains funding grant (MBIE contract number C01X19011). The author would like to acknowledge the generosity of Meridian Energy in granting a license to use their electricity system model, LPCon, for the duration of the research fellowship, and in particular Grant Telfar, architect and creator of LPCon, for his generosity and assistance.

Future work in the Deep South Science funded project involves working with NIWA to compile high resolution NIWA Topnet hydrological river flow projections and NIWA RCM wind projections for inclusion in LPCon electricity system scenario modelling. This work is currently underway and should be published in late 2023 or early 2024.

6. Appendix

Error analysis

Detailed error assessments around projections have not been undertaken for this study. However, some assessment of potential spread of projections is needed by users of the data. Forward looking inflow projections are formed from composite models and cannot be compared with actuals. Error around inflow projections is not available at this stage.

However, the error of rainfall projections can be examined. Rainfall error is represented in two ways here, for two representative catchments: Westport and Wellington. Firstly, rainfall projections from GCM and RCMs are estimated back to 1971, and so can be compared with observed values over the period 1971-2021, the assumption being that error statistics for this period should equate to error statistics in projected values. No such modelling is available for wind speed projections, although this will become available in the next couple of years.

Secondly, the ensemble spread of model projections from different GCMs (& RCMs) can be shown for rainfall, for different emissions scenarios (RCPs), to give some idea of the spread of projections from different models and emissions pathways. Rainfall projections are derived from 6 global models for four RCPs. This study uses a six model average projection, for RCP4.5 (a middle of the road scenario). The graphs below go into more detail than this, and show the spread of rainfall projections for all six model outputs, for a low emissions scenario (RCP2.6) and a high emissions scenario (RCP8.5) for 2 locations: the West Coast and Wellington. This information gives an indication of how aligned the model projections are.

Westport

Projections compared to observed rainfall

The minimum, mean, and maximum model projections from the six GCM-RCM projections can be seen for RCP2.6 in figure A1, and RCP8.5 in figure A2 for Westport. Observed rainfall for Westport for the period 1971-2021 can also be seen.

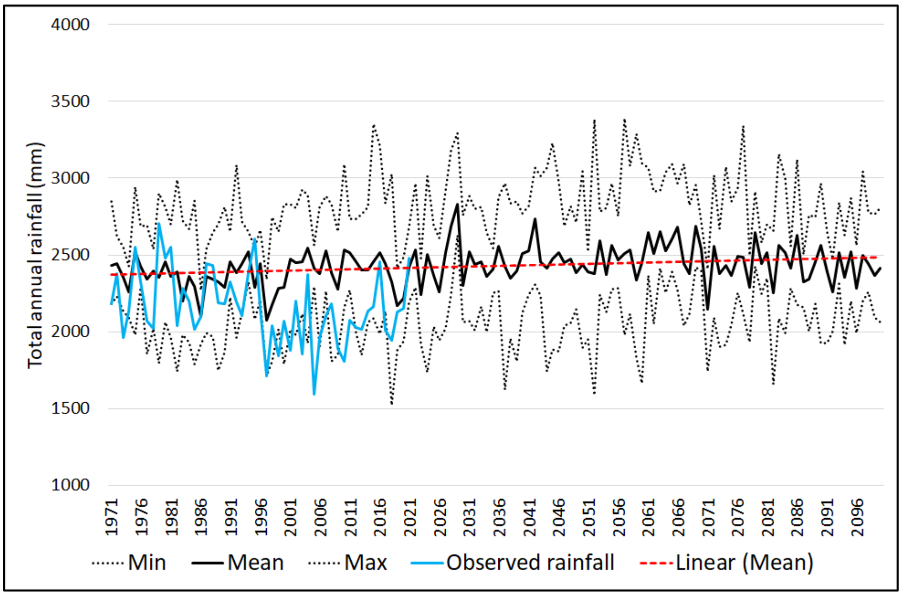


Figure A1: Model spread of RCP2.6 West Coast rainfall projections. Min, mean, and max of 6 GCM projections of West Coast Annual rainfall, 1971-2100, linear least squares regression of mean, and observed rainfall (1971-2021).

