Prepared by Bodeker Scientific for the Queenstown Lakes District Council

Climate change implications for the Queenstown Lakes District

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Table of Contents

Contents

1. Executive summary

As a result of climate change, the Queenstown Lakes District (QLD) is likely to warm by several degrees by the end of the 21st century, with some parts of the District potentially warming by up to 7°C under a high greenhouse gas (GHG) emissions scenario. While total annual precipitation is not projected to change much across the District, the distribution and intensity of rainfall is likely to change, with a greater likelihood[1] of more extreme rainfall events. The total snow volume that accumulates on QLD mountain ranges over the winter, and then melts in spring and summer, is projected to reduce significantly by the end of the century as a direct result of increasing temperatures and rising snowlines. By the end of the century, under the highest GHG emissions scenario, the District could expect:

- An increase in annual maximum temperatures of between 1 and 7°C depending on the location within the District.
- A considerable reduction in mountain snow-packs and resultant water storage, with snow-melt occurring earlier in each season, leading to a reduction in the volume of water from snow-melt being available through the spring melt season.
- Precipitation that would previously have fallen as snow and been stored in the snowpack will instead be more likely to fall as rain and contribute more immediately to variability in river flows and lake levels.
- Extreme rainfall events are likely to increase in intensity due to more moisture being held in a warmer atmosphere.
- On average, about 12 to 64 fewer frost days, and up to 60 more `summer day's' (daily maximum temperature above 25°C) each year.
- Summers in the QLD will get warmer with the seasonal (December-February) maximum temperatures increasing by as much as 6 to 9°C, and summer season daily minimum temperatures increasing between 2°C and 3°C, under the very high emissions scenario and depending on location.
- Winters (June-August) in the QLD will also get warmer with the seasonal lowest minimum temperatures increasing by as much as 2 to 3°C and the winter season highest daily maximum temperatures increasing by 5 to 7°C compared to the baseline period (2000 to 2009), under the very high emissions scenario and depending on location.

The potential impacts of these climate changes for the District include:

- Higher temperatures that may allow for different crop types to be grown. It is likely that crops could be sown earlier in the growing season and will reach maturity faster.
- Increased heat stress from heatwaves, with adverse impacts for human health, particularly for vulnerable age groups (the very young and the very old), and for stock.

[1] 'Likely' here corresponds to a 66-100% probability under the IPCC terminology - refer to Appendix B for details.

- Changes in the range and habitat of native flora and fauna, as well as the distribution of pest species and crop diseases.
- Changes in the timing of seasonal activities such as flowering, breeding, and migration.
- Increased temperatures heightening the risk associated with wild-fire, particularly for forested areas.
- Higher intensity extreme rainfall events may lead to increased likelihood of landslides and flooding.
- Extreme precipitation events during winter may result in very high snowfall with implications for road hazards and avalanche risk – noting that overall annual snow accumulation may simultaneously diminish.
- A reduction in the number of winter frost days is likely to see a reduced hazard from ice on roads.
- A range of likely effects on roading from higher summer temperatures, which may affect construction and cause heat damage (e.g., damage to bitumen).
- An increase in the likelihood of flood events caused by extreme rainfall, snowfall or snowmelt runoff which may increase the potential for greater damage to bridges and roads and stretch the capacity of stormwater infrastructure.
- Increased demand for potable water as temperatures rise.
- Changes in the characteristics of snowfall and snowmelt, which has implications for the management of ski-fields and the capacity for hydroelectric power generation.
- Possible indirect effects from climate change pressures outside of the District - for example, sea level rise affecting areas around Dunedin (and elsewhere) which may further increase the demand for housing in the QLD.

2. Background

This report provides an analysis of both historical and projected changes in the climate of the QLD, including an assessment of changes in the following six essential climate variables (ECVs):

1. Temperature
2. Wind
3. Relative humidity
4. Precipitation (rainfall and snowfall)
5. Snowpack as a resource
6. Solar radiation

Historical changes in these climate variables[2] for the QLD have been diagnosed from analyses of climate data collected in the New Zealand National Climate Database[3]. Projections of changes in the climate variables have been extracted from regional climate model (RCM) simulations conducted under the auspices of the Deep South National Science Challenge. In addition, we assess projected changes in rainfall based on data extracted from the High Intensity Rainfall Design System (HIRDS).

The report includes an assessment of potential implications for Council services (water, storm-water, sewerage, local roading, and emergency response activities) and considers potential changes in snowpack and implications for industries including, recreation, tourism and energy. We have provided context for these potential impacts based on existing literature.

The analysis in this report incorporates the following key elements:

- Assessment of historical changes in the six ECVs for the region to the extent that measurement time series are available. This includes an examination of historical changes in selected extreme weather events in the District.
- Projections of changes in the selected ECVs under four representative concentration pathway (RCP) emissions scenarios (i.e. RCP2.6, RCP4.5, RCP6.0 and RCP8.5) to 2100.
- Advanced simulation approaches such as use of the EPIC method to estimate uncertainties on the range of projections of changes in the ECVs under any single RCP scenario.
- An outline of a range of implications of climate change for the consideration of the Council.

[2] For both wind-speed and solar radiation few long-term measurements were found for the District. For relative humidity, no sufficiently long-term records were identified within the District to allow for robust analysis of trends.
[3] https://cliflo.niwa.co.nz/

2.1. Climate change in New Zealand

The latest report on climate change projections for New Zealand from the Ministry for the Environment[4] is based on approaches taken by the Intergovernmental Panel on Climate Change (IPCC). The climate research community has **very high confidence[5]** that New Zealand's climate is changing with long-term trends toward higher surface air and sea surface temperatures. However, as a result of the thermal buffering effect of the ocean surrounding New Zealand, changes in climate over New Zealand to date have been less severe than over other locations at similar latitudes, such as Australia and Southern Africa. It is **virtually certain** that warming will continue through the 21st century along with other changes in climate. We have **very high confidence** that warming will drive rising snowlines, and **high confidence** that there will be more frequent hot extremes and less frequent cold extremes. Projections in rainfall are more difficult to simulate with confidence and so there is only **medium confidence** that New Zealand will experience an increase in extreme rainfall and related flood risk. In general, rainfall is expected to decrease in the northeast of the South Island and northern and eastern North Island and will **likely increase** over other parts of New Zealand but not everywhere. While regional sea level rise will **very likely** exceed the rate seen over 1971-2010, this, of course, will have no direct impact on the QLD.

2.2. The Paris Agreement on climate change

The Paris Agreement on climate change is an agreement within the United Nations Framework Convention on Climate Change (UNFCCC) dealing with GHG emissions mitigation, adaptation and finance, starting in 2020. The stated goal of the agreement is to limit increases in global mean surface temperature to "well below" 2°C above pre-industrial levels, with an ambitious additional goal of keeping warming below 1.5°C "if possible". The content of the agreement was negotiated by representatives of 196 parties at the 21st Conference of the Parties of the UNFCCC in Paris and adopted by consensus on 12 December 2015. New Zealand is a member of the Paris Agreement High Ambition Coalition committed to keeping increases in global mean surface temperature below 1.5°C above pre-industrial conditions.

The impacts of global warming of 1.5°C above pre-industrial levels were assessed in a recent IPCC report (IPCC, 2018). The report outlines that if current GHG emissions rates continue, the 1.5°C limit could be exceeded as soon as 2030 or at the latest by 2052. Therefore, the global community must reduce GHG emissions as quickly as possible to avoid or delay exceeding that limit. Restricting warming to 1.5°C requires a mammoth global effort, including reducing the use of fossil-fuels by 50% within 15 years and eliminating them entirely within 30 years. In addition, it is likely that large-scale capture and storage of CO_2 will be required – technology that does not yet exist at scale.

The IPCC report finds that "risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C". It paints a dire picture of the impacts of 2°C of global warming, including 50% more people facing water stress compared to a 1.5°C world.

As of February 2019, 195 UNFCCC members have signed the Paris Agreement, and 185 members, including New Zealand, have ratified it. In the Paris Agreement, each country determines, plans and regularly reports the contribution it should make to mitigate climate change – these were communicated at the time as "Intended Nationally Determined Contributions" (INDCs). These INDCs are not legally binding as there is no mechanism to force a country to set and adhere to a specific target by a specific date. Once ratified, the INDCs become NDCs, and New Zealand ratified the

[4] Climate Change Projections for New Zealand (2018). Available at: http://www.mfe.govt.nz/node/21990
[5] See Appendix B: for definitions of IPCC terminology on confidence and likelihood.

national target in October 2016. New Zealand's NDC is to reduce GHG emissions by 30% below 2005 levels by 2030.

According to a study published in *Nature* in June 2016, current country pledges are insufficient to meet the Paris Agreement goal of keeping global mean surface temperature rise to well below 2°C (Rogelj *et al*, 2016).

2.3. Local government and climate change

Local government in New Zealand has recognised the need for coordinated collaboration between local and central government, together with other active agencies, to achieve New Zealand's NDC. Around half of the Mayors and Chairs of Councils across New Zealand have signed the Local Government Leaders' Climate Change Declaration[6] and Local Government Climate Change Position Statement[7], including the Mayor of the QLD. A key component of the declaration and statement is the requirement to act at a local level to ensure that both adaptation to climate change and mitigation of emissions is effectively progressed.

2.4. Snow in New Zealand

New Zealand relies on snowmelt to provide a more even seasonal distribution of water for irrigation and power generation. Furthermore, snow and ice form a vital component of the tourism and recreation industry in the form of ski fields and glaciers, particularly important in the QLD. Seasonal accumulation and melt of snow is an important control on the hydrological cycle as the snowpack stores and regulates the release of water. Water from snowfall is released into rivers days, months or decades after precipitation events. Seasonally variable snow controls the long-term input and volume of glaciers (Fitzharris *et al*., 1999; Sirguey, 2009; Cullen *et al*., 2016).

Snowmelt contributes more than 10% to the total annual flow for several large rivers in the South Island, including the Clutha River (Kerr, 2013), and often controls seasonal variation in flow. The accumulation of snow during winter provides up to 20% of the water storage needed for irrigation and provides an important enhancement to base stream flow during the spring growth season (Kerr, 2013). The year-to-year variability in the volume of snow accumulated in snow-packs therefore creates uncertainty in the energy (hydro-power generation), agriculture, and recreation and tourism sectors.

Long-term changes in snowpack volumes are sensitive to climate change, and it is expected that seasonal snowpack volumes will decrease in a warming climate (Hendrikx *et al*., 2012). More winter precipitation is anticipated to fall as rain, resulting in less accumulated snow and therefore reduced contributions of snowmelt to river flows in spring.

[6] www.lgnz.co.nz/our-work/publications/local-government-leaders-climate-change-declaration-2017
[7] www.lgnz.co.nz/our-work/publications/local-government-position-statement-on-climate-change

3. Methodology

3.1. Climate indices

When assessing the effects of climate change on a region, indices provide a useful means of quantifying and communicating changes as they are derived to provide insights into potential impacts of changes in the climate system. For this study, several indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI[8]) are reported on. Additional indices were also constructed specifically for this report to quantify and communicate estimates of the impacts of climate change of interest to the QLD. The indices used in this report are summarised in Table 1.

Table 1: List of climate indices used in this study to quantify changes in climate for the QLD.

Temperature Indices	
Frost days	Number of days, over some specified period (usually 1 year), where daily minimum temperature is less than 0°C.
Summer days	Number of days, over some specified period (usually 1 year), where the daily maximum temperature is greater than 25°C.
Highest daily maximum temperature	Peak value of daily maximum temperature (in °C) over a specified period (usually 1 year, when it is equivalent to the annual maximum temperature).
Highest daily minimum temperature	Peak value of daily minimum temperature (in °C) over a specified period (usually 1 year).
Lowest daily maximum temperature	Lowest value of daily maximum temperature (in °C) over a specified period (usually 1 year).
Lowest daily minimum temperature	Lowest value of daily minimum temperature (in °C) over a specified period (usually 1 year, when it is equivalent to the annual minimum temperature).
Precipitation Indices	
Length of dry spell	Maximum number of consecutive days over a specified period (usually 1 year) with daily precipitation amounts less than 1 mm.
Length of wet spell	Maximum number of consecutive days over a specified period (usually 1 year) with daily precipitation amounts greater than or equal to 1mm.
Maximum 1-day precipitation	Maximum in 1-day precipitation (in mm) over a specified period (usually 1 year).

[8] http://etccdi.pacificclimate.org/indices.shtml - within the World Climate Research Programme

Maximum consecutive 5-day precipitation	Maximum in 5-day precipitation (in mm) over a specified period (usually 1 year).
Precipitation intensity	Simple Daily Intensity Index representing the sum of the daily precipitation amount on wet days (precipitation > 1 mm) divided by the number of wet days over a given period (usually 1 year), in units of mm/day.
Heavy rainfall days	Number of days with precipitation ≥ 10 mm over a specified period (usually 1 year).
Total precipitation	Total precipitation (in mm) on days with more than 1 mm of rainfall over a specified period (usually 1 year).
Relative Humidity	
Average Relative Humidity	Average daily relative humidity (in %) at 1.5m in elevation over a specified period (usually 1 year).
Low humidity days	Number of days when relative humidity < 25% over a specified period (usually 1 year).
High humidity days	Number of days when relative humidity ≥ 75% over a specified period (usually 1 year).
Minimum relative humidity	Minimum relative humidity (in %) over a specified period (usually 1 year).
Maximum relative humidity	Maximum relative humidity (in %) over a specified period (usually 1 year).
Solar insolation	
Average solar insolation	Average surface insolation over a specified period (usually 1 year).
Low solar insolation days	Number of days over a specified period (usually 1 year) when the daily average surface insolation < $50Wm^{-2}$.
High solar insolation days	Number of days over a specified period (usually 1 year) when the daily average surface insolation >= $250Wm^{-2}$.
Solar insolation minimum	Minimum of the daily average surface insolation over a specified period (usually 1 year).
Solar insolation maximum	Maximum of the daily average surface insolation over a specified period (usually 1 year).
Wind	
Average wind-speed	Average wind-speed at 10m in elevation over a specified period (usually 1 year).

Light wind days	Number of days when wind-speed < $5ms^{-1}$ over a specified period (usually 1 year).
Strong wind days	Number of days when wind-speed ≥ $5ms^{-1}$ and ≤ $20ms^{-1}$ over a specified period (usually 1 year).
Minimum wind-speed	Minimum wind-speed over a specified period (usually 1 year).
Maximum wind-speed	Maximum wind-speed over a specified period (usually 1 year).

3.2. Historical climate change

Historical climate trends are examined for locations within the District which have long-term measurement records of each of the ECVs. Time series of measurements from selected sites have been carefully analysed to detect gaps or discontinuities in the data record, e.g. changes associated with the introduction of a new instrument type, relocation of instruments, or changes to site characteristics. Where sufficiently long records are available for the climate indices (Table 1), we have calculated linear trends using a regression model that incorporates the effects of autocorrelation on the regression model residuals (Tiao *et al.*, 1990) to derive robust assessments of the uncertainty on the trends. Trends are reported together with their 1σ uncertainties (i.e., there is a 68% probability that the trend is lies between the bounds specified by the stated uncertainty).

For each of the temperature indices, we indicate where trends in annual means that are statistically significantly different from zero at the 1σ level are found over the historical record at each site (depending on how far back the record stretches for each of the sites). For each of the precipitation indices, we indicate where statistically significant trends (trends that are different from zero at the 1σ level) are found over the historical record covering the period since 1960. In addition to the records for the stations analysed below, precipitation data for thirteen additional stations in the District were supplied by the Council. However, given that their records only extended back to 2013, the data collected from these stations are currently not suitable for detecting long-term changes in precipitation. As their records grow, and as long as they are sufficiently well curated to ensure their long-term homogeneity and quality, these thirteen time-series are expected to become an increasingly valuable resource for detecting changes in precipitation for the region.

3.3. Projections of climate change

To diagnose potential future changes in each of the ECVs, we analyse for their changes at mid-century (centred on 2045) and at the end of the century (centred on 2095) against a base-period of 2000-2009. Simulations conducted with a regional climate model (RCM) were used to generate daily fields of temperature and precipitation at 5 km x 5 km resolution, from which the indices detailed in Table 1 were calculated. Analyses of changes in the frequency of extreme events uses the EPIC approach (Ensemble Projections Incorporating Climate model uncertainty; Lewis *et al.* 2017). EPIC generates large ensembles of projections from a small number of RCM simulations to provide improved representation of uncertainties in the projections and a better representation of extreme events which, by their nature, are very infrequent. Ensembles of EPIC simulations are large collections of simulations that capture a wide variety of sources of uncertainty in possible climate states under the single GHG emissions scenario for which it is run. EPIC allows the generation of such ensembles in a highly cost-effective way.

The indices are averaged seasonally (i.e., 3-monthly means) and are then used as training data for EPIC to identify how they change with respect to changes in annual mean global mean surface temperature. The EPIC method was adapted for this report so that it could be applied to time series of temperature, precipitation, wind, humidity and solar radiation indices.

Projections of changes in climate over the next 10-30 years are more likely to be sensitive to influences that do not result from accumulation of GHGs in Earth's atmosphere; there are long-term processes active in the climate system that can drive climate trends over periods of a decade or more. As we look further into the future, these drivers of medium-term climate variability are overwhelmed by human-induced (anthropogenic) effects on climate such that the anthropogenic signal in the climate record becomes more apparent - climate scientists like to talk about 'the signal emerging from the noise'. By incorporating a wider range of models and by conducting a larger number of simulations, EPIC mitigates the limitations of a small ensemble of RCM simulations. The results presented below are the decadal averages taken from 188 EPIC simulations.

Projections were generated for the 4 different Representative Concentration Pathways (RCPs) to provide an indication of the impact of different potential GHG emissions pathways on the climate of the QLD. RCPs provide a means of creating a self-consistent set of climate projections by defining different plausible scenarios of concentrations of GHGs arising from different global socio-economic development pathways. The scenario resulting in the lowest GHG concentrations, with an associated increase in global mean radiative forcing of 2.6 Wm^{-2} by 2100 (RCP2.6) represents a best-case scenario, with GHG concentrations peaking and declining before 2100. In the scenario resulting in 8.5 Wm^{-2} of additional radiative forcing of the climate system by 2100 (RCP8.5), GHG emissions increase throughout the century; this is often considered the 'take no action' scenario. RCP4.5 and RCP6.0 are also used as they provide pathways between RCP2.6 and RCP8.5. Additional detail on the RCP scenarios is provided in Appendix A.

In addition, for precipitation, data were extracted from the New Zealand High Intensity Rainfall Design System (HIRDS[9]) for five sites across the District (Queenstown, Wanaka, Makarora, Albert Burn, Glenorchy). HIRDS allows for estimates of the magnitude and frequency of high intensity rainfall at any point in New Zealand and is commonly used by engineers to plan and design stormwater drainage, flood defence systems, and other vital infrastructure. HIRDS analysis is based on the same six RCMs, and the same four RCPs used in the other analysis carried out here. However, output is in the form of total precipitation or intensity for a range of storm durations and return periods.

The return period is usually expressed in terms of the 'annual recurrence interval (ARI)', which is the average expected length of time between exceedances of a given rainfall total accumulated over a given duration. Alternatively, the 'annual exceedance probability' (AEP) can be used, which describes the probability of a given rainfall amount over a given duration being exceeded in any one year. So, by way of example, an event with a 100-year ARI (100-year return period), has an AEP of 1% (i.e., a 1% chance of occurring in any given year).

3.4. Snow model projections

Using a temperature-index snow model (Clark *et al*. 2009), where snow occurrence depends on both precipitation rate and air temperature, we calculate snow accumulation and melt for all mountain ranges in the QLD. This then provides estimates of the total volume of water stored in the winter snowpack (i.e., snow water equivalent).

The snow model accounts for (i) reduced snow-melt due to lower solar radiation in winter, (ii) reduced snow-melt after fresh snow fall, and (iii) enhanced melt during rain-on-snow events. The model requires hourly data for temperature and precipitation for the region of interest. Here, daily output from several regional climate model simulations, for four RCP emissions scenarios, are used to generate

[9] Data from: https://hirds.niwa.co.nz/search

hourly gridded temperature and precipitation data as described in Clark *et al*. (2009). The results presented here are based on six RCM simulations[10], where each simulation is assumed to represent an equally probable temperature and precipitation time series over the 2000 to 2100 period. While this assumption may not be entirely correct, owing to variation in the quality and complexity of the individual RCMs, there is a great deal of subjectivity in selecting which RCMs should have greater weighting over others.

Here we present projected changes in the snow-covered area and snow cover duration, compared with the present-day climate (2000-2009). These are averaged over all six RCM simulations, for all mountain ranges, and all four RCP emissions scenarios (see below). Coarse spatial resolution output is converted to higher resolution (250 m x 250 m) format, using base-period temperature and precipitation data (adjusted for rain-gauge under-catch which is a well-known issue with rainfall and snowfall measurement) which were interpolated for previous work carried out at the University of Otago (Jobst, 2016).

[10] For RCP6.0 the output from only four GCMs were available for analysis

4. Results

Figure 1 displays a map of the District, indicating the location of stations used in this analysis.

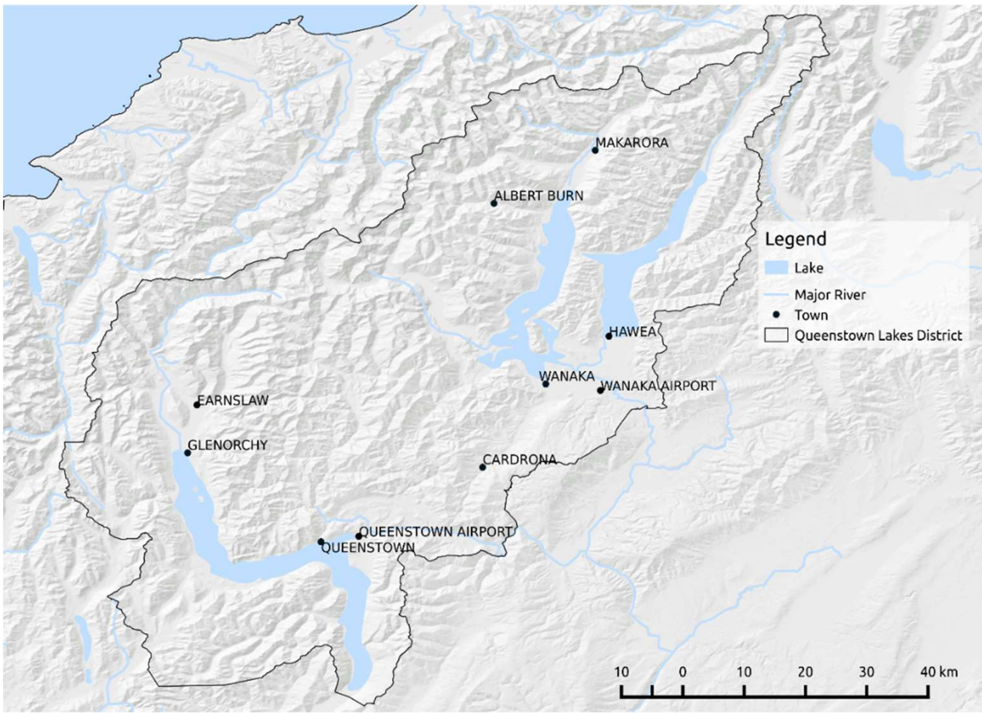

Figure 1: Locations of key climate stations for which data are analysed in this report.

4.1. Historical change

4.1.1. Temperature

Four sites were available for extracting relatively long-term temperature data from within the District (Table 2). The longest of these (Queenstown) extends from at least 1930, with some measurements at that site extending back even further.

Site	Period of data availability
Queenstown	1930-2018
Wanaka Airport	1992-2018
Queenstown Airport	1992-2018
Albert Burn	2008-2018

Table 2: Sites for which long-term temperature records are available

Annual frost days

The annual number of frost days has reduced by about 21±3.5 days since 1930 in Queenstown (i.e., a trend of 0.24±0.04 fewer frost days year on year – see Figure 2, left). At Wanaka Airport, the number of frost days has reduced by 31±5.2 days since 1992 at (i.e., a trend of 1.2±0.20 fewer frost days year on year). Both trends are statistically significant at the 1σ level. Unsurprisingly, the reduced number of frost days occurs during the autumn and winter months. While Albert Burn appears to have shown a significant reduction in the number of frost days since 2008, the ~10-year period since 2008 is too short to draw a robust conclusion regarding the likely persistence or importance of this change.

Queenstown Airport has seen no statistically significant trend in the annual number of frost days since 1992.

Annual summer days

A statistically significant increase in the annual number of summer days has occurred in Queenstown since 1930 (22±3.4 more days with daily maximum temperatures >25°C), corresponding to a trend of 0.26±0.04 more days per year over the 88-year period (Figure 2, right). Both Wanaka Airport (0.55±0.19 days/year) and Queenstown Airport (0.57±0.16 days/year) now experience 14-15 more summer days per year since 1992. Again, it is no surprise to find that the increase in the number of summer days occurs during the spring and summer months.

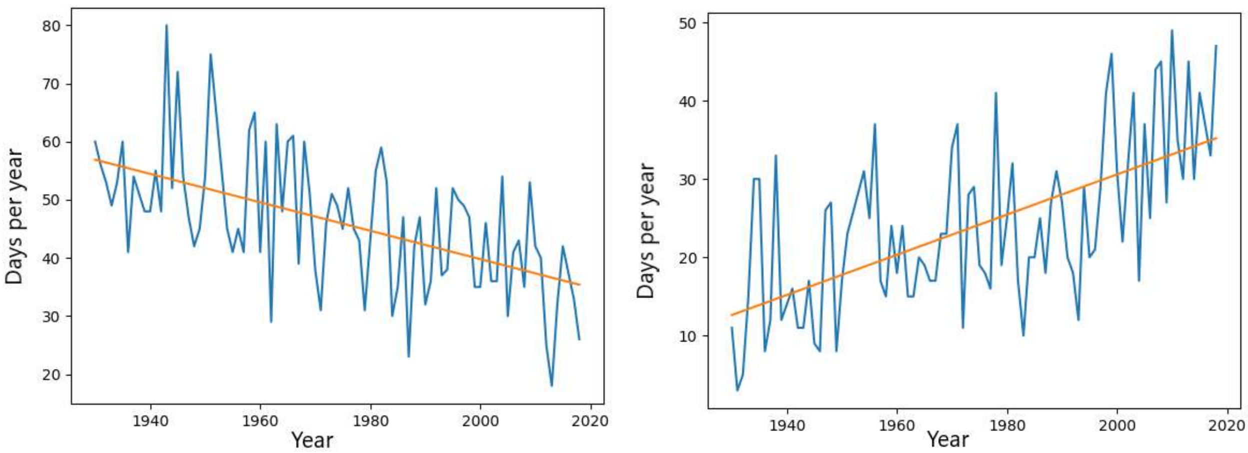

Figure 2: The annual number of frost days (left) and the annual number of summer days (right) for Queenstown. The blue line shows the annual values, while the orange line is the regression fit to the data.

Annual highest temperature

Over 1930 to 2018, Queenstown has shown a statistically significant trend of 0.30±0.07°C/decade in the annual maximum temperature, corresponding to an increase of 2.2±1.1°C in this metric over the period. For Queenstown airport, over the period 1992 to 2018, the trend in annual maximum temperature has been 0.96±0.46°C/decade, corresponding to an increase of 2.5±0.58°C over the period. No statistically significant trend is apparent for either Albert Burn or Wanaka Airport.

Annual peak daily minimum temperature

Over 1930 to 2018, Queenstown has experienced a trend of 0.11±0.05°C/decade in annual peak daily minimum temperatures, corresponding to an increase of 0.90±0.45°C in this metric over the period. At Albert Burn, there appears to be an increase in annual peak daily minimum temperature of about 1°C since 2008, but this record is too short to have confidence in the statistical significance of that trend. There is no statistically significant change at Queenstown Airport or Wanaka Airport.

Annual lowest daily maximum temperature

Over 1930 to 2018, Queenstown has experienced a trend of 0.12±0.05°C/decade in annual lowest daily maximum temperatures, corresponding to an increase of 0.98±0.44°C over the period. At Wanaka Airport, there has been a trend of 0.41±0.26°C/decade since 1992, corresponding to an increase of 0.94±0.61°C in this metric over the period. For Queenstown airport, the trend in annual lowest daily maximum temperature has been 0.57±0.27°C/decade since 1992, corresponding to an increase of 1.3±0.63°C over the period. Neither of the other stations show a statistically significant change.

Annual lowest temperature

Over 1930 to 2018, Queenstown has experienced a trend of 0.10±0.05°C/decade in the annual lowest temperature, corresponding to an increase of 0.87±0.40°C in this metric over the period. Wanaka Airport has experienced a trend of 0.72±0.36°C/decade from 1992 to 2018 in annual lowest temperature, corresponding to a net increase of 1.7±0.40°C over the period. Neither Queenstown Airport nor Albert Burn exhibit statistically significant trends in this metric.

Temperature Summary

In summary, the nearly 90 years of data collected at the Queenstown site allows us to confidently conclude that annual highest and lowest daily maximum and minimum temperatures have increased by between 0.9°C and 2.2°C, with 18-24 fewer frost days each year and 19-25 more summer days each year since 1930. Shorter records at the other sites lead to less robust conclusions but the conclusions that can be drawn are consistent with the changes observed at Queenstown. Efforts to gather historical climate data from non-traditional sources (e.g. Weather Underground[11] or weather logs maintained by farmers) could lead to a richer database from which long-term historical changes in climate could be inferred.

[11] https://www.wunderground.com/

4.1.2. Precipitation

Precipitation data from across the District was extracted at four sites where relatively long-term data were available (Table 3).

Site	Period of data availability
Cardrona	1960-2014
Earnslaw	1960-2014
Hawea	1960-2009[12]
Queenstown	1960-2015[13]

Table 3: Sites for which long-term precipitation records are available

Total precipitation

Over 1960-2015, the total annual precipitation at Queenstown (Figure 3, left) has shown a trend of 20±13 mm/decade, corresponding to a net increase of 112±74 mm over the nearly 60-year period (i.e., increasing from ~800 to ~900 mm total annual precipitation). No statistically significant trend is

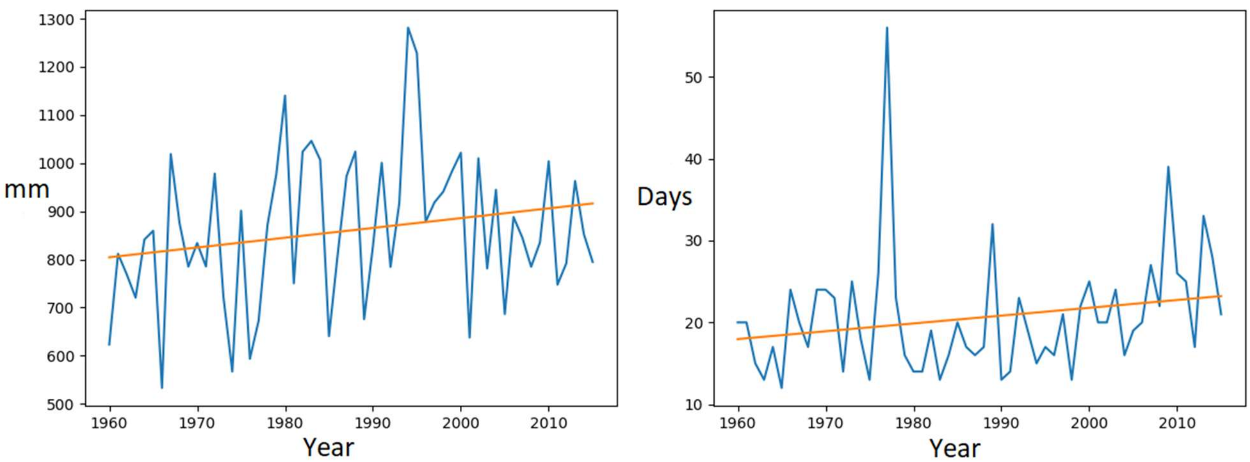

Figure 3: Total annual precipitation (left) and the length of dry spells (maximum number of consecutive dry days, right) for Queenstown. The blue line shows the maximum annual value, while the orange line is the regression fit to the data.

apparent for Earnslaw, Hawea or Cardrona. There is no evidence of a significant change in total seasonal precipitation since 1960 at any of these four sites.

Length of dry spell

Since 1960, the length of dry spells at Cardrona has shown a trend of 1.3±0.54 days/decade, corresponding to an increase in the annual maximum longest dry spell of ~20 consecutive dry days in the 1960s, to ~25 consecutive dry days in the early 2000s, with several recent years exhibiting over 40 consecutive dry days. Statistically significant trends in this metric are also seen for Earnslaw (0.75±0.64 days/decade) and Queenstown (0.95±0.70 days/decade, Figure 3, right), in both cases corresponding to an increase from around 18 to 22 consecutive dry days. For Hawea, an increase in

[12] Records ceased for a variety of reasons, including rationalisation of the network. In the case of this station, the recording ended as a result of the observer passing away.
[13] This site is still operating, but due to an issue with the data portal we were only able to extract data to 2015.

the length of dry spells has also been seen, with 5.7± 2.4 more days in dry spells currently compared to 1960 (i.e., a trend of 2.5±0.42 days/decade).

Heavy rainfall days

The number of heavy rainfall days (≥ 10mm/day) has shown a statistically significant increase in Cardrona (from around 17 days in 1960 to around 21 days per year presently), corresponding to an increase of 0.96±0.64 days/decade. Queenstown has also seen an increase in the number of heavy rainfall days (from 26 to 31 days per year), which corresponds to a trend of 0.80±0.39 days/decade. Neither Earnslaw nor Hawea display any significant trend for this metric.

Length of wet spell

None of the four sites analysed here demonstrate a significant trend.

Maximum 1-day / consecutive 5-day precipitation

There is no statistically discernible trend in the maximum precipitation over a 1-day period for any of the four sites for which sufficiently long precipitation records are available. For consecutive 5-day precipitation, only Queenstown has experienced a statistically significant increase, from 80 mm in 1960 to around 100 mm in 2015 (i.e., 3.81±2.30mm increase per decade).

Precipitation intensity

A statistically significant increase in precipitation intensity is seen at Cardrona (from 7 mm/day around 1960 to 8 mm/day currently), which corresponds to an increase of 0.13±0.11 mm/day per decade. Hawea has also seen an increase in intensity of 0.572±0.484 mm/day (trend of 0.13±0.11 mm/day per decade). Precipitation intensity in Queenstown has increased from 8 to 9 mm/day (i.e., change of 0.18±0.10 mm/day per decade). Earnslaw sees an increase in intensity of 0.572±0.475 mm/day (i.e., trend of 0.13±0.11 mm/day per decade).

Precipitation Summary

In summary, over the 55 years examined here for the Queenstown site it is observed that total precipitation has increased by approximately 100mm per annum, but with a concomitant increase in both the length of dry spells and the number of heavy rainfall days (both up by about 5 days), as well as a greater volume of precipitation in a consecutive 5-day period (up by about 25%), and increased average rainfall intensity (up by about 1mm/day). Fewer statistically significant results and shorter records at the other sites limit the robustness of the conclusions from those sites, but where results are available, they appear generally consistent with the findings for Queenstown.

4.1.3. Wind-speed

Site	Period of data availability
Queenstown Airport	1979-2018
Queenstown	1972-2007[14]

Table 4: Sites for which long-term wind-speed records are available

Average wind-speed

The annual average wind-speed at Queenstown Airport (Figure 4) has increased by 0.657±0.179m/s, corresponding to an increase of 0.17±0.05 m/s per decade. The trend in average seasonal (3-monthly) wind-speed indicates no significant pattern of change. At Queenstown there has been a

[14] Wind-speed records at Queenstown were unavailable from 2008 onward.

statistically significant decrease in annual average wind-speed of about 1.3 m/s over the period 1972 to 2007 (from 3.0 to 1.7 m/s), corresponding to a decadal decrease of 0.4±0.17 m/s.

Light, moderate, strong wind days

For Queenstown airport there are now about 18.81±8.32 fewer low wind-speed days (wind-speed < 5 m/s) than observed in 1979 (a decrease of 4.95±2.19 days per annum). No trends are apparent for either Queenstown or Queenstown Airport for moderate or high wind-speed days, or for Queenstown for low wind-speed days.

Maximum wind-speed

No statistically significant change is apparent for annual maximum wind-speed at either Queenstown Airport or Queenstown. Nor does the maximum seasonal (3-monthly) wind-speed indicate any significant pattern of change at either site.

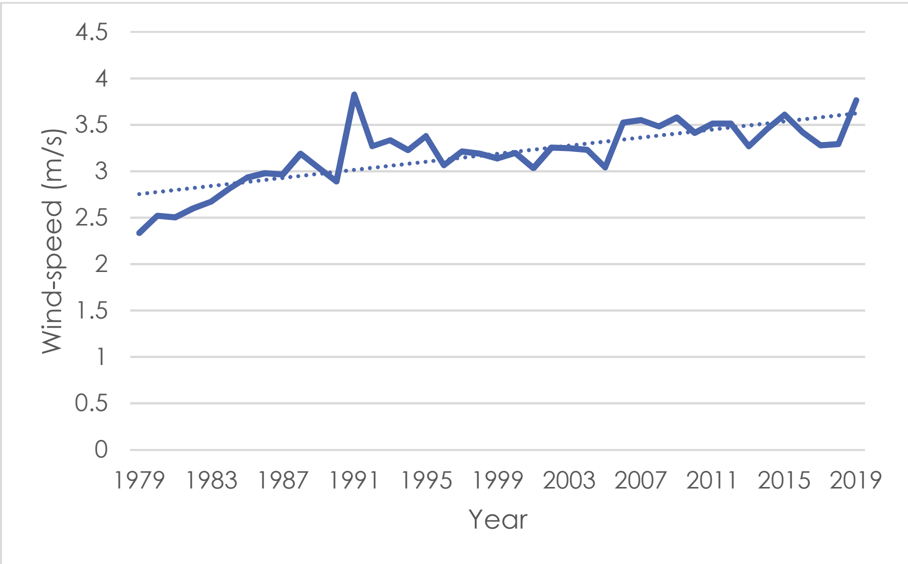

Figure 4: Average annual wind-speed at Queenstown airport, 1979-2019 (blue solid line) with the regression fit (blue dotted line).

4.1.4. Solar radiation

Site	Period of data availability
Queenstown Airport	1992-2018

Table 5: Sites for which long-term solar radiation records are available

Average, minimum/maximum, low/high

Of these metrics, only the annual maximum solar insolation over the period has shown a significant change at Queenstown Airport, having increased by 28.34±13.86 Wm^{-2} (or an increase of 10.9±5.3 Wm^{-2} per decade). No statistically significant trend at Queenstown Airport is found for average annual solar insolation, minimum solar insolation, or the number of high solar insolation (>= 250 Wm^{-2}) or low solar insolation (< 50 Wm^{-2}) days.

4.1.5. Relative Humidity

As noted above (Section 2), there were insufficient data for Relative Humidity (RH) to allow for analysis of this variable and any of its associated metrics. Analysis of RH metrics from the climate model output is included in the projections section (5.2.5) of this report.

4.1.6. Snow cover

The long-term variability of snow cover in the Southern Hemisphere is not well understood (Clark, 2009; Hendrikx, 2013). While longer term records do exist for glacier snowlines, they are limited by being an annual snapshot at a single point in time. These have indicated that over the last four decades, about one-third of the 'permanent' snow and ice on the Southern Alps has melted, but do not indicate how the seasonal snow-pack has altered over time.

Due to lack of measurements, physical models which simulate the snow conditions are commonly used in New Zealand and calibrated against satellite imagery. Previous research used the SnowSim snow model to estimate the behaviour of seasonal snow for the period from 1931 to 1993 (Fitzharris and Garr, 1995). No trend was apparent over that period, but large inter-annual variability was observed. High year to year variation is attributed to New Zealand's maritime climate and is exacerbated by the effect of snow being redistributed by strong winds (Fitzharris et al, 1999).

One method for mapping seasonal snow cover across the South Island hydro-lakes used MODIS satellite imagery for the period 2000-2007 at a spatial resolution of 250m and 500m (Sirguey et al, 2009). Satellite data can be compared with model data (Figure 5), which indicates discrepancies between measurements and model results, and highlights high inter-annual variability which can make it difficult to identify a long-term signal of change in the snow-pack. Recent work has used MODIS data to create a record of seasonal snow over the period 2000-2016 for the Clutha catchment (Redpath et al, 2019). Over that time period, no significant decrease in snow cover duration was observed.

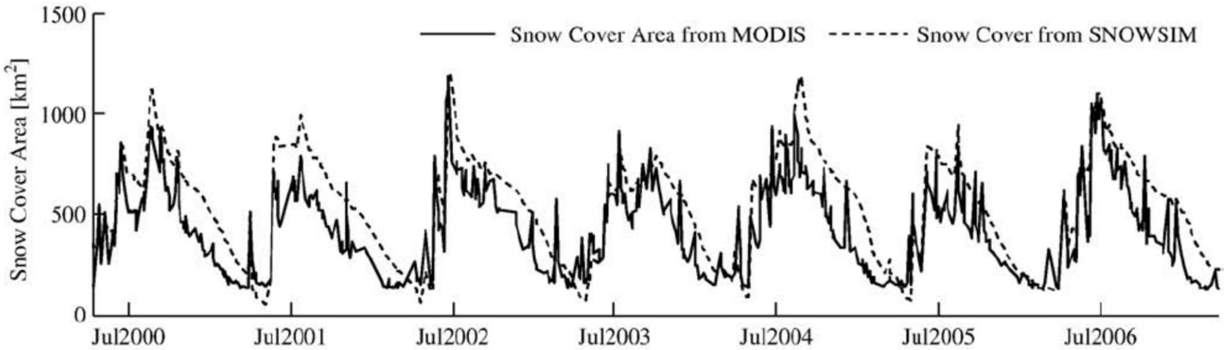

Figure 5: Time series of MODIS-derived snow-covered area in the Pukaki catchment compared to snow-cover predicted from the SNOWSIM model. Source: Sirguey et al (2009) – their figure 15.

Recognising the lack of robust historical snow records in New Zealand, the National Snow and Ice Monitoring Network (SIN) was set up in 2006 to monitor changes in this resource (Hendrikx and

Harper, 2013). This network currently has a total of 11 sites in the Southern Alps monitoring snow accumulation, with plans to expand this in the coming years[15].

4.1.7. Extreme events

In this section we provide a brief overview of some categories of extreme events at selected sites. A thorough investigation of the change in frequency and magnitude of such events is beyond the scope of this report. Flooding of Lake Wakatipu at Queenstown has been one of the most significant and high-profile extreme events experienced in the District. Figure 6[16] outlines the 10 highest lake levels since 1878 as well as showing the most recent flood event in 2013. Figure 7 (top right) provides a snapshot from the major event in 1999. Though it is difficult to attribute any single event to climate change, increased storm severity is consistent with the increased temperature and water-holding capacity of the atmosphere. Scientists are working on the developing new area of climate event attribution to identify the likelihood of such events happening in the absence of climate change – in some cases the modelling can show that a particular storm event would not have been likely to occur without the influence of climate change. Lake Wanaka has also been susceptible to flooding, with the 1999 event causing extensive damage to the Wanaka CBD. Other parts of the District have also been affected by lake flooding to varying extents (e.g., Glenorchy, Kingston, etc.).

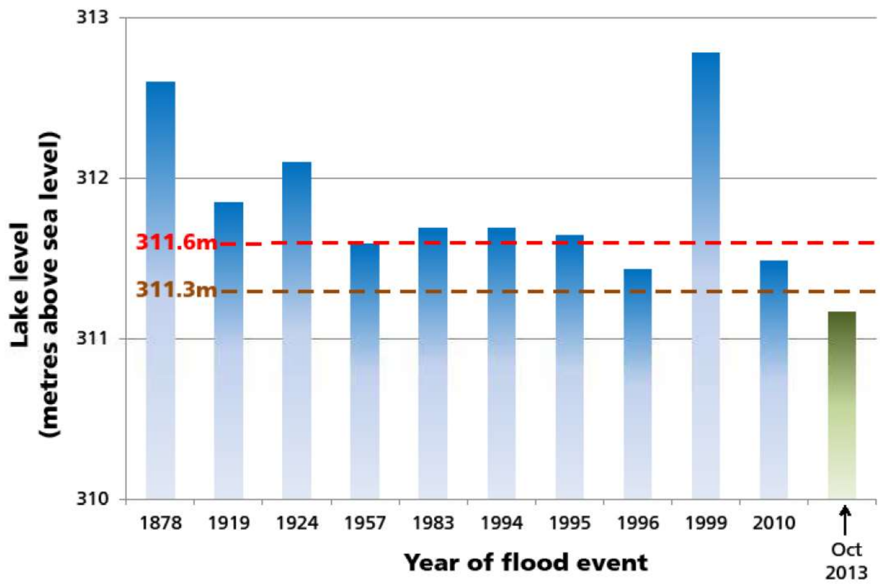

Figure 6: Historic 10 largest flood events at Lake Wakatipu, and the most recent high flood level in 2013 (Source: Otago Regional Council).

Other hazard types which are experienced across the District, and have the potential to be exacerbated by higher intensity or frequency rainfall include:

- Landslides: Steep and landslide-prone land has frequently been affected by landslide events.
- River flooding: High intensity rainfall events have caused historic flooding events in many catchments across the District.

[15] https://www.niwa.co.nz/publications/isu/instrument-systems-update-16-december-2010/first-phase-of-snow-and-ice-monitoring-network-complete
[16] https://www.orc.govt.nz/media/2955/queenstown-2014-updated-web.pdf

- Instability of alluvial fans: Changes in these landforms have caused regular and widespread damage to roads, pipes and bridges across the District (see Figure 7, top left).
- Heavy snow-fall: Events can occur at almost any time of year, and can affect much of the District, with implications for traffic and travel and dampening of economic activity (Figure 7, bottom left).
- Avalanche: The worse effects of avalanches are usually restricted to the peak winter and spring season (Figure 7, bottom right) and are affected by the type, amount and frequency of snow-fall, as well as the pattern of warming during the spring thaw.

In addition, during an extreme event it is possible that more than one of these hazard types may occur simultaneously, adding to the total degree of impact experienced across the District.

Figure 7: (Above left) Damage caused by alluvial fan debris at Pipson Creek (near Makarora), March 2004 (Source: Otago Regional Council). (Above right) Lake Wakatipu flooding at Queenstown in 1999 (Source: Otago Regional Council). (Below left) A car flips in a heavy snow-storm on the Crown Range in July 2015 (Source: https://www.stuff.co.nz/southland-times/news/70416363/null. (Below right) Avalanche warning sign on the Rob Roy track in Mount Aspiring National Park (Source: https://girleatworld.net/rob-roy-glacier-track-new-zealand).

4.2. Climate projections

In this section we describe the projected changes in key climate indices out to mid-century (based on the 2040-2049 decade) and end of the century (based on the 2090-2099 decade) with respect to the 2000-2009 decadal baseline period across the QLD, obtained from climate model simulations based on the EPIC methodology (see Section 3.3). Projected changes in the QLD's climate are analysed for all four GHG emissions scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). The geographical diversity of changes in the different ECVs are shown in these sections by means of maps generated for the 'very high' scenario (i.e., RCP8.5), as this shows most clearly the spatial variation of the projected changes. Maps for the three other RCP scenarios for both mid-century and end of century for each ECV are included at Appendix C. For most of the District the results discussed here are statistically significant at the 1σ level. Areas where the results are non-significant are discussed below. The indices presented below are the decadal averages taken from 188 EPIC model simulations for the emissions scenario of interest. Analysis of seasonal changes for selected locations (namely Queenstown, Wanaka, Albert Burn, and Glenorchy) and climate variables (namely the seasonal maximum and minimum temperatures, total seasonal precipitation, and seasonal rainfall intensity) is included at Appendix E.