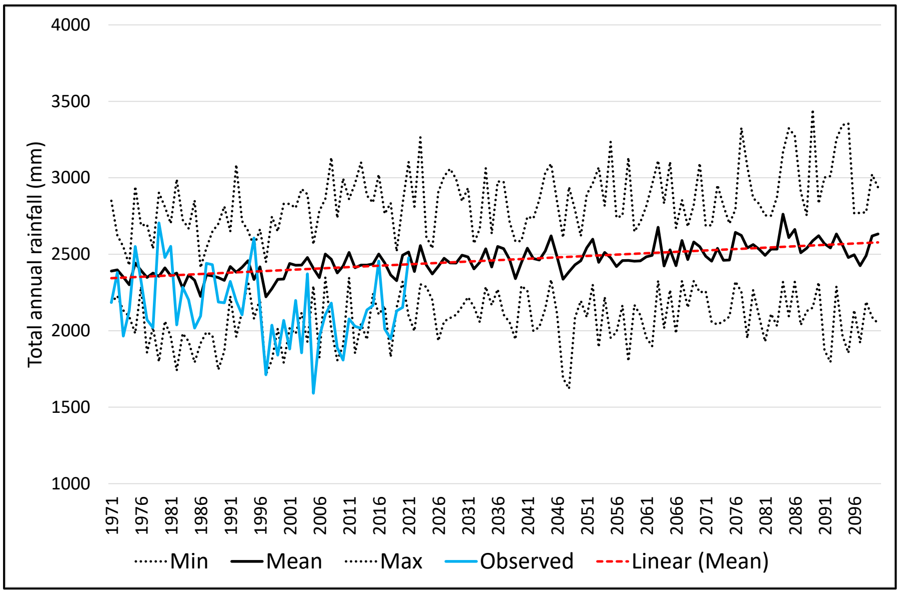


Figure A2: Model spread of RCP8.5 West Coast rainfall projections. Min, mean, and max of 6 GCM projections of West Coast Annual rainfall, 1971-2100, linear least squares regression of mean, and observed rainfall (1971-2021).

The Mean Absolute Percentage Error (MAPE) of observed rainfall vs mean predicted rainfall from the six model average for 1971-2021 for both RCPs is 13%.

The graphs show that all model projections for both low and high emissions show increases in West Coast rainfall. The RCP2.6 scenario shows an average increase over the 120 year period of 5%, and the RCP8.5 scenario shows an average increase over the 120 year period of 10%.

Spread of projections from different global models

The spread of projections of rainfall for 2050 from different global models are shown in figure A3.

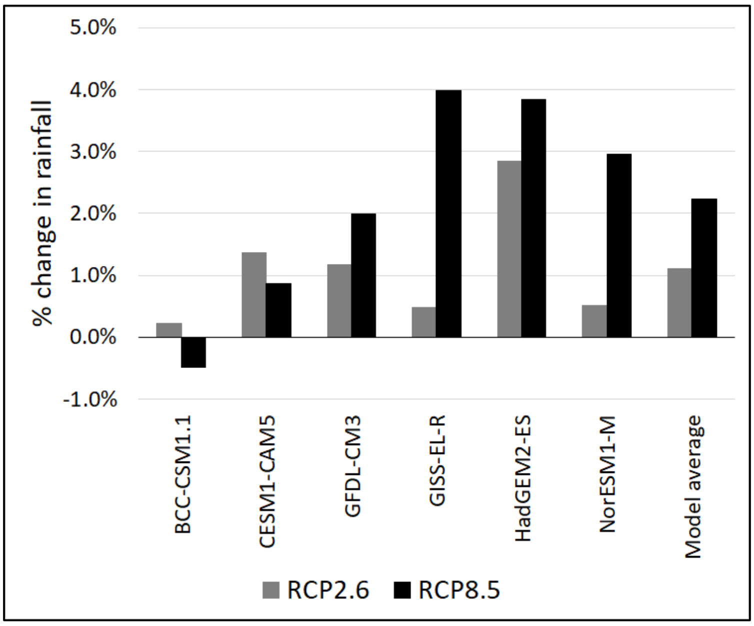


Figure A3: Projected change in Westport rainfall between 2020 and 2050 for six global models (downscaled using an RCM), for RCP2.6 and RCP8.5.

It can be seen that almost all changes are for increased rainfall, and that RCP8.5 changes are higher than RCP 2.6 changes. It can be seen that the spread of model projections ranges from a -0.5% change in annual rainfall between 2020 and 2050, to a +4% change. The models are almost all consistent (11 out of 12 predictions) in their projection of the direction of change (wetter). This graph shows that some representation of wetter conditions in Westport by 2050 should be shown in the electricity system modelling.

Extrapolating beyond 2050

The error around 2050 projections means that extrapolating trends out to 2060 or beyond should be undertaken with caution. The spread of projections about the mean projection can be seen in figure A4. It can be seen that difference between mean projections for 2050 and 2065 is small relative to the spread of projections from the 6 different models.

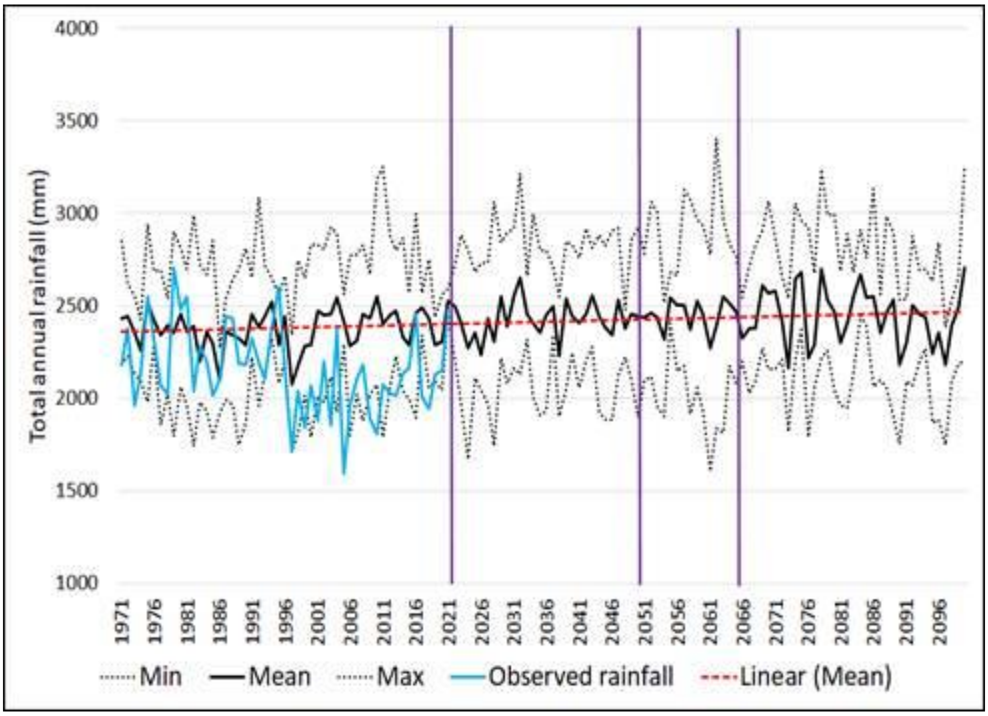


Figure A4: Annual rainfall projection for Westport from 1971 to 2100 for RCP4.5, with the min, mean, and max projections from the six models shown, as well as observed values in blue. Purple lines occur at 2021, 2050, and 2065.

Projections of seasonal Westport annual rainfall for 2030, 2040, 2050, and 2065 are shown in figure A5.

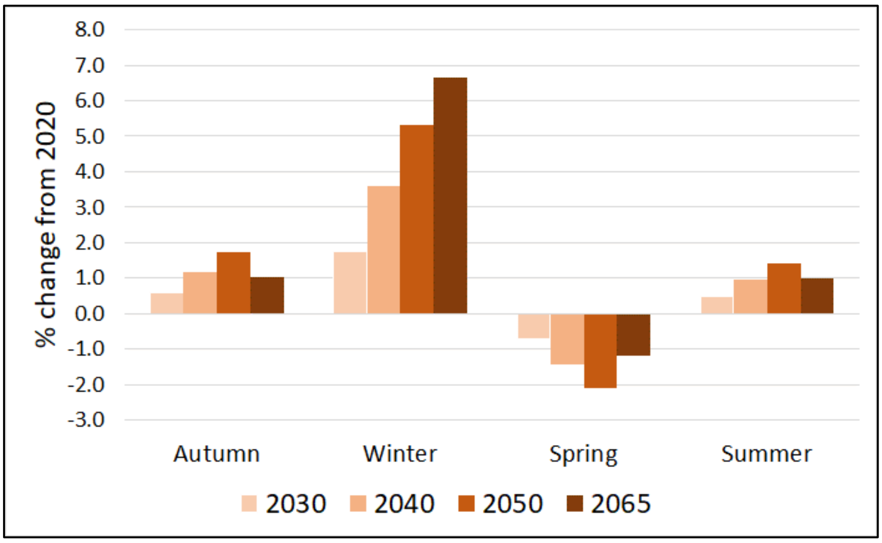


Figure A5: Projections of Westport annual rainfall for 2030, 2040, 2050, and 2065 for each season.

It can be seen that 2065 winter values are 20% higher than 2050 values, but projections counterintuitively decrease between 2050 and 2065 for Autumn, Spring, and Summer. This should be considered the noise in the model projections, where the general trend (see figure A4) is a gently upward trend over time.