4.2.1. Temperature

Summer days (days exceeding 25°C)

Table 6 below summarizes the change in the number of summer days each year in the QLD under each of the four RCPs with respect to the base line period (2000-2009). The spread in values reflects geographical difference in summer day increases across the region.

Scenario	*Mid-century*	*End of century*
RCP2.6	0-10 more days	0-10 more days
RCP4.5	0-16 more days	0-29 more days
RCP6.0	0-18 more days	0-48 more days
RCP8.5	0-24 more days	0-71 more days

Table 6: The increase in the number of summer days each year across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099).

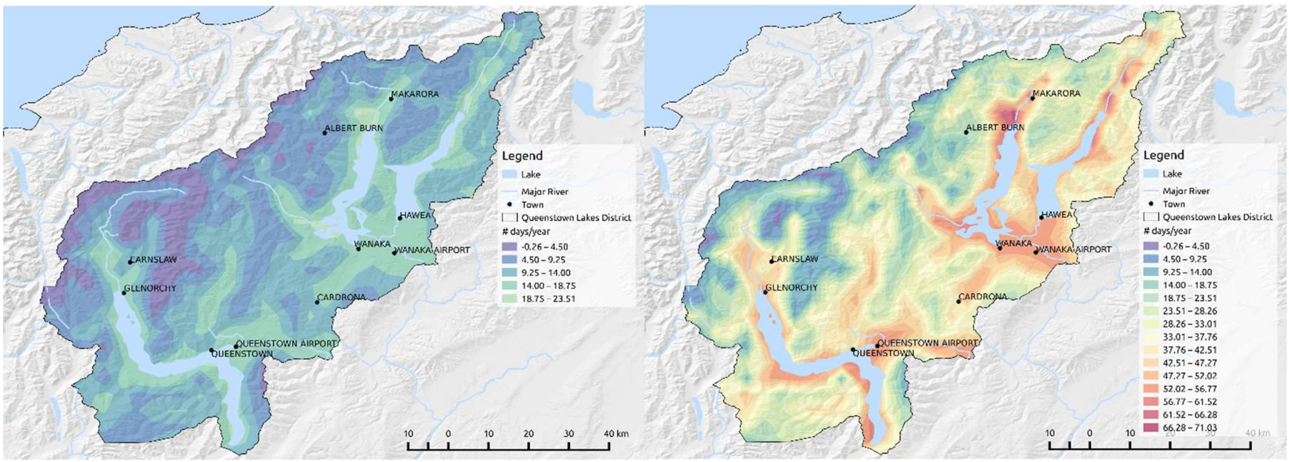

Figure 8: Change in the number of summer days each year (maximum temperature above 25°C) for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in scale as shown in the legends.

Under the RCP8.5 scenario, the model simulations project that the by the middle of this century (Figure 8, left panel) some low-elevation and eastern parts of the District will experience up to 24 more summer says compared to the baseline period of 2000-2009, while other parts of the District at higher elevation and further to the west (where there are few days where the daily maximum temperatures exceed 25°C) may see no change at all. By the end of this century (Figure 8, right panel) some eastern parts of the District may see an additional 60-70 summer days each year. The changes in the number of summer days in the mid-century projections are non-significant across the higher elevation areas toward the western boundary of the District, and for the end of century projected changes are non-significant at the very edge of the western boundary. Similar figures for the other RCPs are provided in Appendix C (Figure C1).

Frost days

Table 7 below summarizes the change in the number of frost days each year in the QLD under each of the four RCPs with respect to the base line period (2000-2009). The spread in values reflects geographical difference in frost day reductions across the region.

Scenario	***Mid-century***	***End of century***
RCP2.6	0-9 fewer days	0-10 fewer days
RCP4.5	4-18 fewer days	3-31 fewer days
RCP6.0	2-18 fewer days	8-45 fewer days
RCP8.5	4-24 fewer days	10-64 fewer days

Table 7: The change in the number of frost days across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099).

For RCP8.5, the geographical distribution of the frost day reduction is shown in Figure 9 for mid-century (left panel) and end of the century (right panel). Similar figures for the other RCPs are provided in Appendix C (Figure C2). In contrast to changes in the number of summer days, it is the higher elevation areas that will experience the largest reduction in frost days – i.e., those areas that currently have the highest numbers of frost days each year.

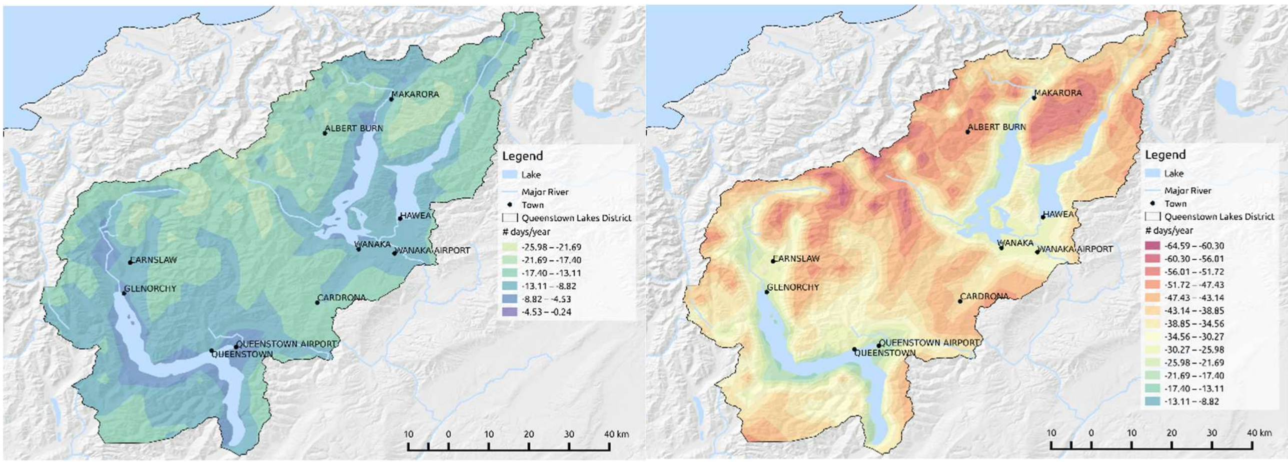

Figure 9: Change in the number of frost days per year (where the minimum temperature is below 0°C) for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario.

Highest daily maximum temperature

Overall, and not surprisingly, the QLD is projected to become warmer over the course of this century with an increase in the annual highest daily maximum temperatures. A summary of expected changes in annual maximum temperatures is provided in Table 8 for each of the RCPs, while the geographical distribution of the changes in this metric under the RCP8.5 scenario are shown for mid-century and end-of-century periods in Figure 10. Similar maps for the other RCPs are provided in Appendix C (Figure C3).

Scenario	*Mid-century*	*End of century*
RCP2.6	0.3 to 1.1°C warmer	0.5 to 1.6°C warmer
RCP4.5	0.9 to 1.8°C warmer	1.4 to 3.3°C warmer
RCP6.0	0.5 to 1.4°C warmer	1.8 to 4.2°C warmer
RCP8.5	0.9 to 2.4°C warmer	2.7 to 7.0°C warmer

Table 8: The change in annual peak daily maximum temperature relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences which are shown for RCP8.5 in Figure 7.

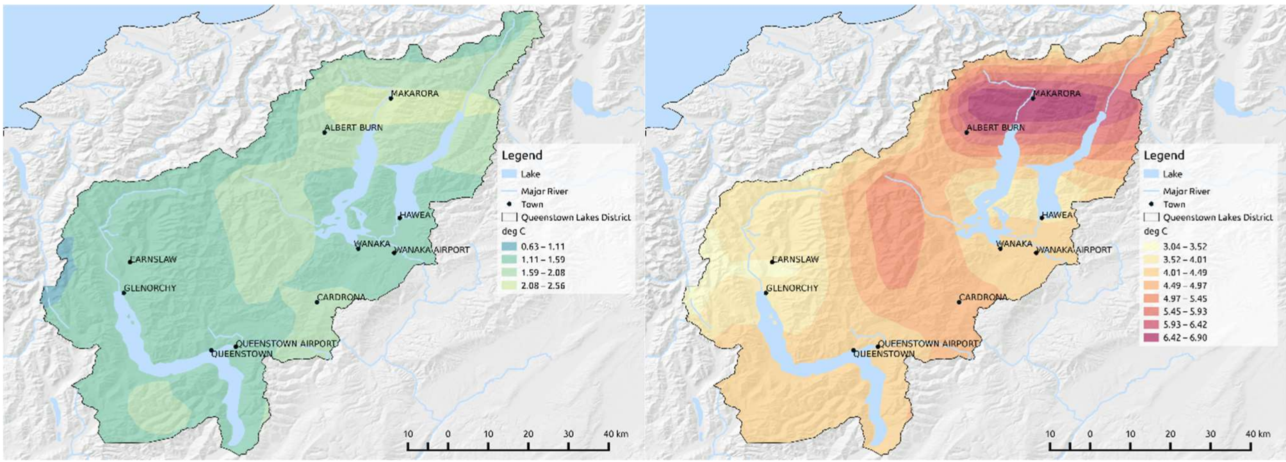

Figure 10: Change in highest daily maximum temperature for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour scale in the legend.

Lowest daily maximum temperature

The geographical spread in the projected changes in lowest daily maximum temperatures experienced this century is shown for RCP8.5 in Figure 11. The greatest increases are likely to occur in the northern areas surrounding Makarora, and to the north of Lake Wanaka and Lake Hawea. The smallest increase in this metric is expected to the north of Glenorchy. Overall, the projected changes in the annual maximum temperatures (see above) are more pronounced in than the changes in the annual minima of daily maximum temperatures. A summary of expected changes in annual lowest daily maximum temperatures is provided in Table 9 for each of the RCPs, while maps of change in lowest daily maximum temperatures for the other RCPs are provided in Appendix C (Figure C4).

Scenario	*Mid-century*	*End of century*
RCP2.6	0 to 0.5°C warmer	0 to 0.6°C warmer
RCP4.5	0 to 0.6°C warmer	0.2 to 1.0°C warmer
RCP6.0	0.1 to 0.6°C warmer	0.6 to 1.7°C warmer
RCP8.5	0.3 to 0.8°C warmer	1.0 to 2.5°C warmer

Table 9: The change in annual lowest daily maximum temperatures relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

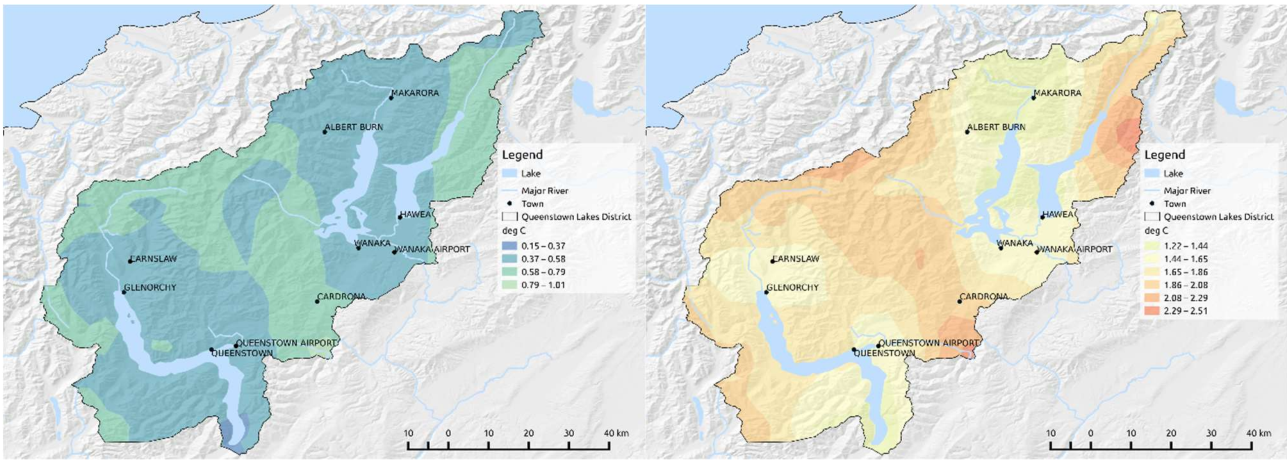

Figure 11: Change in the lowest daily maximum temperature projected for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour scale in the legend.

Annual highest daily minimum temperature

Like the daily maximum temperatures, daily minimum temperatures are also projected to increase, reflecting the overall warming of the QLD. The largest changes occur in northern (Makarora) and southern parts of the District (to the west of Lake Wakatipu). Results for mid-century and end of century for RCP8.5 are shown in Figure 12, while similar maps for the other RCPs are included in Figure C5. Projected changes in the annual maximum of daily minimum temperatures are summarized in Table 10.

Scenario	*Mid-century*	*End of century*
RCP2.6	0.1 to 0.5°C warmer	-0.1 to 0.5°C warmer
RCP4.5	0.1 to 0.9°C warmer	0.2 to 1.6°C warmer
RCP6.0	0.1 to 1.1°C warmer	0.5 to 3.0°C warmer
RCP8.5	0.2 to 1.4°C warmer	0.5 to 4.1°C warmer

Table 10: The change in annual maxima of daily minimum temperatures relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

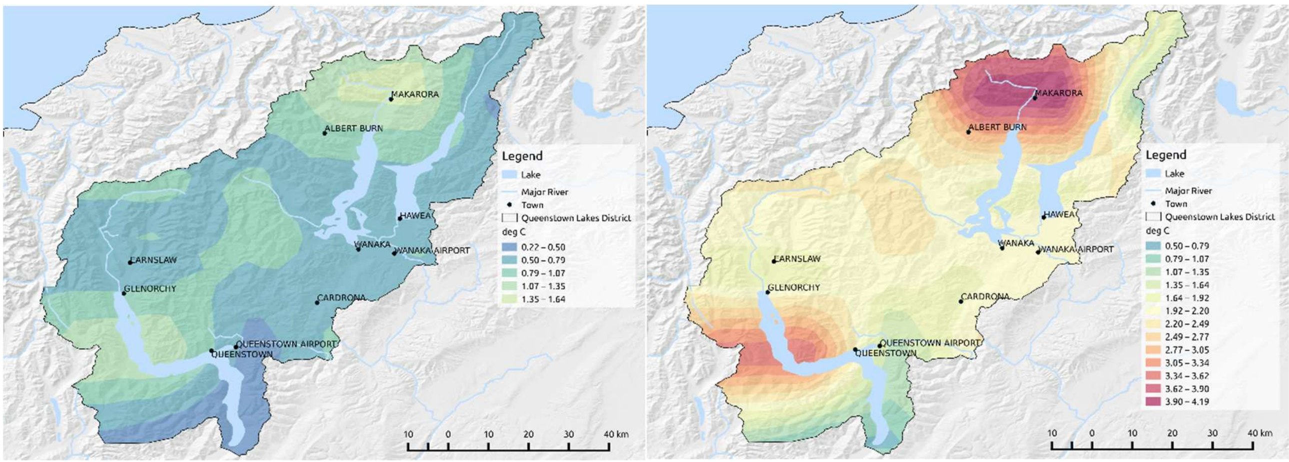

Figure 12: Change in the annual highest daily minimum temperatures for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour scale in the legend.

Annual lowest daily minimum temperature

The geographical spread in the change in annual minimum temperatures is shown for RCP8.5 in Figure 13, with the largest changes occurring in the upper Shotover and near the Barrier range in the north-east. Similar maps for the other RCPs are included in Figure C6. Projected changes in annual minimum temperatures are summarized in Table 11.

Scenario	***Mid-century***	***End of century***
RCP2.6	0.0 to 0.5°C warmer	0.2 to 0.8°C warmer
RCP4.5	0.1 to 0.6°C warmer	0.2 to 1.0°C warmer
RCP6.0	0.1 to 0.6°C warmer	0.2 to 1.6°C warmer
RCP8.5	0.1 to 0.8°C warmer	0.4 to 2.3°C warmer

Table 11: The change in annual minimum temperatures relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

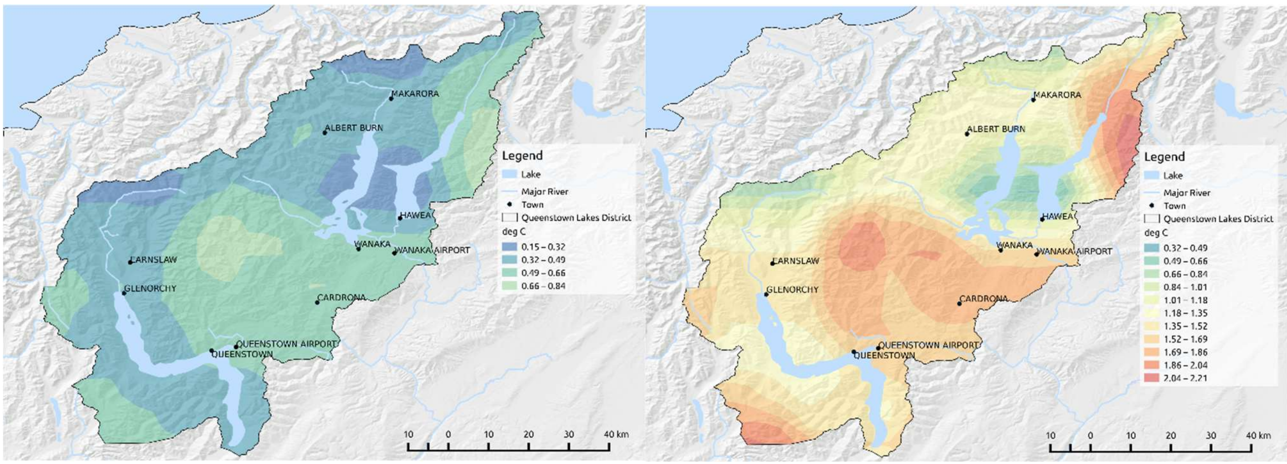

Figure 13: Change in the annual lowest daily minimum temperatures for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour scale in the legend.

4.2.2. Precipitation

Total annual precipitation

A summary of projected changes in annual precipitation under each of the RCPs is provided in Table 12.

Scenario	*Mid-century*	*End of century*
RCP2.6	Up to 50mm drier in the east, up to 280mm wetter in the west	Up to 100mm drier in the east, up to 330mm wetter in the west
RCP4.5	Up to 50mm drier in the east, up to 280mm wetter in the west	Up to 100mm drier in the east, up to 470mm wetter in the west
RCP6.0	Up to 50mm drier in the east, up to 480mm wetter in the west	Up to 100mm drier in the east, up to 1200 mm wetter in the west
RCP8.5	Up to 50mm drier in the east, up to 800mm wetter in the west	Up to 100mm drier in the east, but up to 1780mm wetter in the west

Table 12: The change in annual precipitation relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

The geographical spread in projected changes in total annual precipitation is shown for RCP8.5 in Figure 14. Under the RCP8.5 scenario, while the largest increases in precipitation are projected to occur in the west of the region by the end of this century, some eastern areas may experience small decreases in total annual precipitation, or only very small increases. Similar figures for the other RCPs are provided in Appendix C (Figure C7).

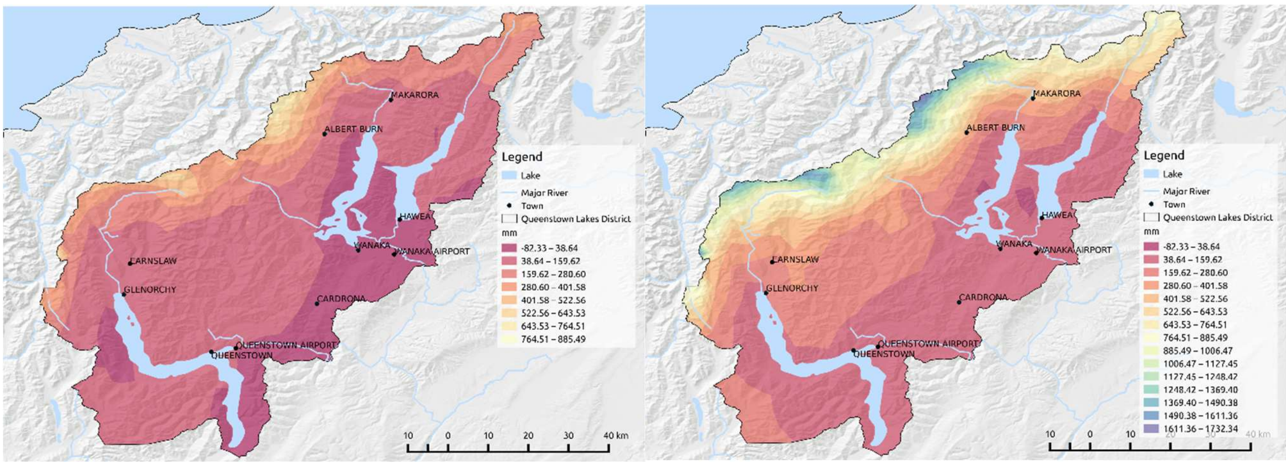

Figure 14: Changes in total annual precipitation for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour scale in the legend.

Precipitation intensity

A summary of projected changes in annual precipitation intensity under each of the RCPs is provided in Table 13.

Scenario	*Mid-century*	*End of century*
RCP2.6	-0.8 to 1.6 mm/day	-0.8 to 1.7 mm/day
RCP4.5	-1.6 to 1.9 mm/day	-1.6 to 3.3 mm/day
RCP6.0	-1.3 to 3.0 mm/day	-0.9 to 6.8 mm/day

RCP8.5	-0.2 to 3.7 mm/day	0.5-4 mm/day in the east, but up to 8 to 9 mm/day in the west

Table 13: The change in annual precipitation intensity relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

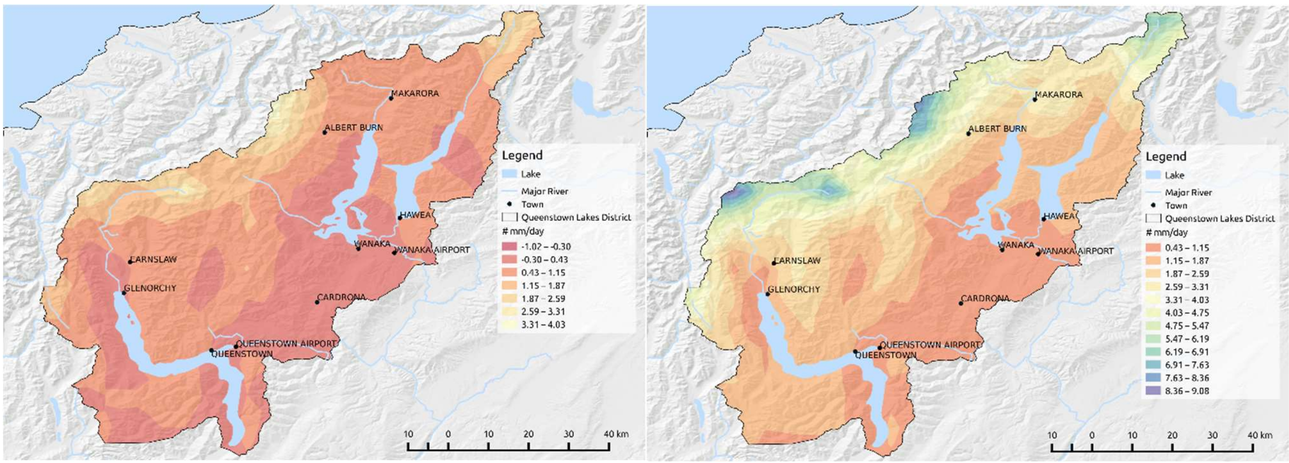

Figure 15: Changes in annual precipitation intensity for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario.

The geographical spread in the change in precipitation intensity is shown for RCP8.5 in Figure 15. An increase in precipitation intensity of between 0.5 and 4 mm/day is projected for most of the QLD for the RCP8.5 scenario for the end of the century (Figure 12, right). However, the western part of the District is projected to have 8-9mm/day greater precipitation intensity. Similar figures for the other RCPs are provided in Appendix C (Figure C8).

Heavy rainfall days (more than 10mm)

By the end of the century, under the RCP8.5 scenario, and over the western areas of the District, the number of heavy rainfall days in each year is projected to increase significantly by about 5 to 7 days (Figure 16). Similar figures for the other RCPs are provided in Appendix C (Figure C9). For QLD there is a great deal of spatial variability in daily rainfall across the District, where what is classified as a

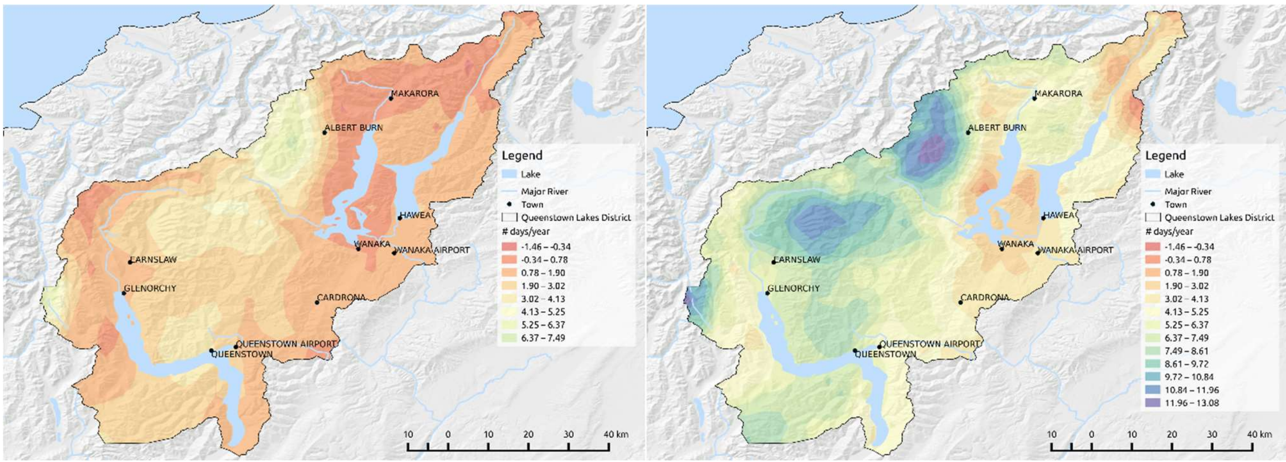

Figure 16: Changes in the number of heavy rainfall days for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario.

'heavy rainfall day' in the east of the District may be comparable to a 'light rainfall day' to the west.

Future analysis would benefit by examining different thresholds for ‘heavy’ rates of rainfall for different parts of the District. A summary of projected changes in the number of days of heavy rainfall under each of the RCPs is provided in Table 14.

Scenario	***Mid-century***	***End of century***
RCP2.6	-2.2 to 3.4 days	-2.0 to 3.4 days
RCP4.5	-3.0 to 2.6 days	-0.3 to 4.4 days
RCP6.0	-0.6 to 3.4 days	0.2 to 7.6 days
RCP8.5	-0.5 to 6.0 days	-0.3 to 7.6 days

Table 14: The change in the number of heavy rainfall days relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

Annual maxima in 1-day precipitation

By the end of the century, under the RCP8.scenario, the annual maximum in 1-day precipitation (Figure 17) is projected to decrease slightly (by about 4mm) to the east of the region and increase considerably in the west (by about 90mm). Similar figures for the other RCPs are provided in Appendix C (Figure C10). A summary of projected changes in this metric under each of the RCPs is provided in Table 15.

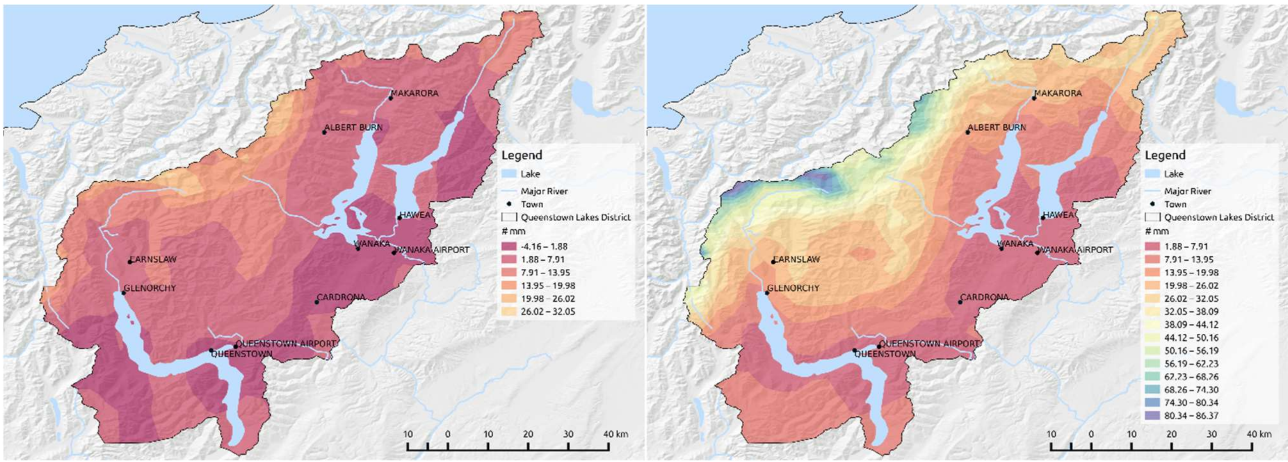

Figure 17: Changes in the annual maximum in 1-day precipitation for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario.

Scenario	***Mid-century***	***End of century***
RCP2.6	-5 to 28mm	-4 to 38mm
RCP4.5	-5 to 19mm	-4 to 38mm
RCP6.0	-5 to 25mm	-4 to 66mm
RCP8.5	-2 to 34mm	3 to 87mm

Table 15: The change in annual maximum in 1-day precipitation relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

Annual maxima in consecutive 5-day precipitation

A pattern similar to the changes in annual maxima in 1-day precipitation is seen in annual maxima in consecutive 5-day precipitation, but with little change in the east and increases of up to 115mm in the west by the end of this century for RCP8.5 (Figure 18). Similar figures for the other RCPs are provided in Appendix C (Figure C11). A summary of projected changes in this metric under each of the RCPs is provided in Table 16.

Scenario	***Mid-century***	***End of century***
RCP2.6	-9 to 38 mm	-9 to 48 mm

RCP4.5	-9 to 26 mm	-9 to 48 mm
RCP6.0	-4 to 44 mm	-9 to 77 mm
RCP8.5	0 to 47 mm	1 to 115 mm

Table 16: The change in annual maxima in consecutive 5-day precipitation relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

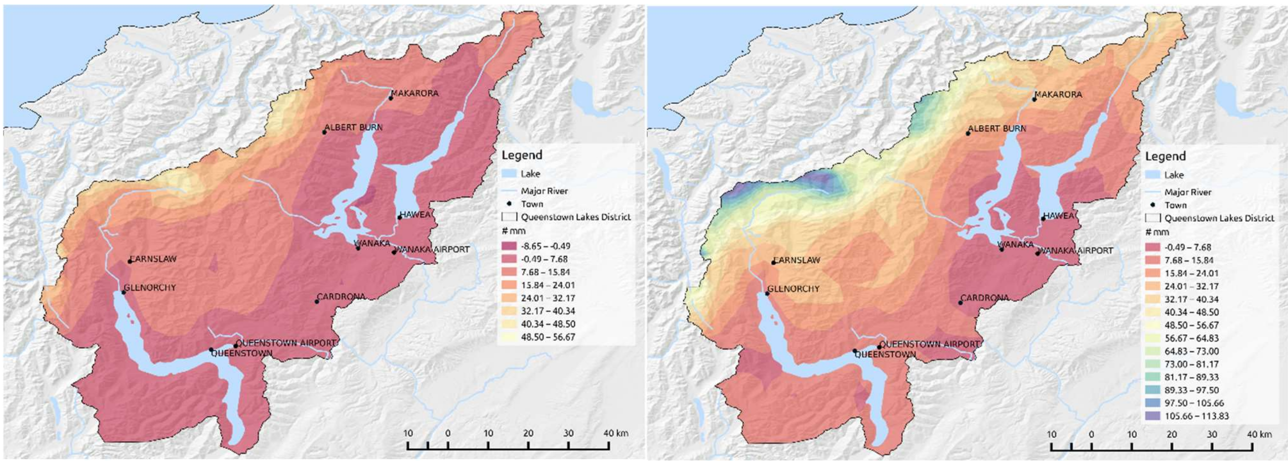

Figure 18: Changes in annual maxima in consecutive 5-day precipitation for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the difference in colour-scale between the two panels.

Length of dry spell

By the end of this century, under RCP8.5, the length of dry spells (i.e. the annual maximum number of consecutive days with precipitation of <1mm), is projected to decrease by up to 4 days in some parts of the District, while increasing by up to 4 days in other areas (Figure 19). Similar figures for the other RCPs are provided in Appendix C (Figure C12). A summary of projected changes in the length of dry spells under each of the RCPs is provided in Table 17.

Scenario	***Mid-century***	***End of century***
RCP2.6	2 fewer to 1.3 more days	2.2 fewer to 1.1 more days
RCP4.5	3.2 fewer to 1.3 more days	4.2 fewer to 1.8 more days
RCP6.0	2.4 fewer to 0.9 more days	4.2 fewer to 1.8 more days
RCP8.5	2.4 fewer to 2.1 more days	4.2 fewer to 3.7 more days

Table 17: The change in the length of dry spells relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

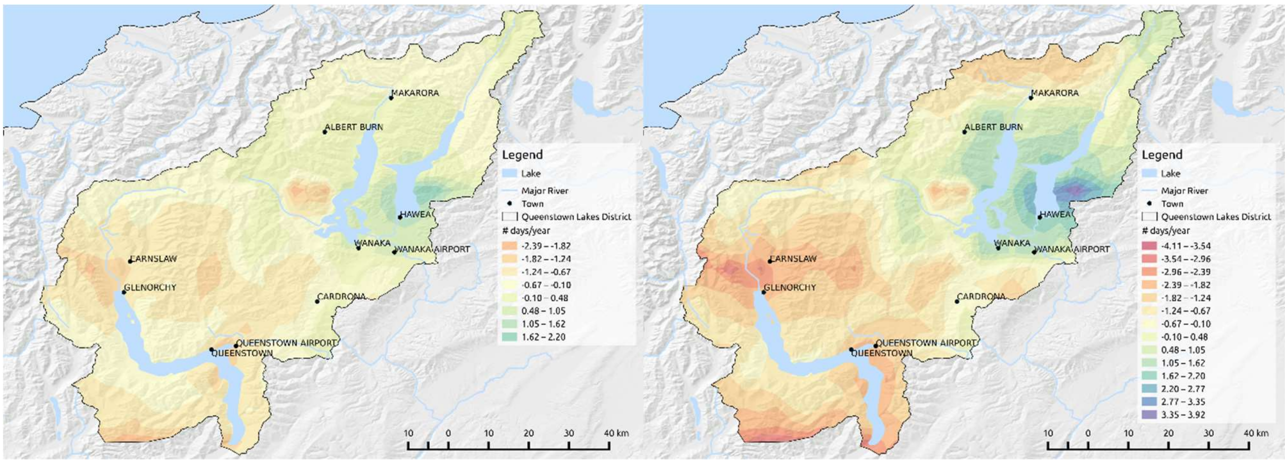

Figure 19: Change in length of a dry spell for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour-scale between the two panels.

Length of wet spell

By the end of this century, under RCP8.5, the length of wet spells (i.e. the annual maximum in the number of consecutive wet days with precipitation ≥1mm) shows less change than the change in the length of dry spells, with a range of -1.6 to 1.1 days difference in each year (Figure 20). Similar figures for the other RCPs are provided in Appendix C (Figure C13). A summary of projected changes in the length of wet spells under each of the RCPs is provided in Table 18.

Scenario	***Mid-century***	***End of century***
RCP2.6	1.0 fewer to 1.2 more days	1.4 fewer to 1.3 more days
RCP4.5	1.2 fewer to 1.0 more days	1.4 fewer to 1.0 more days
RCP6.0	0.4 fewer to 2.1 more days	1.4 fewer to 1.6 more days
RCP8.5	1.0 fewer to 0.7 more days	1.7 fewer to 1.0 more days

Table 18: The change in the length of wet spells relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

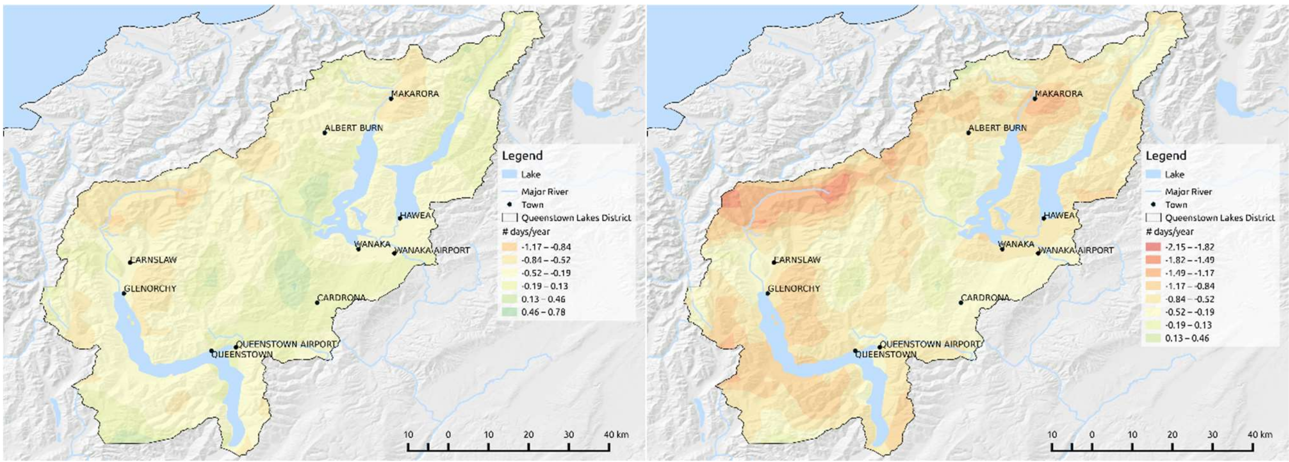

Figure 20: Change in length of a wet spell for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour-scale between the two panels.

HIRDS precipitation analysis

Analysis of HIRDS precipitation output, under RCP8.5, at five sites (Queenstown, Wanaka, Makarora, Albert Burn, Glenorchy) indicates the following broadly consistent patterns of change:

- About one-third more rainfall for short-duration rainfall events (10minutes to 2 hours) across all Annual Recurrence Intervals (ARIs), with the greatest increase for events with 80 to 100-year ARIs
- Between 20% and 30% more rainfall for medium-duration events (6-24hours) for all ARIs, with the greatest increase in events with 60 to 100-year ARIs
- About 15 to 20% more rainfall for long-duration events (48-120hours), with the greatest increase in events with 30 to 250-year ARIs

Results for Queenstown are shown in Figure 21, where the X-axis shows the range of ARIs provided as standard output from HIRDS, and the Y-axis shows the percentage increase in rainfall under RCP8.5 by the end of the century (the HIRDS output uses the 20-year period 2080-2100 as opposed to the end of decade period we have used previously). The coloured bars indicate the rainfall duration, ranging from 10 minutes to 120 hours (5 days).

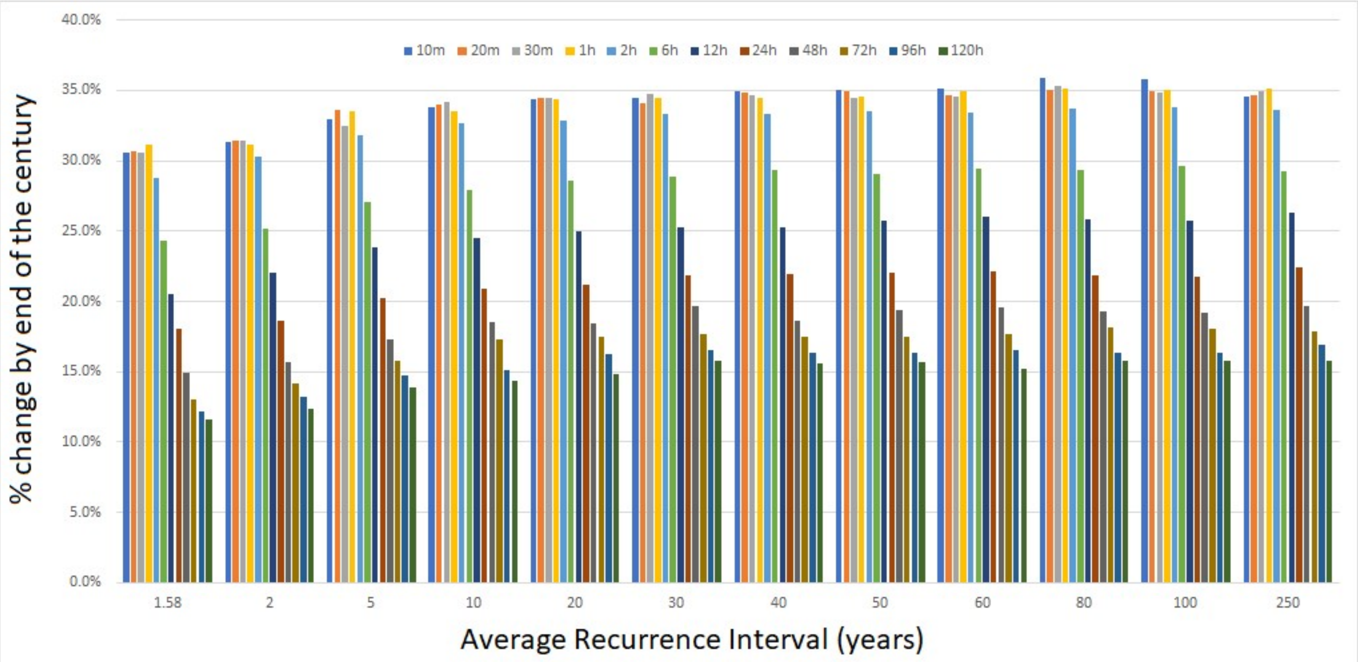

Figure 21: Results from analysis of HIRDS data for Queenstown. Data shown are the percentage projected change in rainfall over the period 2080-2100 compared to the baseline period (2000-2009) under the RCP8.5 emissions scenario for a range of rainfall duration events (coloured bars) and a ARIs.

4.2.3. Wind-speed

Average wind-speed

Under RCP8.5, by the end of this century, little change is projected in average wind-speed, ranging from 0.2m/s lower to 0.5m/s higher wind-speeds compared to the baseline period (Figure 22). Decreases are likely to the west of Albert Burn, while increases are projected to occur to the west of Glenorchy. Similar figures for the other RCPs are provided in Appendix C (Figure C14). A summary of projected changes in the average wind-speed under each of the RCPs is provided in Table 19.

Scenario	***Mid-century***	***End of century***
RCP2.6	-0.2 to 0.2 m/s	-0.2 to 0.3 m/s
RCP4.5	-0.1 to 0.1 m/s	-0.4 to 0.6 m/s
RCP6.0	0 to 0.1 m/s	-0.4 to 0.6 m/s
RCP8.5	-0.1 to 0.1 m/s	-0.2 to 0.5 m/s

Table 19: The change in annual average wind-speed relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

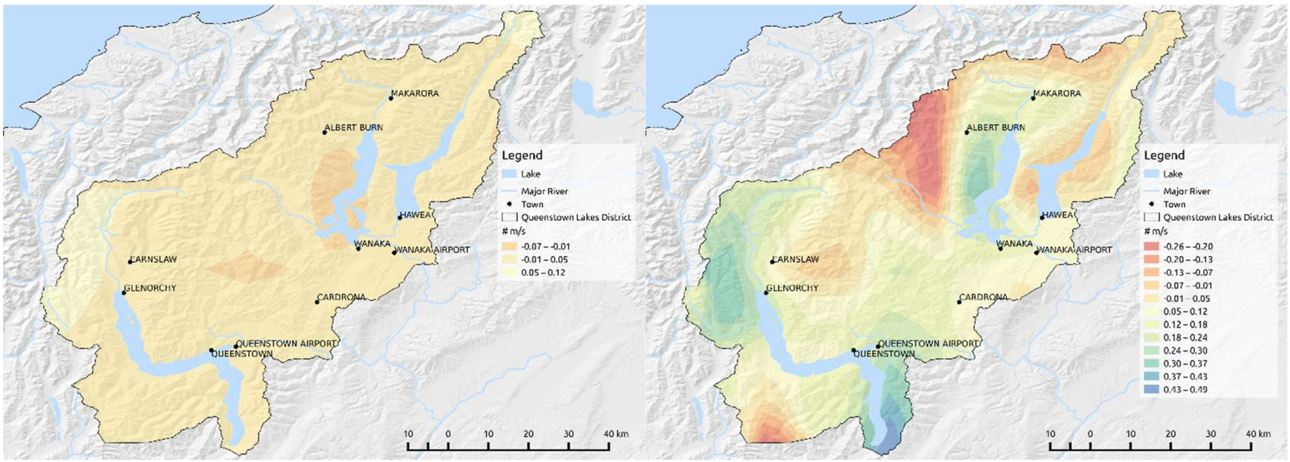

Figure 22: Change in average wind-speed for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour-scale between the two panels.

Light wind days

The projected change in the number of light wind (<5m/s) days over the course of this century under the RCP8.5 emissions scenario is consistent with the patterns projected in changes in average wind-speed (above), with decreases of up to 22 days in each year in the south of the District, and increases of around 10 days to the west of Albert Burn (Figure 23). Similar figures for the other RCPs are provided in Appendix C (Figure C15). A summary of projected changes in the annual number of light wind days under each of the RCPs is provided in Table 20.

Scenario	***Mid-century***	***End of century***
RCP2.6	12 fewer to 10 more days	9 fewer to 10 more days
RCP4.5	4 fewer to 7 more days	16 fewer to 18 more days
RCP6.0	6 fewer to 4 more days	22 fewer to 22 more days
RCP8.5	8 fewer to 4 more days	22 fewer to 15 more days

Table 20: The change in annual number of light wind days relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

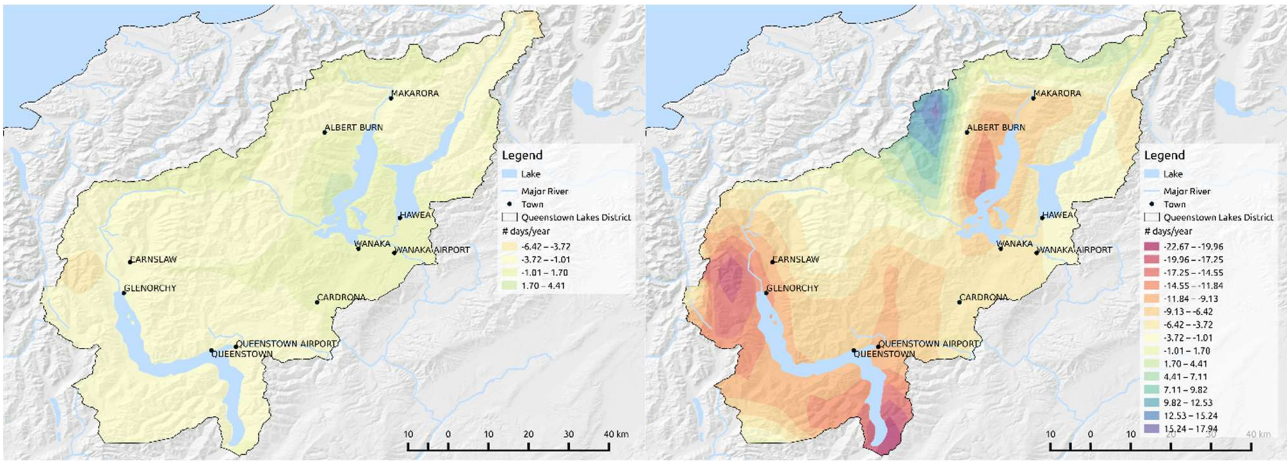

Figure 23: Change in the number of days with light winds for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) under the RCP8.5 emissions scenario. Note the change in colour-scale between the two panels.