Wellington

Projections compared to observed rainfall

The minimum, mean, and maximum model projections from the six GCM-RCM projections can be seen for RCP2.6 in figure A6, and RCP8.5 in figure A7 for Wellington. Observed rainfall for Wellington for the period 1971-2021 can also be seen.

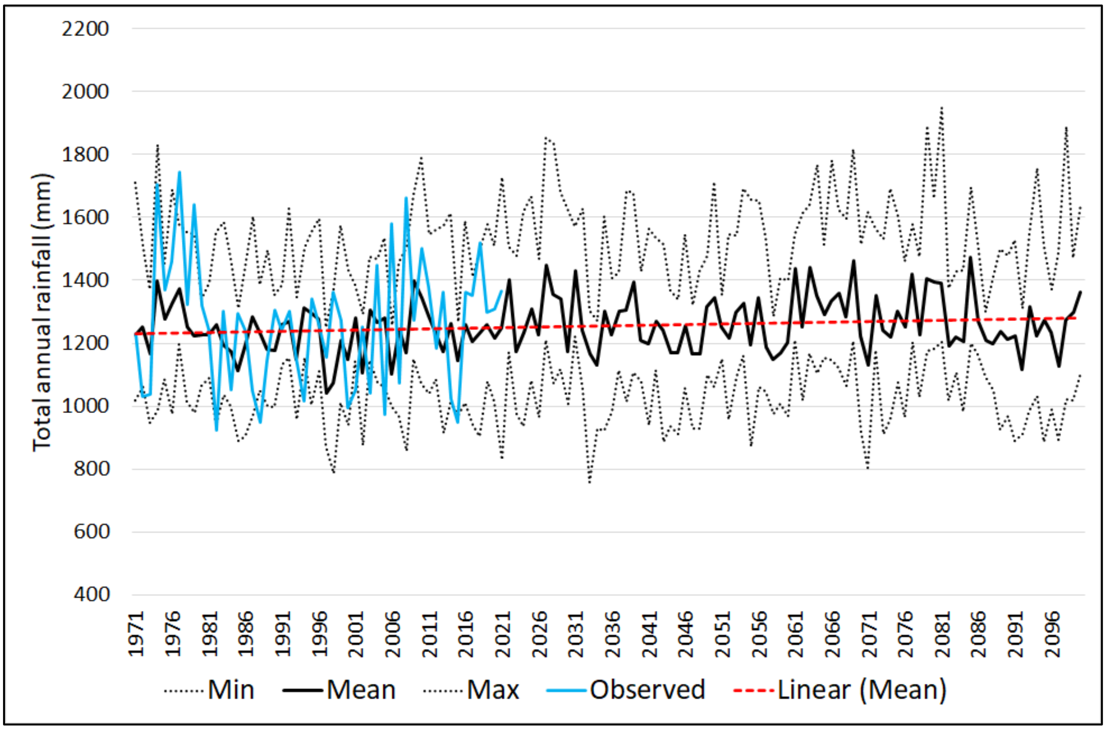


Figure A6: Model spread of RCP2.6 Wellington rainfall projections. Min, mean, and max of 6 GCM projections of Wellington annual rainfall, 1971-2100, linear least squares regression of mean, and observed rainfall (1971-2021).