Strong wind days

Even under the RCP8.5 emissions scenario, there is very little change in the projected number of strong wind days (winds of ≥ 5ms^{-1} and ≤ 20ms^{-1}) over the course of this century (Figure 24). Similar figures for the other RCPs are provided in Appendix C (Figure C16). A summary of projected changes in the annual number of strong wind days under each of the RCPs is provided in Table 21.

Scenario	***Mid-century***	***End of century***
RCP2.6	-0.3 fewer to 0.2 more days	-0.3 fewer to 0.2 more days
RCP4.5	-0.3 fewer to 0.2 more days	-0.8 fewer to 0.2 more days
RCP6.0	-0.3 fewer to 0.2 more days	-0.8 fewer to 0.2 more days
RCP8.5	0.3 fewer to 0.3 more days	0.7 fewer to 0.5 more days

Table 21: The change in annual number of strong wind days relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

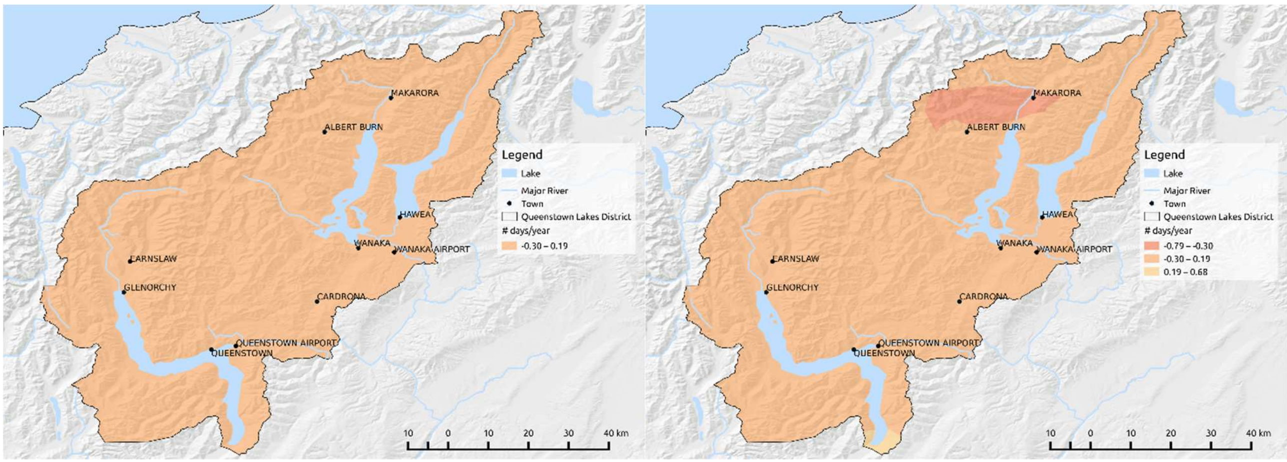

Figure 24: Change in the number of days with strong winds for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) under the RCP8.5 emissions scenario. Note the change in colour-scale between the two panels.

Annual maximum wind-speed

Under the RCP8.5 scenario, the annual maximum wind-speed is projected to decrease by about 1 m/s toward the north of the District and increase by approximately the same margin in the south under RCP8.5 (Figure 25). Similar figures for the other RCPs are provided in Appendix C (Figure C17). A summary of projected changes in the annual maximum wind-speed under each of the RCPs is provided in Table 22. Little change is observed in the annual number of moderate (10-20 m/s) or strong wind days (>20 m/s), and there is also little evidence of any change in projected minimum wind-speeds.

Scenario	***Mid-century***	***End of century***
RCP2.6	-0.8 to 0.1 m/s	-0.9 to 0.5 m/s
RCP4.5	-0.4 to 0.3 m/s	-0.9 to 0.7 m/s
RCP6.0	-0.4 to 0.3 m/s	-1.3 to 1.1 m/s
RCP8.5	-0.4 to 0.3 m/s	-1.1 to 1.1 m/s

Table 22: The change in annual maximum wind-speed relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

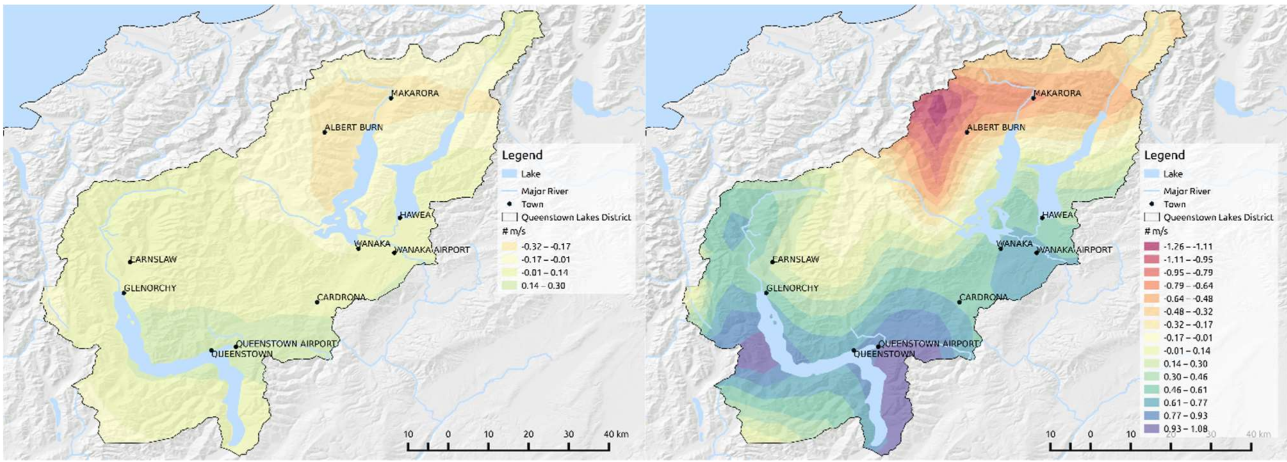

Figure 25: Change in maximum wind-speed for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour-scale between the two panels.

Annual minimum wind-speed

Little change is observed for this metric, which is not surprising given that the minimum wind-speed is likely to maintain a value of close to zero and shows no significant change across the district. Nonetheless we show the maps here for completeness for RCP8.5 (Figure 26).

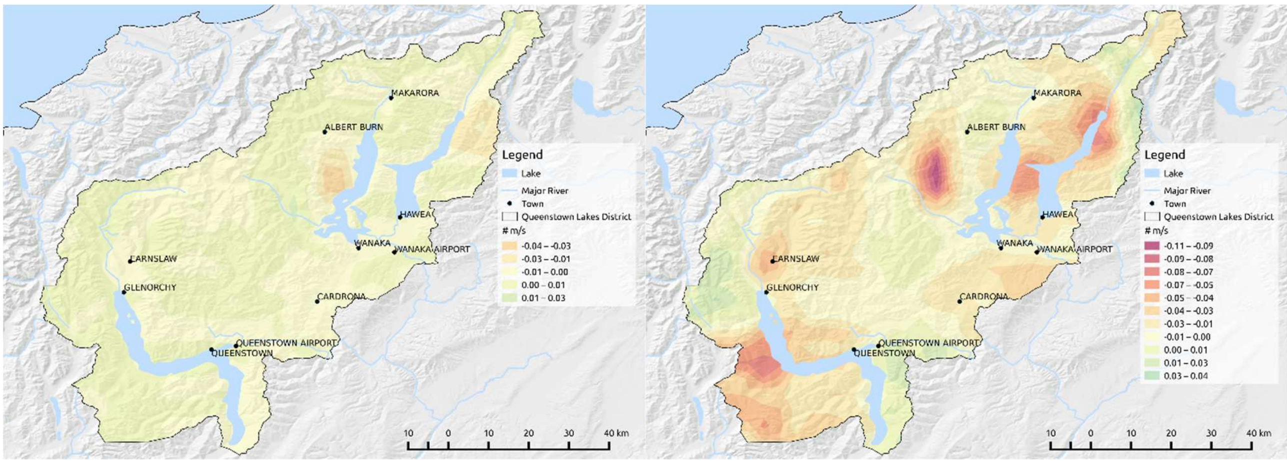

Figure 26: Change in minimum wind-speed for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour-scale between the two panels.

4.2.4. Solar radiation

Annual average SR

A north/south pattern in change in average solar radiation (SR) under RCP8.5 is projected for the end of the century, with an increase of about 2 Wm^{-2} in the north of the District and decrease of about 3 Wm^{-2} in the south (Figure 27). Similar figures for the other RCPs are provided in Appendix C (Figure C18). A summary of projected changes in the average SR under each of the RCPs is provided in Table 23.

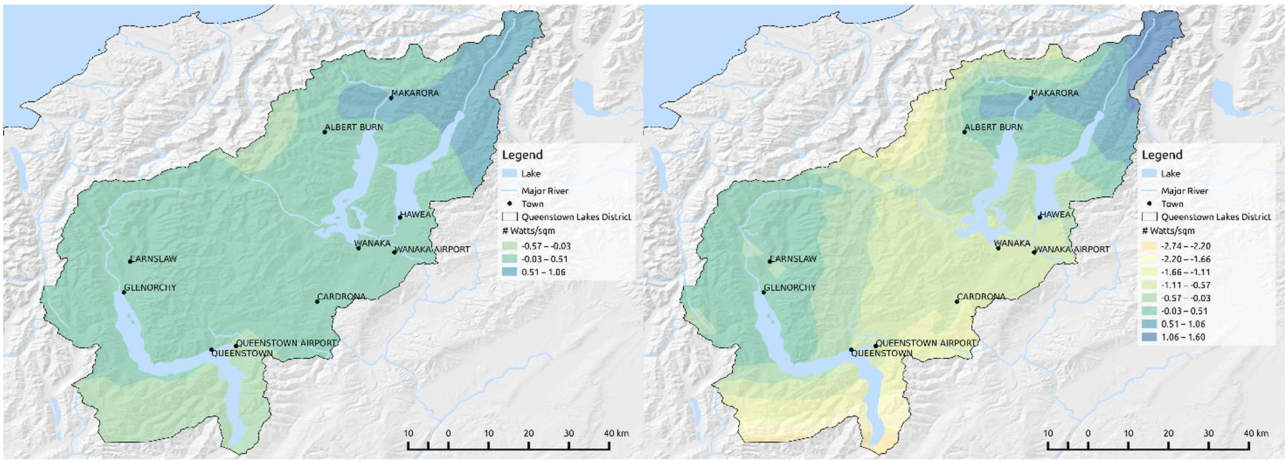

Figure 27: Change in annual average solar radiation for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario.

Scenario	***Mid-century***	***End of century***
RCP2.6	-0.4 to 1.7 Wm^{-2}	-0.7 to 1.6 Wm^{-2}
RCP4.5	-1.0 to 0.2 Wm^{-2}	-2.4 to 0.4 Wm^{-2}
RCP6.0	-1.0 to 0.8 Wm^{-2}	-3.6 to 0.5 Wm^{-2}
RCP8.5	-0.7 to 1.1 Wm^{-2}	-3.0 to 1.6 Wm^{-2}

Table 23: The change in annual average SR relative to the baseline period (2000-2009) across the District under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

Low SR days

The number of low SR days (days with peak solar insolation of <50 Wm^{-2}) is projected to increase by 4-17 days under RCP8.5 by the end of the century (Figure 28). Similar figures for the other RCPs are provided in Appendix C (Figure C19). A summary of projected changes in the number of low SR days under each of the RCPs is provided in Table 24.

Scenario	***Mid-century***	***End of century***
RCP2.6	1.7 fewer to 2 more days	2 fewer to 2 more days
RCP4.5	0.4 to 5 more days	1 to 8 more days
RCP6.0	2 to 5 more days	5 to 14 more days
RCP8.5	1 to 5 more days	4 to 17 more days

Table 24: The change in the number of low SR days in each year relative to the baseline period (2000-2009) across the District under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

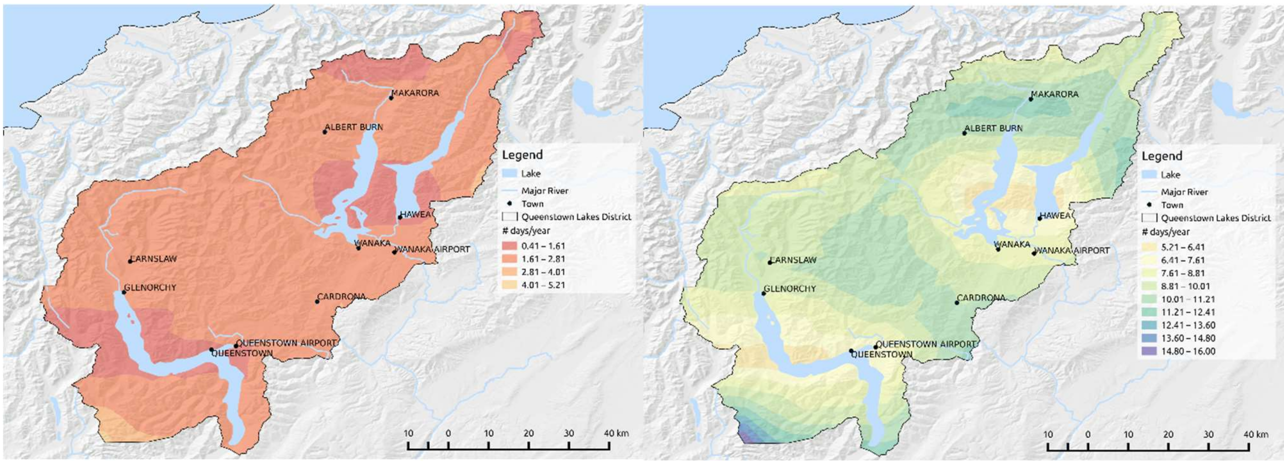

Figure 28: Change in the number of low solar radiation days annually for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario.

High SR days

Under the RCP8.5 scenario, by the end of this century, the number of high SR days (days with peak solar insolation ≥ 250 Wm^{-2}) is projected to increase by 1-7 days. (Figure 29). Similar figures for the other RCPs are provided in Appendix C (Figure C20). A summary of projected changes in the number of high SR days under each of the RCPs is provided in Table 25.

Scenario	***Mid-century***	***End of century***
RCP2.6	1.7 fewer to 2 more days	2 fewer to 2 more days
RCP4.5	0.4 to 5 more days	1 to 8 more days
RCP6.0	2 to 5 more days	5 to 14 more days
RCP8.5	1 to 5 more days	1 to 7 more days

Table 25: The change in the number of high SR days in each year relative to the baseline period (2000-2009) across the District under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

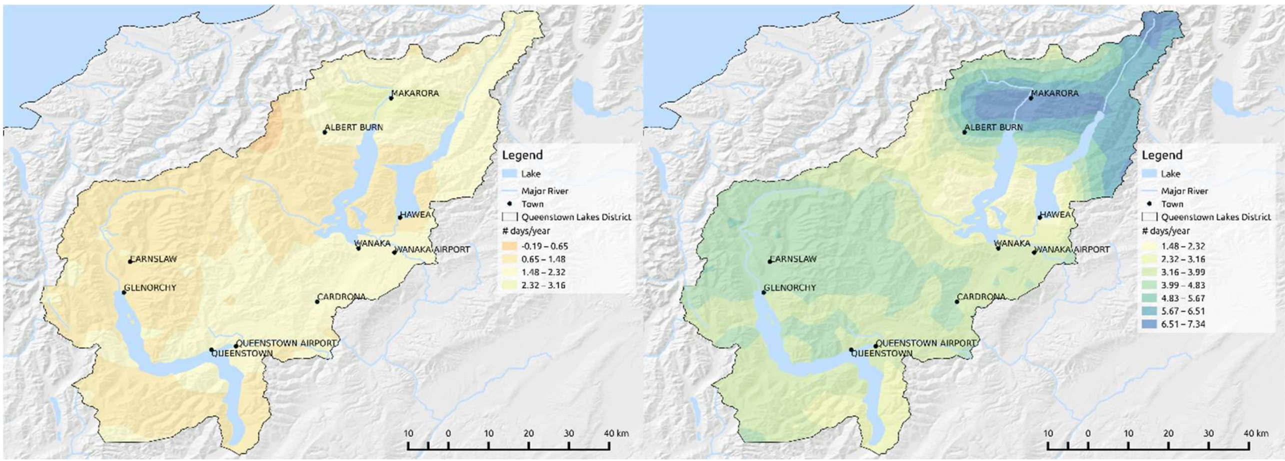

Figure 29: Change in the number of high solar radiation days in each year for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario.

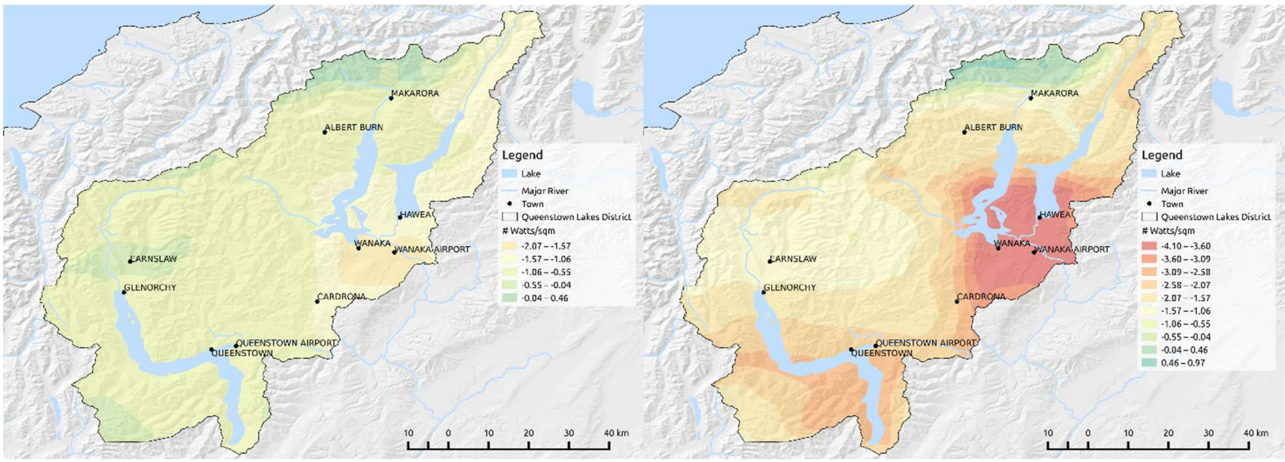

Figure 30: Change in annual maximum solar radiation in each year for the mid-century period (2040-2049, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour-scale between the two panels.

Annual maximum SR

For the RCP8.5 scenario by the end of this century maximum SR is projected to decrease by up to 4.5 Wm^{-2} to the east of the District and increase by up to 1.2 Wm^{-2} in the north (Figure 30). Similar figures for the other RCPs are provided in Appendix C (Figure C21). A summary of projected changes in the number of high SR days under each of the RCPs is provided in Table 26.

Scenario	*Mid-century*	*End of century*
RCP2.6	-1.9 to 0.3 Wm^{-2}	-2 to 0.5 Wm^{-2}
RCP4.5	-2.9 to 1.0 Wm^{-2}	-4.5 to 1.3 Wm^{-2}
RCP6.0	-2.4 to 0.1 Wm^{-2}	-3.8 to 0.5 Wm^{-2}
RCP8.5	-1.9 to 1.3 Wm^{-2}	-4.5 to 1.2 Wm^{-2}

Table 26: The change in maximum SR relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

Minimum SR

Minimum SR is projected to decrease by 0-2.5 watts/m^2 across the District under the RCP8.5 scenario by the end of the century (Figure 31). Similar figures for the other RCPs are provided in Appendix C (Figure C22). A summary of projected changes in the number of high SR days under each of the RCPs is provided in Table 27.

Scenario	*Mid-century*	*End of century*
RCP2.6	-1.5 to 0.6 Wm^{-2}	-1.7 to 0.8 Wm^{-2}
RCP4.5	-1.1 to 1.2 Wm^{-2}	-1.2 to 2.1 Wm^{-2}
RCP6.0	-1.1 to 0 Wm^{-2}	-2.9 to 0 Wm^{-2}
RCP8.5	-0.9 to 0.4 Wm^{-2}	-2.5 to 0 Wm^{-2}

Table 27: The change in minimum SR relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

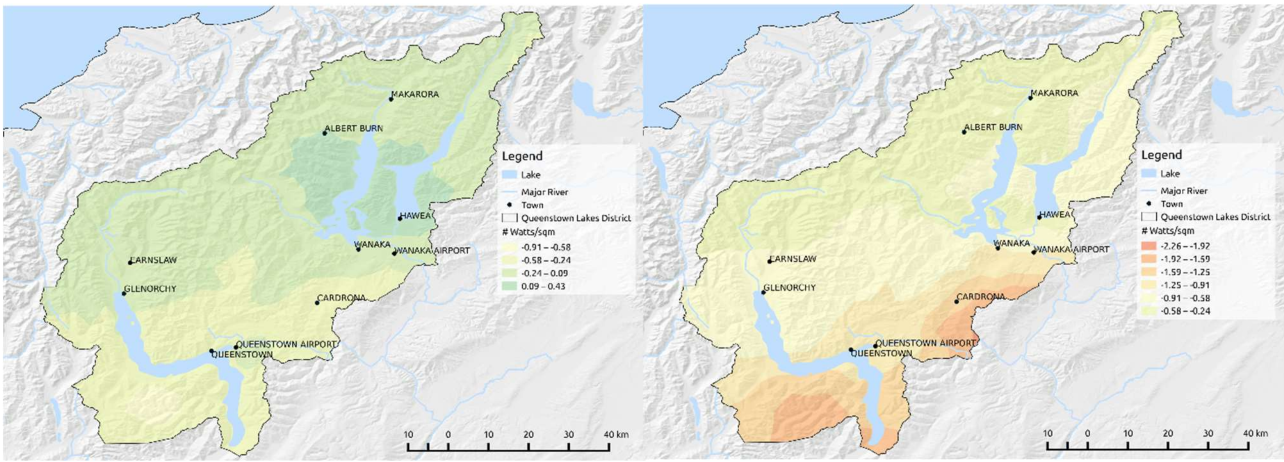

Figure 31: Change in minimum solar radiation for the mid-century period (2040-49, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario.

4.2.5. Relative Humidity

Annual number of low RH days

By the end of this century, under the RCP8.5 emission scenario, there is little change projected in the number of low RH days for most of the District. The exception is that there are projected to be about 2 more low RH days each year in the mid-Lake Wanaka/Lake Hawea area (Figure 32). Similar figures for the other RCPs are provided in Appendix C (Figure C23). A summary of projected changes in the number of low RH days under each of the RCPs is provided in Table 28.

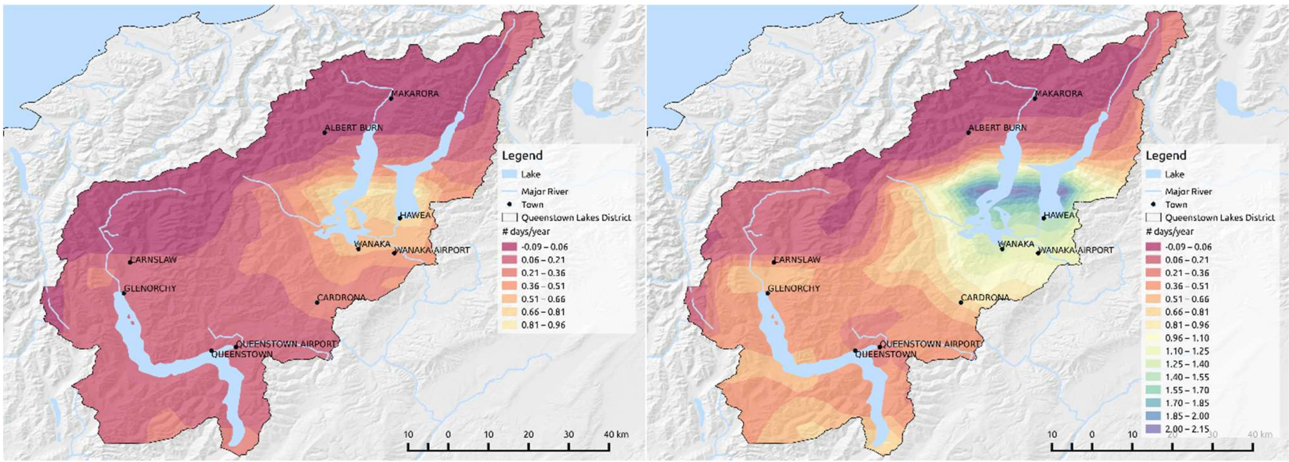

Figure 32: Change in the number of low RH days for the mid-century period (2040-49, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. Note the change in colour-scale between the two panels.

Scenario	***Mid-century***	***End of century***
RCP2.6	0.1 fewer to 0.7 more days	0.1 fewer to 0.8 more days
RCP4.5	0.1 fewer to 0.8 more days	0.1 fewer to 1.3 more days
RCP6.0	0.1 fewer to 0.7 more days	0.1 fewer to 1.6 more days
RCP8.5	0.1 fewer to 0.9 more days	0.1 fewer to 2.1 more days

Table 28: The change in the number of low RH days relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

Annual number of high RH days

A much larger reduction in the number of high RH days (compared with low RH days – above) is projected under the RCP8.5 scenario by the end of the century (Figure 33), with 17-69 fewer high RH days in each year and the highest reduction in the north and mid-west of the District, and the lowest reduction to the south of Wanaka. Similar figures for the other RCPs are provided in Appendix C (Figure C24). A summary of projected changes in the number of high RH days under each of the RCPs is provided in Table 29.

Scenario	***Mid-century***	***End of century***
RCP2.6	1.6-17.5 fewer days	22.4 fewer to 0.9 more days
RCP4.5	3.9-19.8 fewer days	4.9-34.0 fewer days
RCP6.0	3.9-19.8 fewer days	10.7-51.5 fewer days
RCP8.5	4-24 fewer days	19-69 fewer days

Table 29: The change in the number of high RH days relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

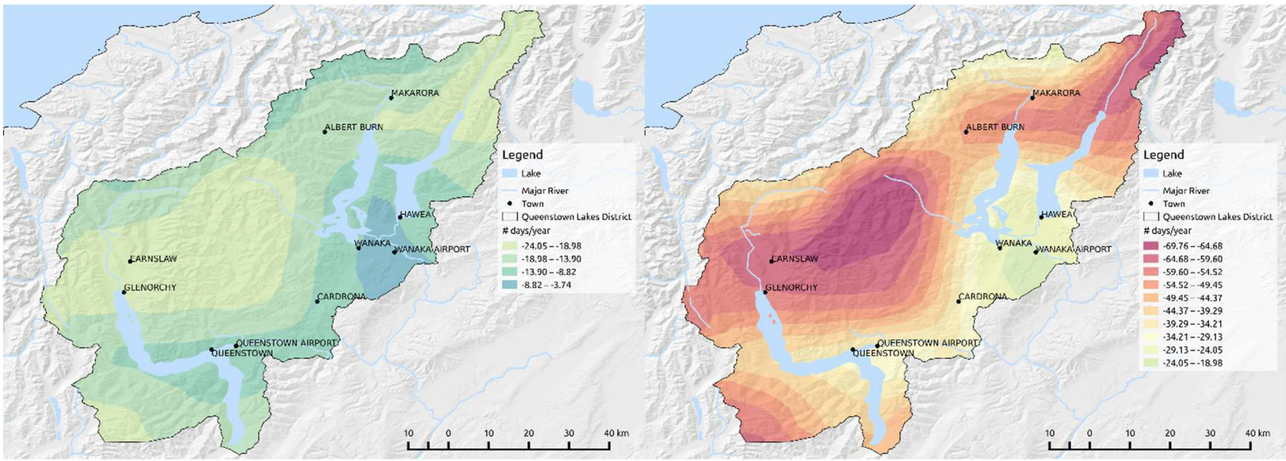

Figure 33: Change in the number of high RH days for the mid-century period (2040-49, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario. . Note the change in colour-scale between the two panels.

Annual minimum in daily RH

The minimum annual value of daily RH is projected to decrease by 1-7% across the District under the RCP8.5 scenario by the end of the century (Figure 34). Similar figures for the other RCPs are provided in Appendix C (Figure C25). A summary of projected changes in minimum RH under each of the RCPs is provided in Table 30.

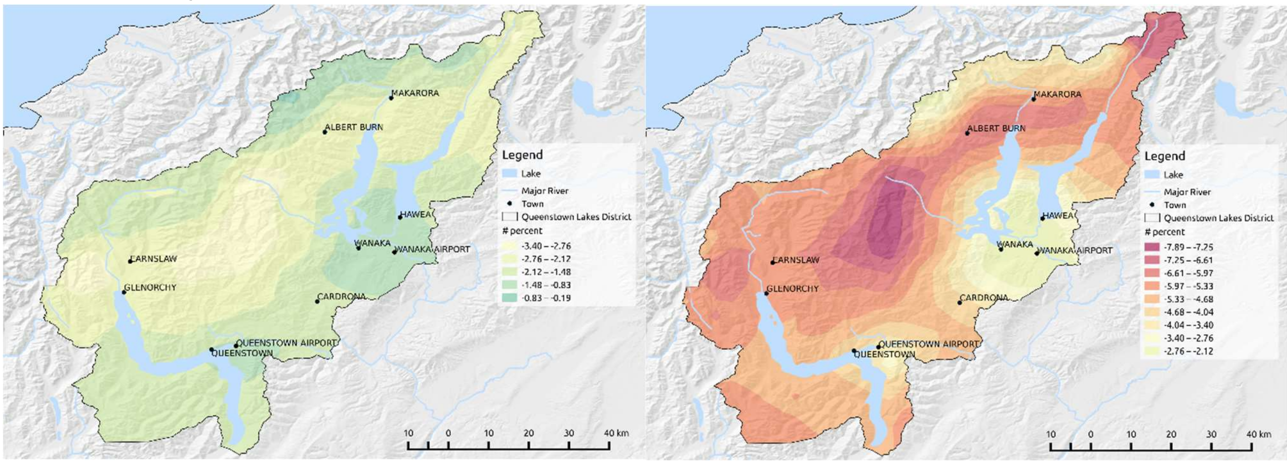

Figure 34: Change in minimum RH for the mid-century period (2040-49, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario.

Scenario	***Mid-century***	***End of century***
RCP2.6	0.7 to 2.3% lower	0.6 to 2.3% lower
RCP4.5	0.4 to 2.6% lower	0.6 to 3.7% lower
RCP6.0	0 to 2.6% lower	0.8 to 5.9% lower
RCP8.5	0.4 to 3% lower	1.5 to 7.4% lower

Table 30: The change in minimum RH relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

Annual maximum in daily RH

The maximum annual value of daily RH is projected to reduce only slightly (0-2%), if at all, across the District under the RCP8.5 scenario by the end of the century (Figure 35). Similar figures for the other RCPs are provided in Appendix C (Figure C26). A summary of projected changes in maximum RH under each of the RCPs is provided in Table 31.

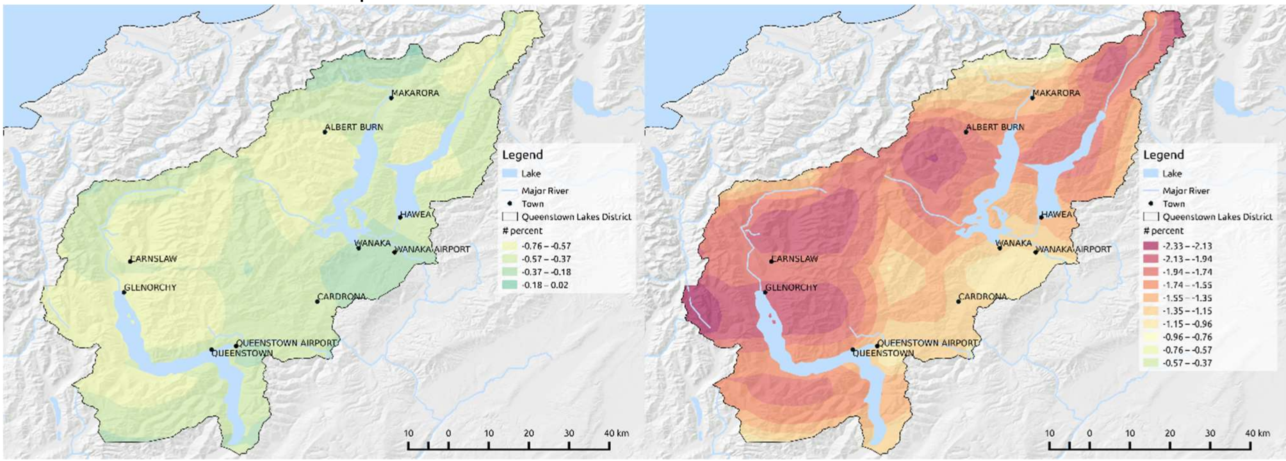

Figure 35: Change in maximum RH for the mid-century period (2040-49, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario.

Scenario	*Mid-century*	*End of century*
RCP2.6	0 to 0.7% lower	0.2 to 0.7% lower
RCP4.5	0.1 to 0.7% lower	0 to 1.4% lower
RCP6.0	0.1 to 0.8% lower	0.2 to 1.8% lower
RCP8.5	0.1 to 0.8% lower	0.2 to 2.3% lower

Table 31: The change in minimum RH relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

Annual average RH

The average annual RH is projected to reduce by up to 7% across the District under the RCP8.5 scenario by the end of the century (Figure 36). Similar figures for the other RCPs are provided in Appendix C (Figure C27). A summary of projected changes in maximum RH under each of the RCPs is provided in Table 32.

Scenario	*Mid-century*	*End of century*
RCP2.6	0.1 to 1.7% lower	0.1 to 1.7% lower
RCP4.5	0.1 to 2.2% lower	0.6 to 3.3% lower
RCP6.0	0.1 to 2.2% lower	0.6 to 4.9% lower
RCP8.5	0.6 to 2.7% lower	1.7 to 7.50 % lower

Table 32: The change in minimum RH relative to the baseline period (2000-2009) across the region under each of the RCPs at mid-century (2040-2049) and end of the century (2090-2099). The spread in values reflects geographical differences.

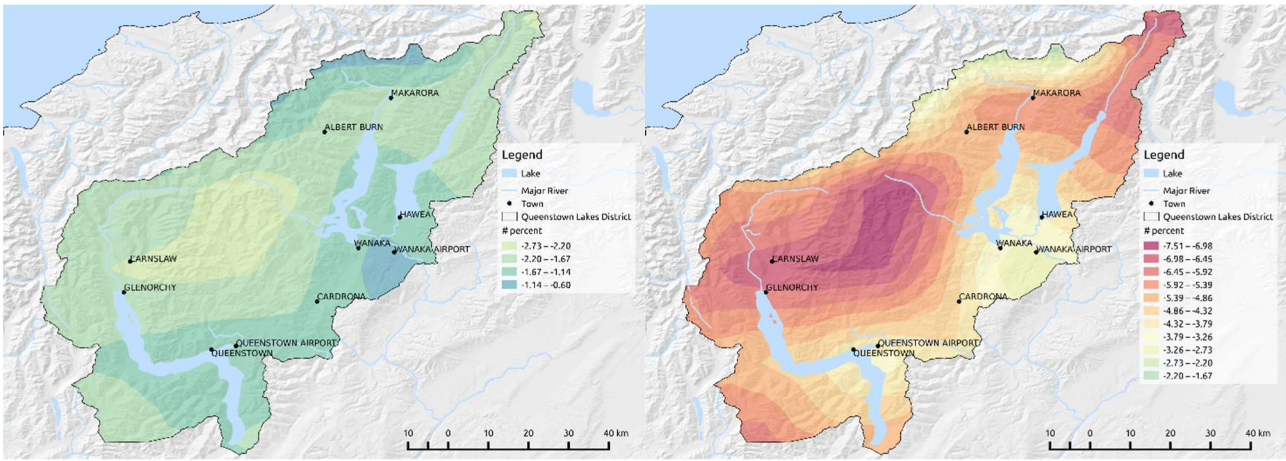

Figure 36: Change in average RH for the mid-century period (2040-49, left) and the last decade of the century (2090-2099, right) for the RCP8.5 emissions scenario.

4.2.6. Snow cover

We derive annual snow-covered area and snow cover duration from model estimates of snowfall and snow-melt at each grid cell using the model described in Clark *et al*. (2009). For the high emissions scenario (RCP8.5), there is a considerable reduction in both snow cover duration and total snow-covered area over the winter period by the end of this century.

The decadal average snow cover duration for the QLD over the two 10-year periods representing the start and end of the 21st century is shown in Figure 37. Additional figures showing the comparable

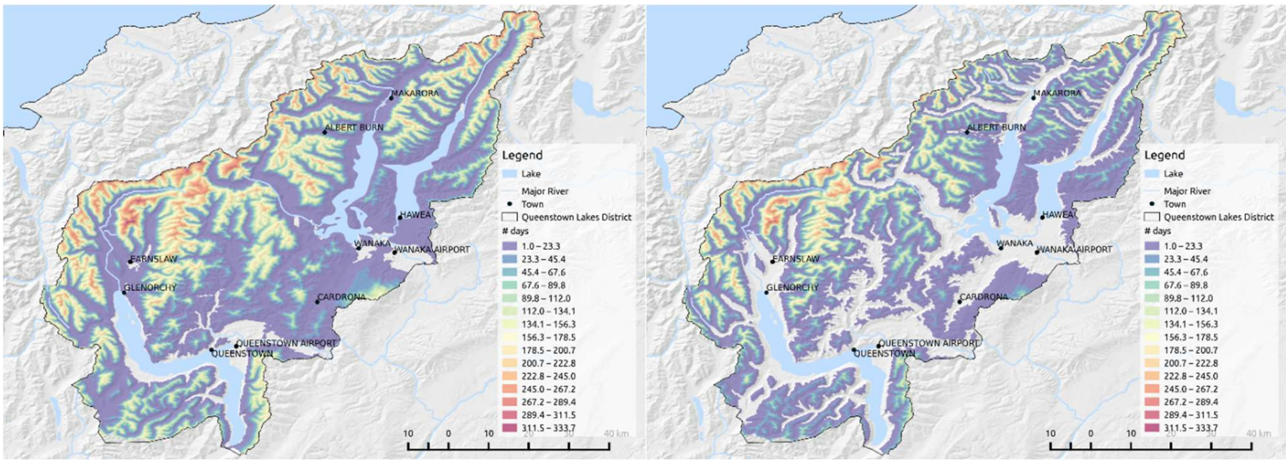

Figure 37: Average snow-cover duration (days) for the District for the base-period (2000-2009, left), and for the end of the century (2090-2099, right) under RCP8.5.

District-wide maps for all of the RCPs and including the mid-century period (2040-2049) are provided at Appendix D.

The proportion of area covered by seasonal snow for each of the four RCPs, and for each of the decadal periods (baseline, middle and end of century) is shown in Figure 38. Key conclusions from these snow model simulations under RCP 8.5 for the end of this century, compared to the baseline period (2000 to 2009) are:

- The peak snow-covered area is projected to reduce by approximately 20%.
- The snow cover duration is likely to reduce across all parts of the District but is particularly pronounced toward the east.
- There is low likelihood of snow settling on the ground in many of the river valleys and lake flats of the District.
- The ski-field areas are all projected to be considerably affected by the reduction in snow cover duration, with Cardrona and Coronet Peak appearing to be the worst hit.

The results found here are consistent with previous work. An examination of the likely effects of climate change on snow cover (Hendrikx and Hreinsson, 2012) found that under the high emissions scenario[17] the number of snow-days (i.e., the number of days when the snow depth exceeds 30cm) is likely to reduce from a maximum of 229 days (in the 1990s) to a maximum of 176 days (in the 2040s) and a maximum of 74 days (in the 2090s). With warming conditions, snow-melt is expected to occur

[17] Note that this study used the A1FI scenario (high growth/fossil fuel intensive) under the previous SRES scheme used by the IPCC, which is not directly comparable with the RCP scenarios.

earlier in the season (mid-July compared to beginning of August). In addition, they found that the potential time available for snowmaking in a ‘worst-case’ year was found to reduce to between 53-82% (in the 2040s), and to between 17-59% (in the 2090s) compared to the 1990s. However, snowmaking was found to remain possible in these conditions and at the locations studied (which included the four main ski-fields in the QLD: Treble Cone, Cardrona, Coronet Peak, and The Remarkables).

An earlier investigation of the impact of climate change on river flow within the Clutha/Mata-Au catchment (Jobst, 2016) showed that climate change will lead to substantial increases in streamflow during winter and declines in summer driven by increasing winter precipitation and a reduction in snow storage.

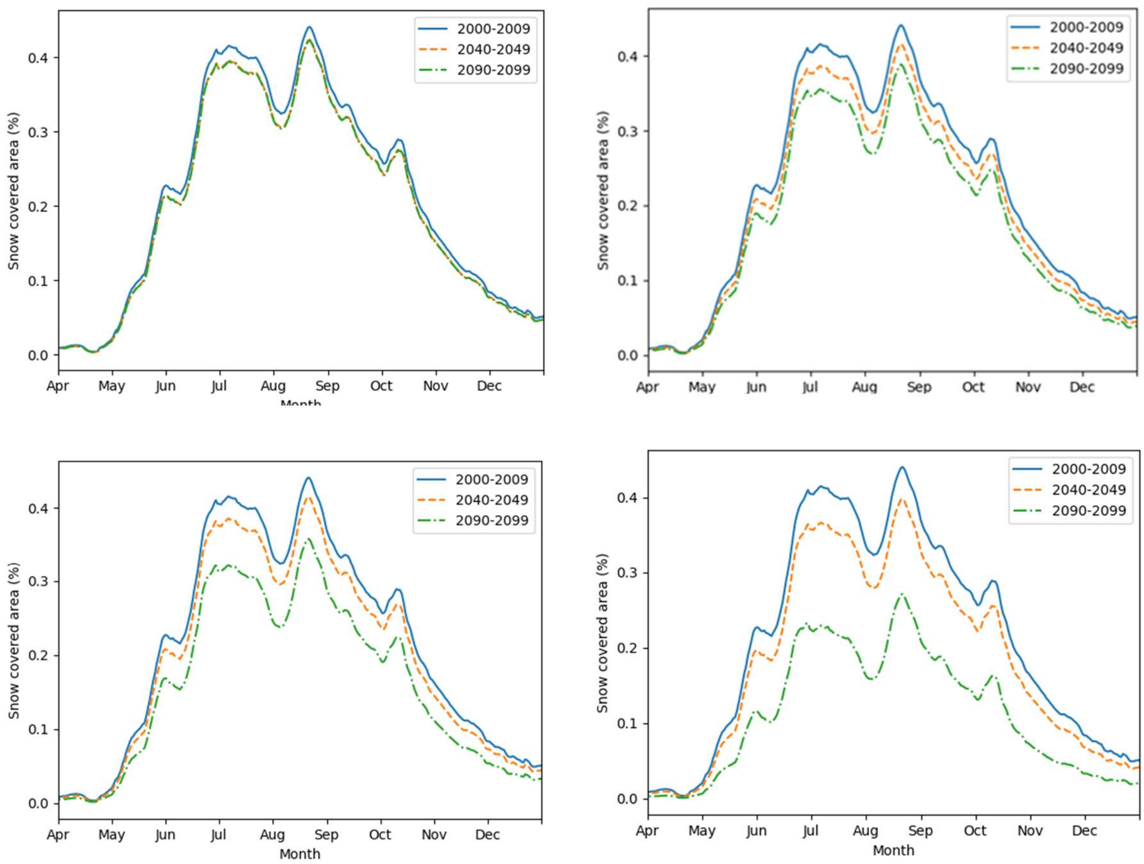

Figure 38: Mean snow-covered area over decadal periods for the base period (2000-2009, blue), the mid-century period (2040-2049, orange) and the end of century period (2090-2099, green) for the Queenstown Lakes District for RCP2.6 (top left), RCP4.5 (top right), RCP6.0 (bottom left) and RCP8.5 (bottom right) emissions scenarios.

4.2.7. Extreme events

With climate change it is possible that both the mean and the range of a chosen climate variable alters. This is illustrated in Figure 39[18] which shows the current distribution of a given climate variable (blue curve), which may for example be the average rainfall at a given location. With climate change (red curve) in this hypothetical situation, the average rainfall increases (moving to the right), and the spread of the distribution also increases (it develops a wider base). This has a compounding effect of increasing the likelihood of damage, both from the shift in the average and due to the 'fatter tail' of the distribution. If for example, a particular category of infrastructure is at risk from a heavy rainfall event exceeding a given limit (black arrow), what may be extremely rare currently (e.g., 1% chance of occurrence in any given year), this becomes much more likely (e.g., 20% chance of occurrence in any given year, red shaded area).

These type of changes to the probability distribution can be calculated based on climate model projections and analysis and used to assist Councils and others in planning for such effects.

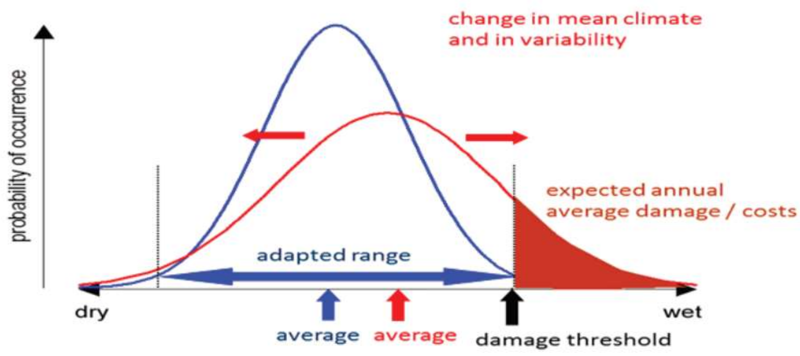

Figure 39: Change in a given climate variable as a result of climate change (Source: Deep South National Science Challenge).

18 https://www.deepsouthchallenge.co.nz/sites/default/files/2017-02/CCII-RA4-Framing-conversations-around-risk-and-uncertainty.pdf

5. Implications for Queenstown Lakes District

A selection of likely implications across a range of sectors as a result of projected climate changes in the District is provided here. This consists of qualitative expert opinion based on a review of existing literature. It covers areas such as Council infrastructure (3 waters, roads/bridges, airport, reserves, flood management infrastructure) as well as some of the important industries for the QLD such as agriculture, fishing and aquaculture, forestry and tourism. In addition, we look at wider social impacts, including public health.

5.1. Snow as a resource

Rising temperatures increase the chance that precipitation will fall as rain instead of snow, resulting in a higher elevation snow-line, and typically a shorter winter 'snow season' with earlier arrival of spring conditions. Indeed, this has been observed already in New Zealand, where the length of winter has reduced from 3 months to two months[19].

When snow does fall, it is likely to melt more quickly. However, because warmer air can hold more moisture and produce more precipitation, some places may experience increases in snow – particularly in storm events. In addition, the type of snow is subject to change as it may undergo more frequent freeze/thaw cycles, thus altering the structure of the snowpack and its subsequent melt characteristics.

Overall, ski-fields would be expected to face a requirement for increased snowmaking, and thus higher water and electricity usage. However, the ability to carry out snow-making activities is temperature dependent and may therefore be expected to become increasingly limited to the shorter winter season, unless snow-making technology advances further to address such limitations.

An additional factor associated with change in the snowpack is that snow melt helps to moisten the soil each spring and promote plant growth – a depletion in the total snowpack may contribute to drier landscapes, and higher drought or wildfire risk.

5.2. Irrigation and drought

For the QLD, increasing temperatures, combined with changes in rainfall patterns and a dwindling snowpack, are more likely than not to increase the risk of drought. It is difficult to pinpoint either the timing or location of such drought events, but it is likely that water users will seek continued expansion of irrigation activities. With many of the older water permits ('Deemed" permits) across the District expiring in 2021[20], and the Otago Regional Council reviewing minimum flows in rivers and streams within the District[21] (including the Arrow and Cardrona rivers), it will be important for the impact of evolving changes in the climate to be considered in water allocation decision-making.