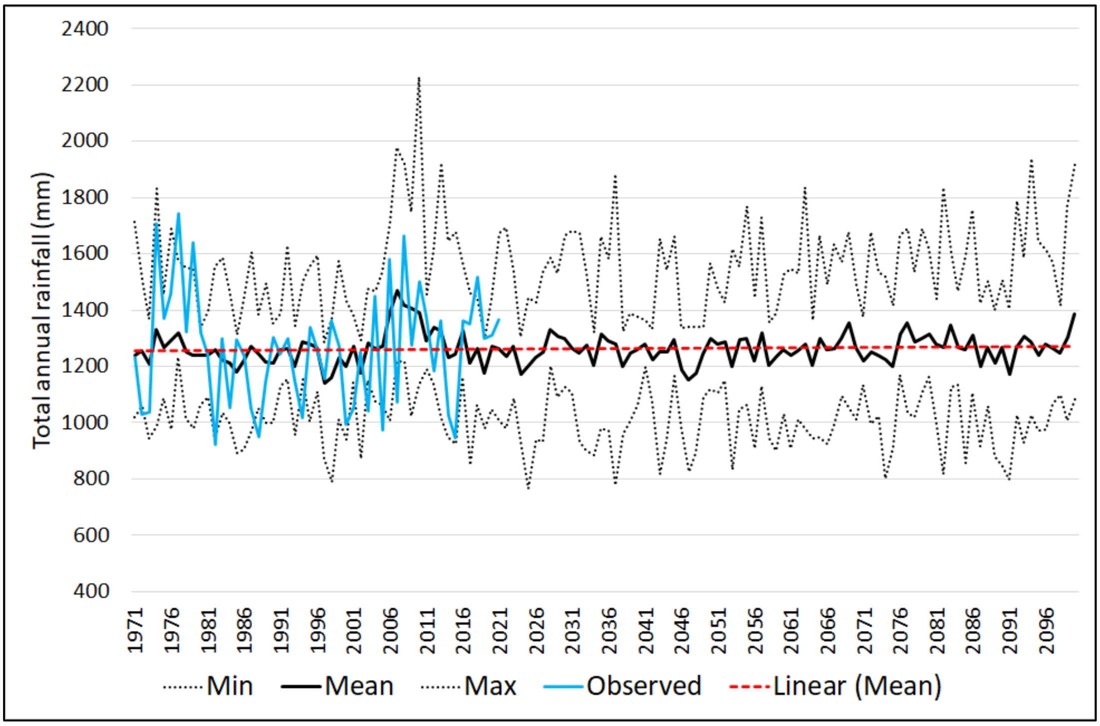


Figure A7: Model spread of RCP8.5 Wellington rainfall projections. Min, mean, and max of 6 GCM projections of West Coast Annual rainfall, 1971-2100, linear least squares regression of mean, and observed rainfall (1971-2021).

The Mean Absolute Percentage Error (MAPE) of observed rainfall vs rainfall predicted from the six model average for 1971-2021 for both RCPs is 13%.

The graphs show fairly flat projections of Wellington rainfall. The RCP2.6 scenario shows an average increase over the 120 year period of 4%, and the RCP8.5 scenario shows an average increase over the 120 year period of 1%.

Spread of projections from different global models

The spread of projections of Wellington rainfall for 2050 from different global models are shown in figure A8.

It can be seen that projections between different models for the period 2020-2050 vary in both magnitude and direction, and that RCP8.5 changes are not necessarily higher than RCP 2.6 changes, as would be expected.

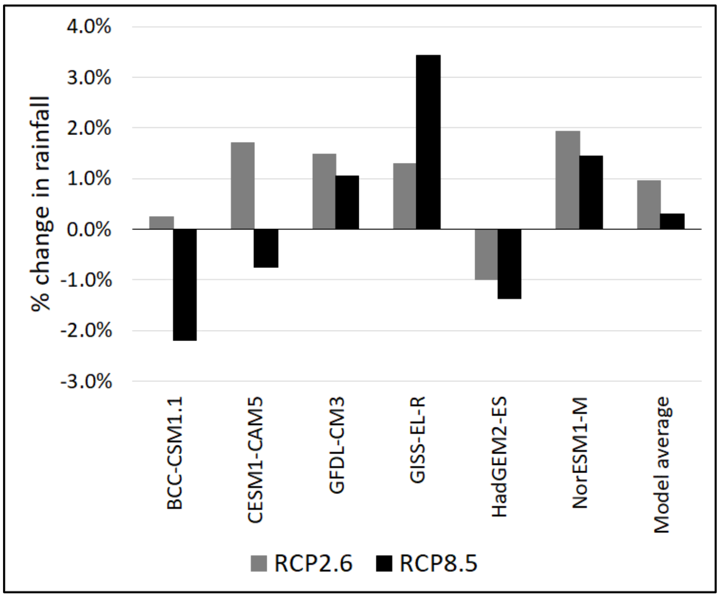


Figure A8: Projected change in Wellington rainfall between 2020 and 2050 for six global models (downscaled using an RCM), for RCP2.6 and RCP8.5.

It can be seen that the spread of model projections is larger in Wellington (ie. less certainty), ranging from a -2.2% change in annual rainfall between 2020 and 2050, to a +3.4% change.

Summary of Error

An appropriate methodology for representing multi-model, multi-RCP projections over long time periods is to use the average of the ensemble of models, for a middle of the road emissions scenario, and to smooth projections over time periods or use linear or non-linear trends rather than individual datapoints.

It is important that, for the adjustments in Table 2 and Table 3 of this document:

- The DIRECTION of change (+ve or -ve) for each week for each region should be maintained.
- The RELATIVE change between seasons and regions should be maintained.
- However, the MAGNITUDES can be toned down a bit, as long as the direction of change and relativity between regions is maintained.

So, for example, all adjustments in Tables 2 or 3 could be multiplied by 0.95 before use in modelling, if a lesser impact on model outcomes was required, as long as ALL data in the tables was adjusted in a similar fashion. Similarly, using 2050 projections to represent 2060 or 2065 would also be an appropriate way to “tone down” impacts in downstream modelling.

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