Droughts are complex hydrologic phenomena subject to influence by numerous factors, including temperature, wind-speed, atmospheric humidity, and precipitation rates. Climate change is expected

[19] https://www.stuff.co.nz/environment/climate-news/98612030/winter-is-one-month-shorter-niwa-data-shows
[20] https://www.orc.govt.nz/consents/before-applying-for-a-consent/transitions-from-deemed-permit-to-rma-consent
[21] https://yoursay.orc.govt.nz/minimumflows

to quicken the set-in speed and intensity of droughts (Trenberth *et al*., 2014). However, timing of drought is also important: drought in late summer when plants have largely completed their growth phase does not have the devastating impact of late winter/early spring drought that prevents achievement of full productive potential (McGlone *et al*., 2010).

5.3. Land-use change

Changes in land-use may include changes in areas for cropping or used for various farming, residential or industrial purposes. Such changes may be driven by climate changes that alter the elevation or latitude at which certain activities can occur, as well as changes in snow cover (e.g., snow line elevations or latitudes). For example, the warming climate may mean that grapes are able to be grown in areas further south or at higher elevation than their current extent (although it is noted that other factors such as rainfall and soil type are also critical to the viability of such crops). Afforestation with exotic tree species may lead to reductions in catchment water yield, with negative impacts on streamflow and freshwater biodiversity. Some specific changes that will have implications for land-use are:

- Higher temperatures may allow for different crop types to be grown across the District.
- It is likely that crops could be sown earlier in the growing season and will reach maturity faster due to higher temperatures.
- Stock may be susceptible to increased heat stress.
- Changes in the range and habitat of native flora and fauna, as well as the distribution of pest species could also impact land-use.
- Changes in the timing of seasonal activities such as flowering, breeding, and migration.
- Grapes thrive when plants are well watered for the first part of the growing seasons, but then deficit irrigated until harvest, so while rainfall in spring and early summer provides needed water and reduces irrigation costs, rainfall later in the season can reduce fruit quality (Girona *et al*., 2006).

5.4. Emergency management

From a weather and climate perspective emergency management is chiefly concerned with extreme events. We consider the impacts resulting from a range of different event types here.

Flooding: An increased likelihood of extreme rainfall events leads to a concomitant increase in the likelihood of flooding. However, a range of other factors contribute to the overall impact of flooding, including protection measures, catchment modification, land-use, presence or absence of snow, and water extraction. The Otago region is particularly susceptible to larger and more frequent flooding, with the largest floods likely to become larger, and greater numbers of rivers in flood at any one time, stretching emergency response resources and recovery budgets[22].

Snowfall: Extreme precipitation events may occur during winter storms, resulting in high snowfall events. Very high snowfall has implications for road and property hazards, including avalanche risk. An increase in motor vehicle accidents is one possible outcome from such conditions. A reduction in the volume of water stored as snow over the winter months (due to higher temperatures) may also lead to increased erosion as rainfall is able to more immediately runoff from hill country areas.

[22] https://www.odt.co.nz/opinion/flooding-likely-become-commonplace

Freezing: A reduction in the number of frost days is likely to see a reduced hazard from ice on roads, reducing the danger of motor vehicle accidents, and the need for anti-icing road treatments such as CMA (Calcium Magnesium Acetate).

Heatwave: From an emergency management perspective the primary concern relates to heat stress and human health, which may put pressure on the health system to cope. Increased mortality has been observed in heatwaves overseas, particularly for vulnerable age groups (the very young and the very old).

Fire: Increased temperatures, combined with drought conditions and less availability of snow melt-water heighten the risk associated with wild-fire. The primary risk is forest fire, where higher volumes of combustible material are available, and is increased in forested areas in close proximity to settlements.

5.5. Public health

Globally, higher temperatures and extreme events are likely to increase incidence of illness and injury, while nutrition will be affected by changing patterns of infectious diseases and water or food shortages. Significant social and mental health impacts are likely through loss of livelihoods, forced migration and conflict.

In New Zealand the potential implications of climate change as it relates to public health impacts have been assessed by organisations such as The Royal Society of New Zealand (RSNZ), and by OraTaiao[23] (The NZ Climate and Health Council). RSNZ (2017) has developed expert advice on the health impacts of climate change[24], drawing on both international (e.g., IPCC assessment reports) and local evidence. They note that there are significant research gaps regarding the effects of climate change on public health in NZ, although it is expected that some people will face serious health threats (in particular those who already suffer from poor health), and indeed climate change is found to already affecting the health of New Zealanders (RSNZ, 2017). On the other hand, increasing temperatures may reduce the incidence of 'cold mortality' – where higher mortality rates occur in the cold winter months.

5.6. Sustainability

The UN's 'Sustainable Development Goals[25]', include a wide range of sustainability concerns (including economic and social) which from an environmental perspective capture the need for clean water, clean energy, sustainable communities, resilient infrastructure, responsible consumption and production, and the urgent need to act on climate change. In the context of this report we are interested in both sustainable land-use and behaviour-change.

Sustainable land-use aims to ensure that land-use activities do not cause long-term, detrimental effects that may be irreversible. For the QLD, one of the main considerations is rapid urban growth, which may reduce amenity value and put pressure on local infrastructure networks.

[23] OraTaiao is a not for profit organisation focussing on the negative impacts of climate change on health, and the health gains that are possible through climate action.
[24] https://royalsociety.org.nz/assets/documents/Report-Human-Health-Impacts-of-Climate-Change-for-New-Zealand-Oct-2017.pdf
[25] https://www.un.org/sustainabledevelopment/

Behaviour-change involves encouraging people to first recognise that an issue exists in the way that current activities are undertaken, then modifying their activities accordingly. It includes the promotion of activity that will lead to better management and enhanced outcomes for the environment.

In the QLD context, there are several behaviour-changes that could be encouraged, with the assistance of the Council. Examples include stimulating a reduction in the use of coal or diesel fired burners and boilers by encouraging organisations to shift to wood-fired heating, or another technology that is less environmentally harmful. In addition, positive behaviours could be encouraged and accelerated, such as the planting of native species to create riparian strips along waterways, providing habitat for native fauna and cutting down on the rate of pollutants entering waterways. The Council could also play a key role in education around the impact of individual and collective activity on GHG emissions.

5.7. Infrastructure

Consideration of climate change is particularly important for designing climate-sensitive infrastructure or assets which are likely to be in place for many decades, and for resource use and land development planning over similar timescales. The QLDC manages a range of infrastructure categories across the District that are critical to ensure the smooth operation of the District for both residents and visitors alike. These include:

Roading: One of the main considerations for roading is frost occurrence, which is projected to decrease significantly by the end of the century (see Section 4.2.1, ‘Frost Days’). However, higher temperatures may hamper road construction and exacerbate heat damage (e.g., bitumen ‘bleeding’). An additional issue is the potential for greater damage to bridges and roads near rivers, due to the likelihood of more extreme flood events caused by extreme rainfall, snowfall or snowmelt runoff.

3-waters (potable, wastewater, stormwater): Demand for potable water is likely to increase as temperatures rise, as both animals and plants demand increased hydration in hotter conditions, particularly over the summer season, where drought conditions may occur more frequently. Stormwater management may potentially become challenging with an increased incidence of extreme precipitation events. The stormwater system may be more frequently exposed to higher volumes of water - which may exceed current design standards - and this should be considered in the provision of pipes and other components of stormwater networks. Existing issues of stormwater overflowing into wastewater systems would also be likely to be exacerbated in this case. Options for more resilient, sustainable or environmentally friendly (e.g., so called blue or green infrastructure systems) could be explored. Network design and management based on reducing exposure to risk is recommended.

Waste: No specific issues regarding the impact of a changing climate have been identified for solid waste. However, there may be implications for handling of sewage sludge with increased maximum temperatures, and an increase in green-waste as a result of improved growing conditions is also a possibility.

Parks: Management of parks areas may be affected by changes to the availability of water from changes to river flows as a result of altering precipitation patterns, increasing temperatures and a reduction in snowmelt.

Urban planning: As for parks, water availability is a key consideration. In addition, the potential impacts on stormwater networks of more extreme rainfall events should be considered in new and existing developments. The QLDC should consider planning urban growth to minimize exposure to fire, flood, and drought as well as to other natural hazards.

5.8. Other sectors

Hydroelectricity: Changes in the characteristics of snowfall and snowmelt have implications for hydroelectric power generation, which currently relies on these contributions to the annual catchment flow pattern. A reduction in snow storage, combined with increased temperatures is likely to lead to substantial increases in streamflow during the winter and reductions in streamflow in summer months. However, superimposed on this annual pattern is a likely increase in variability on a daily, weekly or monthly basis, as the probability of higher intensity storms grows.

Mammalian pests: Warmer and drier winters are thought to extend the breeding seasons of some mammalian predators (e.g., rodents, goats, pigs and possums).

Social effects: Climate change impacts outside the District are likely to have significant indirect impacts on QLD. These include the impact of sea level rise on coastal communities, both in New Zealand and internationally - causing a migration of people inland. Other possible effects include increased costs for transporting goods and services as fuel price rises take effect; and the changing demographic profile meaning an increasingly ageing population as the impacts from climate change ramp up.

Community engagement: Though not a direct effect of climate change it is important that councils engage with their community in a genuine two-way dialogue that informs all participants, provides a common level of understanding of the issues, and aims toward agreed plans and strategies in response to the projected changes. This presents a unique leadership opportunity, with councils ideally placed to take a leadership role in instigating the community discussion, supporting it as it evolves.

Further information: Over the last two years (2017-2018) the Government convened the "Climate Change Adaptation Technical Working Group" or CCATWG. The CCATWG published two reports – a stocktake report[26] and a recommendations report[27]. The first report provides an overview of the expected impacts of climate change on New Zealand, takes stock of existing work on adaptation, and identifies gaps in New Zealand's current approach. The second report provides recommendations for the actions needed to build resilience to the effects of climate change, while growing the economy sustainably. Both reports provide an excellent backgrounder for local government and are available online.

[26] http://www.mfe.govt.nz/publications/climate-change/adapting-climate-change-new-zealand-stocktake-report-climate-change

[27] http://www.mfe.govt.nz/publications/climate-change/adapting-climate-change-new-zealand-recommendations-climate-change

6. References

Clark, M., Örn Hreinsson, E., Martinez, G., Tait, A., Slater, A., Hendrikx, J., Owens, I., Gupta, H., Schmidt, J. and Woods, R., (2009), *Simulations of seasonal snow for the South Island, New Zealand*, Journal of Hydrology, 48, 2, 41-58.

Cullen, N.J., Anderson, B., Sirguey, P., Stumm, D., Mackintosh, A., Conway, J.P., Horgan, H.J., Dadic, R., Fitzsimons, S.J. and Lorrey, A.M., (2016), *An 11-year record of mass balance of Brewster Glacier, New Zealand, determined using a geostatistical approach*, Journal of Glaciology

Fitzharris, B., and Garr,C. (1995) Simulation of past variability in seasonal snow in the Southern Alps, New Zealand, Annals of Glaciology, 21, 1, 377-382.

Fitzharris, B.B., Lawson, W. and Owens, I., (1999), *Research on glaciers and snow in New Zealand*, Progress in Physical Geography, 23 (4), 469-500.

Girona, J., Mata, M., del Campo, J., Arbones, A., Barta, R. & Marsal, J., (2006), *The use of midday leaf water potential for scheduling deficit irrigation in vineyards*. Irrigation Science, 24, 115-127.

Hendrikx, J., Hreinsson, E. Ö., Clark, M. P. and Mullan, A. B., (2012), *The potential impact of climate change on seasonal snow in New Zealand: Part I - an analysis using 12 GCMs*, Theoretical and Applied Climatology, doi: 10.1007/s00704-012-0711-1.

Hendrikx, J., Harper, A. (2013) Development of a National Snow and Ice Monitoring Network for New Zealand. Journal of Hydrology (New Zealand). 52.2

IPCC (2014): *Climate change 2014: Mitigation of climate change. contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, et al (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2018): *Global warming of 1.5°C: Summary for policy-makers.* [Masson-Delmotte, V., Zhai, P., Pörtner, H., Roberts, D., Skea, J., Shukla, P.R., et al (eds.)]. Intergovernmental Panel on Climate Change.

Jobst, A.M., (2016), *The potential impacts of climate change on the hydro-climate of the Clutha/Mata-Au catchment*. Ph.D thesis, University of Otago, Dunedin, New Zealand.

Kerr, T., (2013), *The contribution of snowmelt to the rivers of the South Island, New Zealand*. Journal of Hydrology (New Zealand), Vol. 52, No. 2, pp. 61-82

Lewis, J., Bodeker, G. E., Tait, A., and Kremser, S. (2017), *A method to encapsulate model structural uncertainty in ensemble projections of future climate*, Geosci. Model Dev. Discuss 10, 4563-4575.

Mcglone, M., Walker, S., Hay, R. and Christie, J. E. (2010), Climate change, natural systems and their conservation in New Zealand. In: Nottage, R., Wratt, D., Bornman, J. F. and Jones, K. (eds.) *Climate change adaptation in New Zealand: future scenarios and some sectoral perspectives*. Wellington: New Zealand Climate Change Centre.

Ministry for the Environment (2018), Climate Change Projections for New Zealand.

Mojzisek, J., (2006), *Precipitation variability in the South Island of New Zealand*, PhD thesis, University of Otago, Dunedin, New Zealand.

Redpath, T, Sirguey, P, Cullen, N, (2019, under review) Charactersing spatio-temporal variability in seasonal snow cover at a regional scale from MODIS data: The Clutha Catchment, New Zealand. *Hydrol. Earth Syst. Sci. Discuss.*

Rogelj, J., Den Elzen, M., Höhne, et al. (2016). *Paris Agreement climate proposals need a boost to keep warming well below 2°C*. Nature. 534 (7609): 631–39.

Sirguey, P., Mathieu, R. and Arnaud, Y., (2009), *Subpixel monitoring of the seasonal snow cover with MODIS at 250 m spatial resolution in the Southern Alps of New Zealand: Methodology and accuracy assessment*, Remote Sensing of Environment, 113, 160-181, doi:10.1016/j.rse.2008.09.008.

Tiao, G.C., Reinsel, G.C., Xu, D., et al. (1990), *Effects of autocorrelation and temporal sampling schemes on estimates of trend and spatial correlation*, J. Geophys. Res., 95D12, 20507-2051.

Trenberth, K. E., Dai, A., Van Der Schrier, G., et al., (2014), *Global warming and changes in drought*. Nature Climate Change, 4(1), 17–22.

7. Appendices

Appendix A – Representative Concentration Pathways

"It's tough to make predictions, especially about the future." - Yogi Berra

There are many possible futures regarding global climate. Exactly which one we follow will depend on many factors that are themselves unpredictable. As a result, there is no way to make a reliable prediction on what the future climate may look like. Therefore, rather than making predictions about future climate, we make 'projections'. Projections are different from predictions. A prediction says, 'this is what will happen'. A projection says, 'this is what will happen based on this set of assumptions'. That set of assumptions, together with the simulated outcomes, is referred to as a scenario.

The latest IPCC assessment reports have considered the four scenarios that describe four possible climate futures, all of which are considered possible depending on the quantities of greenhouse gases emitted over the 21st century. The scenarios are referred to as 'representative concentration pathway' (RCP) scenarios. Input from integrated assessment modellers, climate modellers, terrestrial ecosystem modellers and emissions inventory experts is combined to create the storylines that underpin each of the RCPs. The four RCPs (RCP2.6, RCP4.5, RCP6, and RCP8.5) are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 Wm^{-2}, respectively). RCPs are referred to as pathways to emphasize that their main purpose is to provide time series of greenhouse gas emissions and resultant atmospheric concentrations of those gases. The term 'pathway' emphasizes that it is not only a specific long-term radiative forcing level that is aimed for, but also the trajectory that is taken over time to reach that outcome. They are representative in the sense that several different scenarios can have similar radiative forcing and emissions characteristics. CO^2 emissions corresponding to the four RCPs, and the resultant atmospheric CO^2 concentrations are shown in Figure A2.

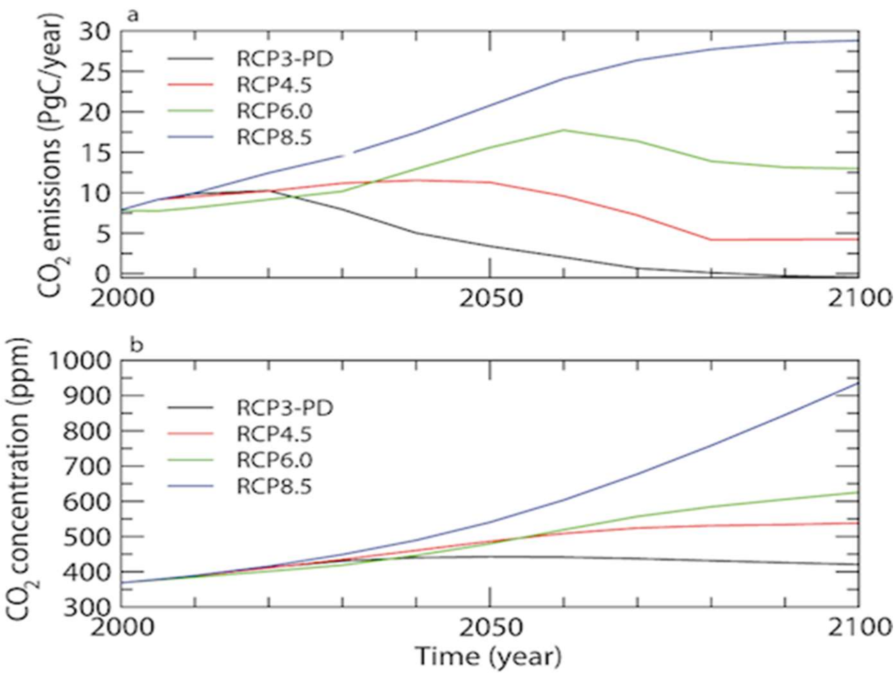

Figure A1: CO^2 emissions and resultant atmospheric CO^2 concentrations for the four RCP scenarios. Note that in this figure RCP2.6 is listed as RCP3-PD i.e., the radiative forcing peaks at 3 Wm^{-2} in mid-century before declining to 2.6 Wm^{-2} in 2100 (IPCC, 2014).

Appendix B – Confidence and likelihood as defined by the IPCC

When IPCC scientists refer to 'confidence' and 'likelihood,' each term has a different and very specific meaning relating to levels of certainty. 'Confidence' refers to the degree of confidence in being correct. For example, issues such as lack of observational data in certain regions, will affect scientists' confidence in their findings. 'Likelihood' refers to the probability of an event or outcome occurring.

Confidence: Confidence levels are based on the evidence (robust, medium and limited) and the degree of scientific agreement (high, medium and low). The combined evidence and agreement results in five levels of confidence (very high, high, medium, low and very low), as shown by the coloured lines in the figure below. If an event is given a very high confidence level, there is a combination of high agreement and robust evidence that it will occur.

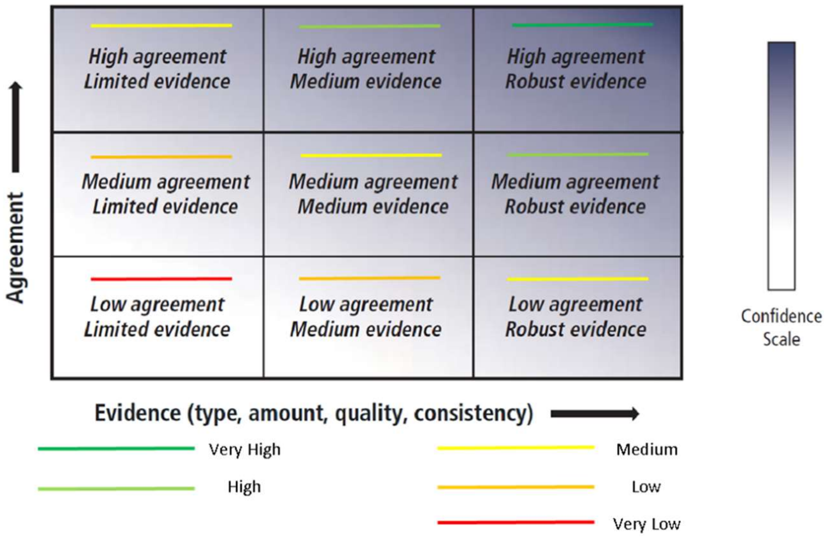

Figure B1: Confidence levels based on level of agreement and evidence (IPCC 2014).

Likelihood: Standard terms used by the IPCC to define likelihood include:

Term	Likelihood of the outcome
Virtually certain	>99% probability
Extremely likely	>95% probability
Very likely	>90% probability
Likely	>66% probability
More likely than not	>50% probability
About as likely as not	33 to 66% probability
Unlikely	<33% probability
Extremely unlikely	<5% probability
Exceptionally unlikely	<1% probability

Appendix C – Low, medium and high RCP scenario maps

Additional figures are included here to show the range of projected changes in the ECVs for RCP2.6, RCP4.5, and RCP6.0. The RCP8.5 projections are included in the body of the report.

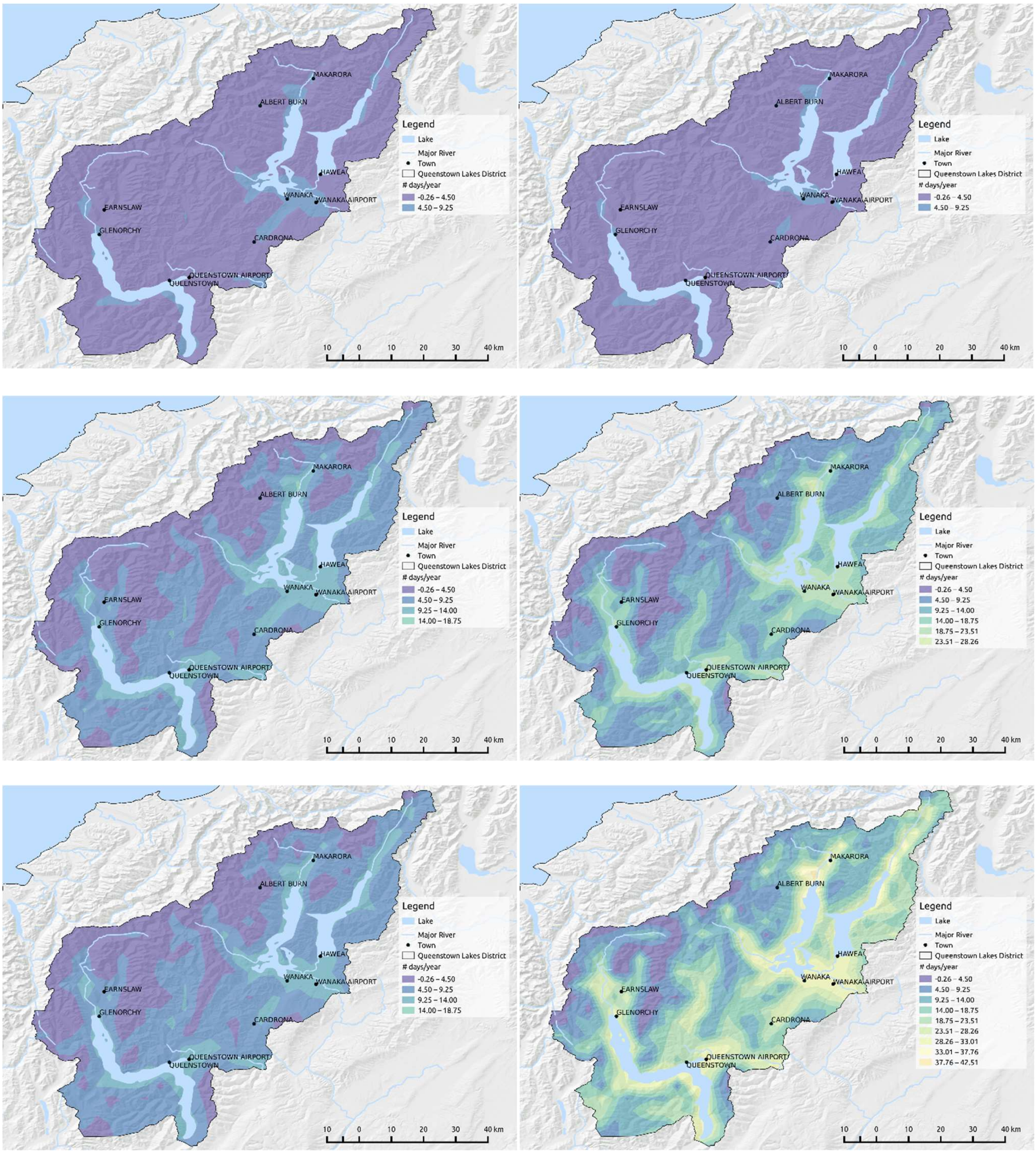

Figure C1: Change in the number of summer days under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

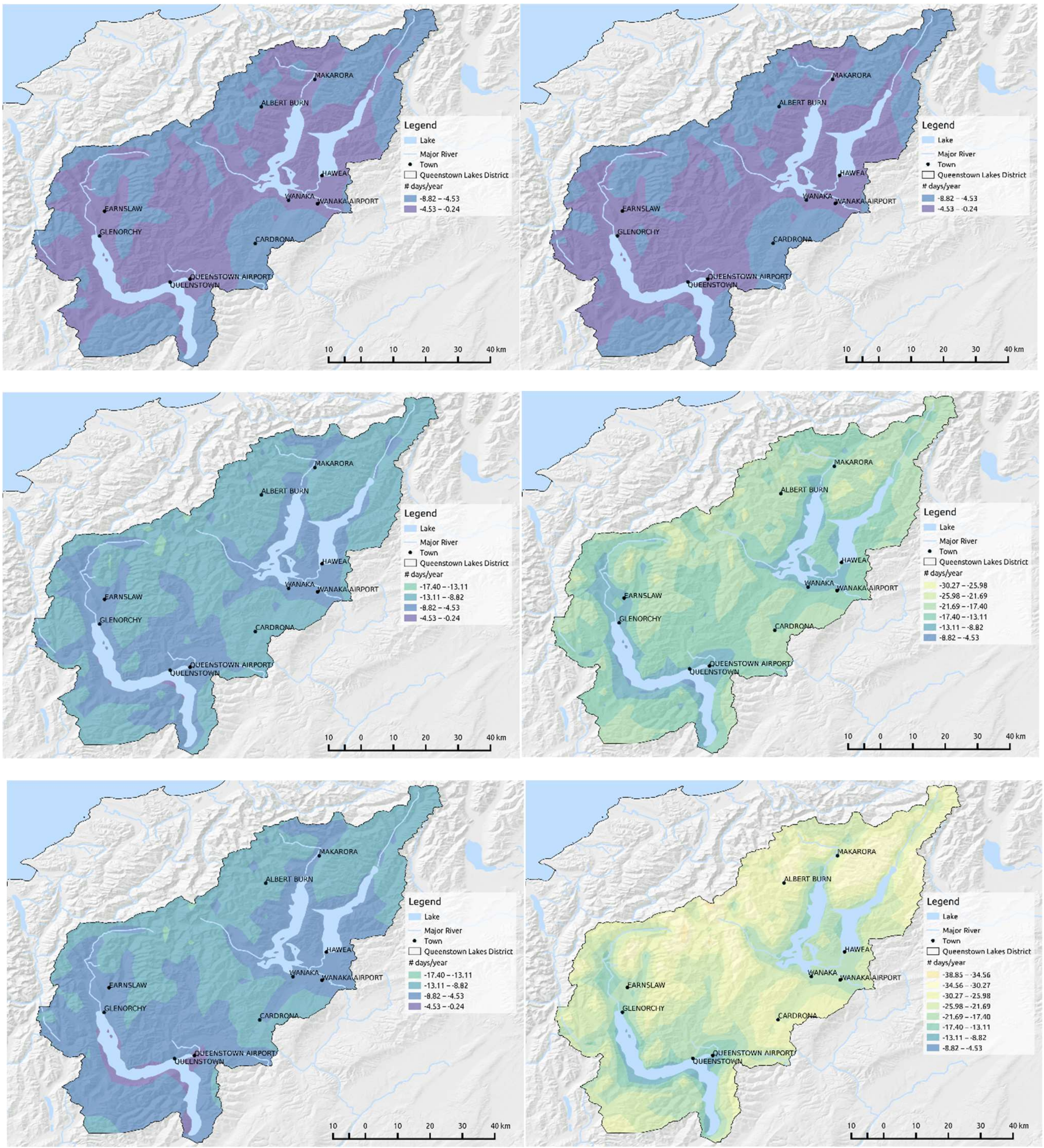

Figure C2: Change in the number of frost days under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

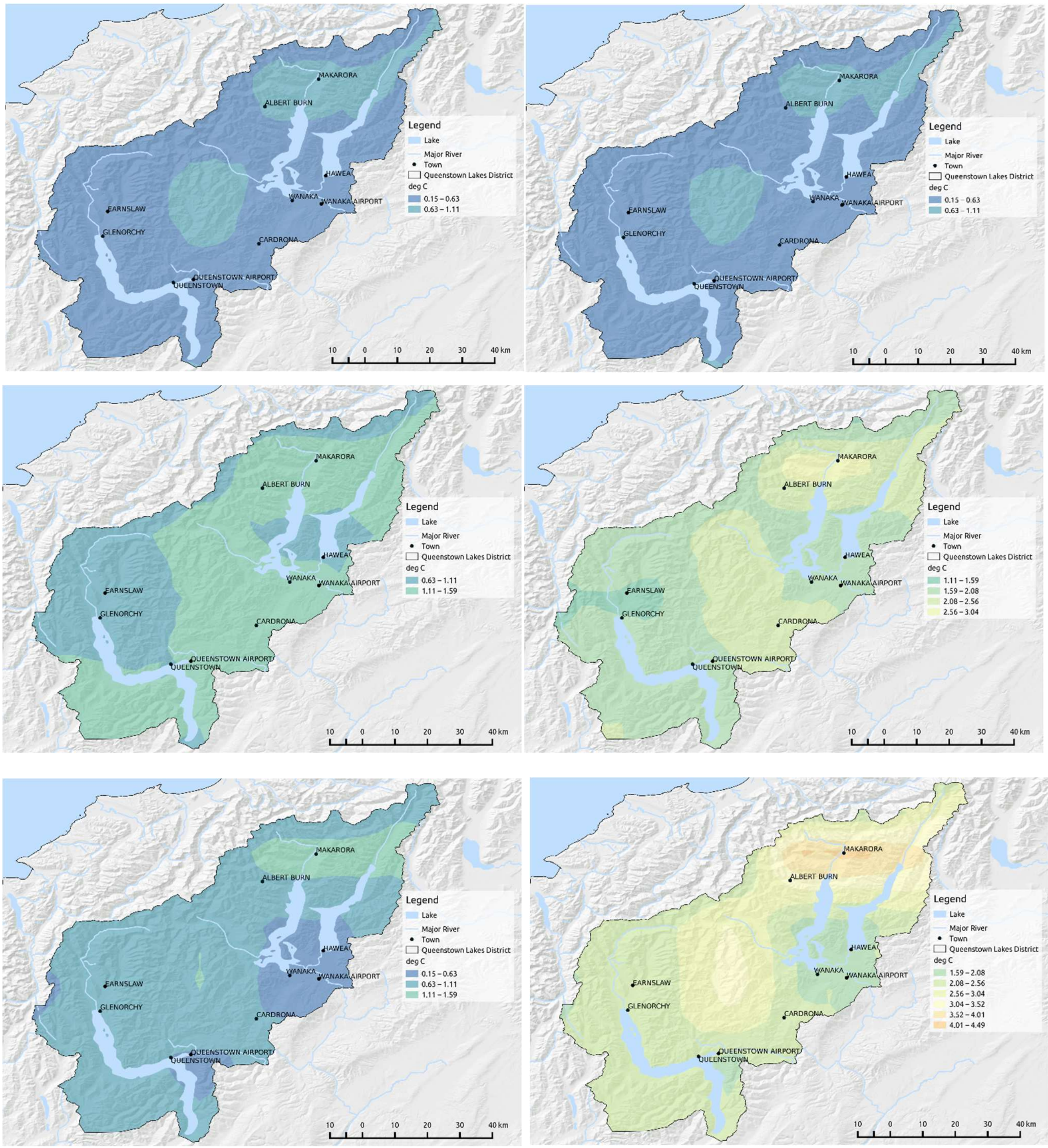

Figure C3: Change in the highest daily maximum temperature under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

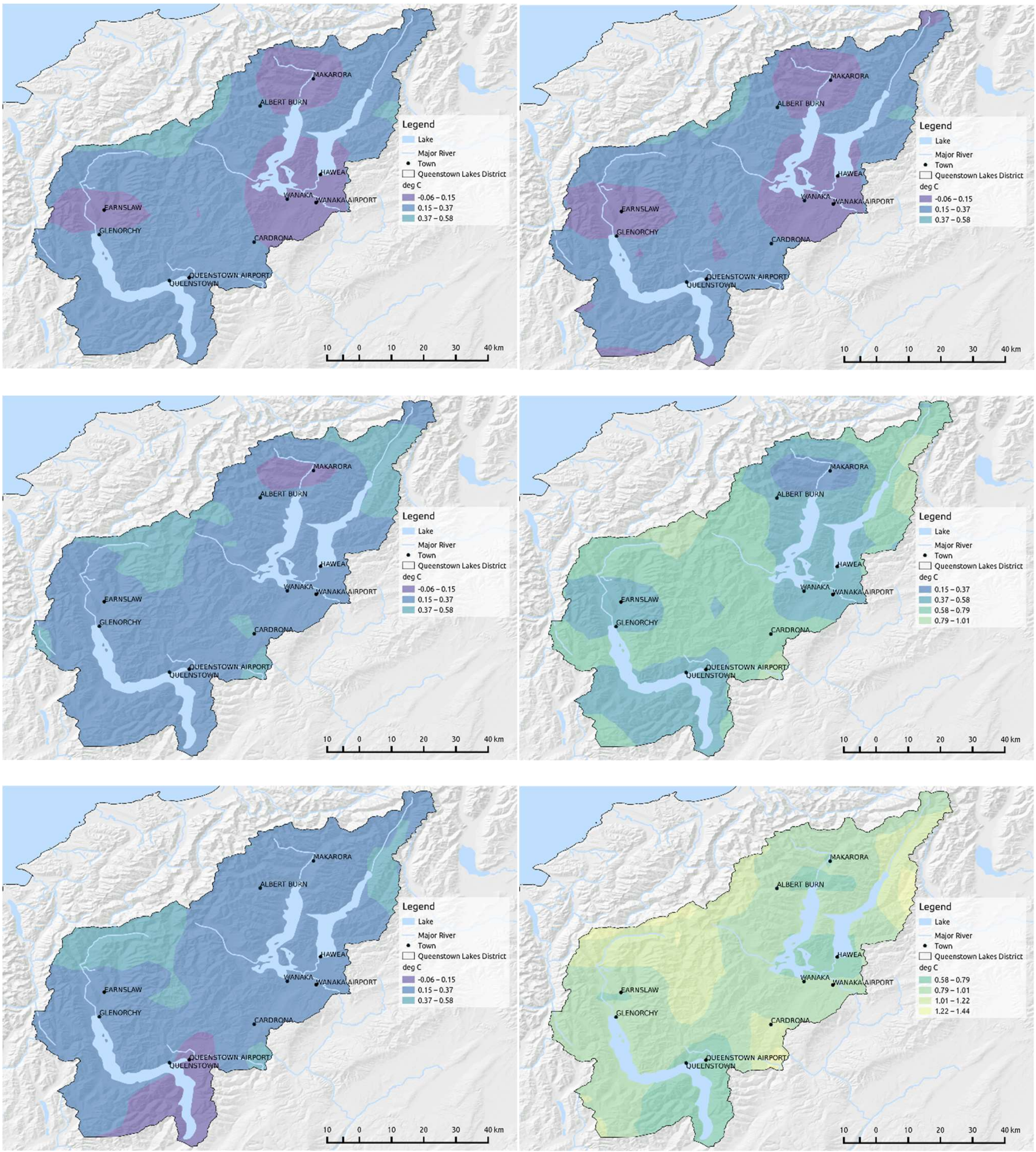

Figure C4: Change in the lowest daily maximum temperature under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

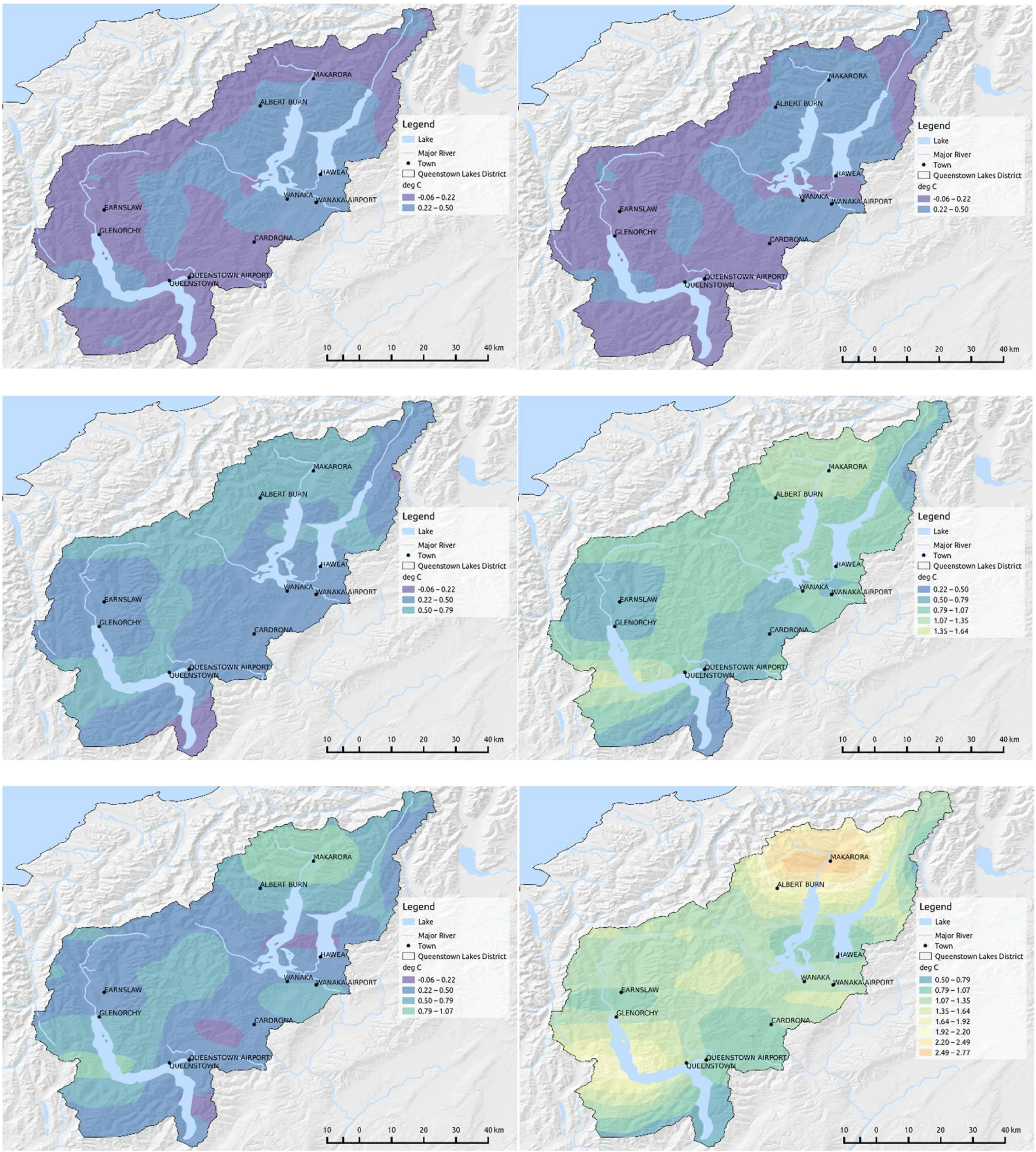

Figure C5: Change in the highest daily minimum temperature under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

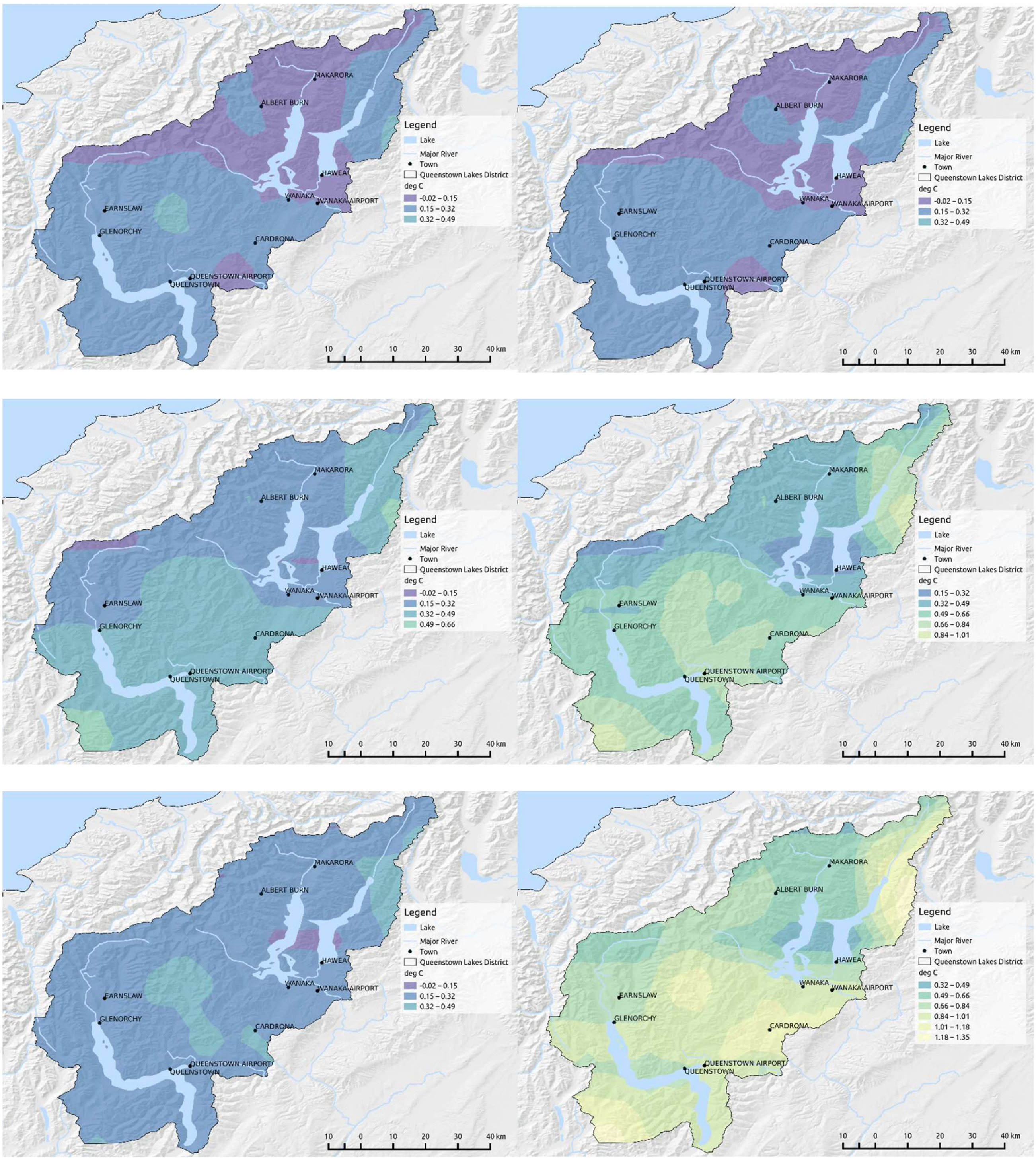

Figure C6: Change in the lowest daily minimum temperature under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

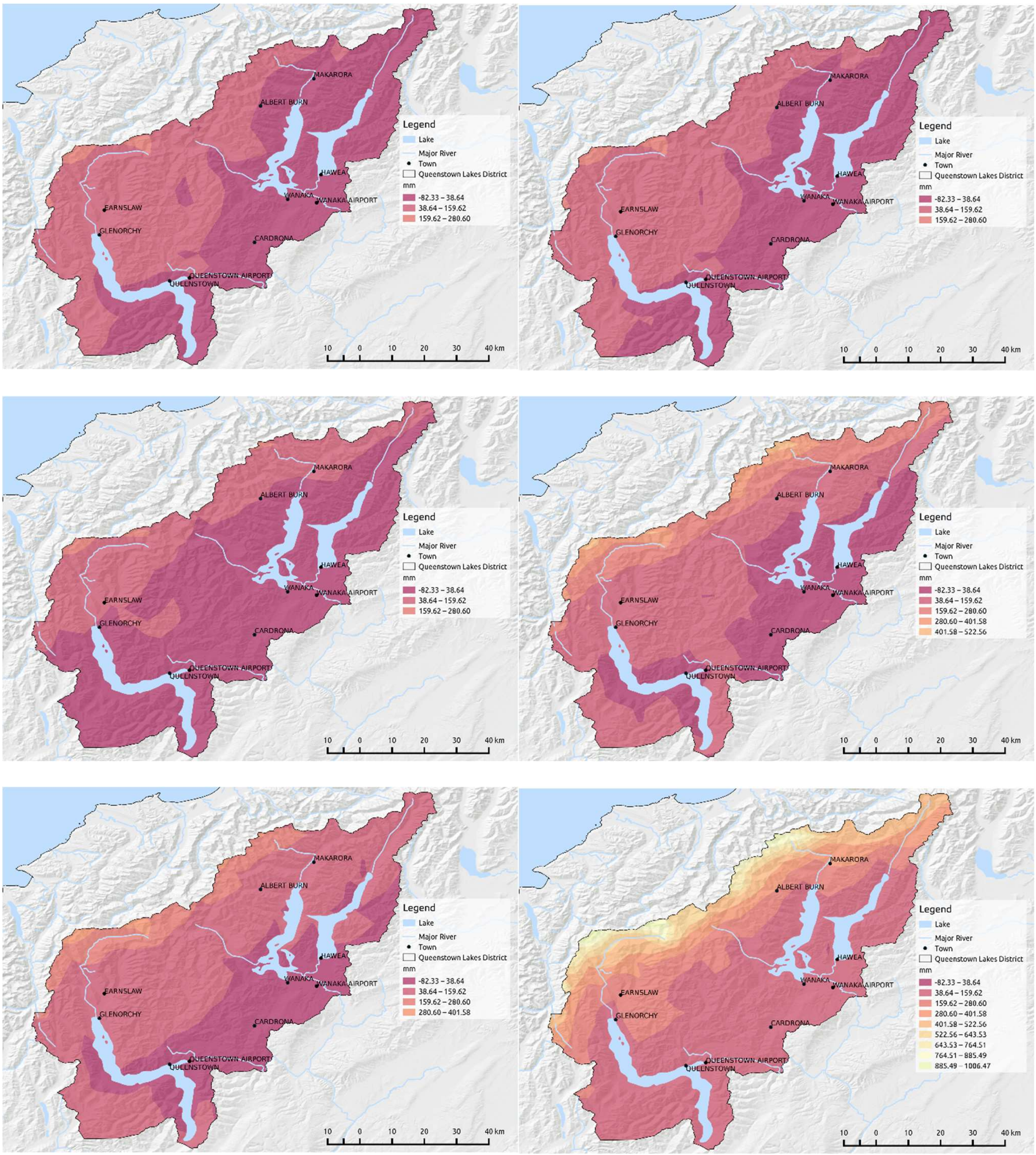

Figure C7: Change in total precipitation under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

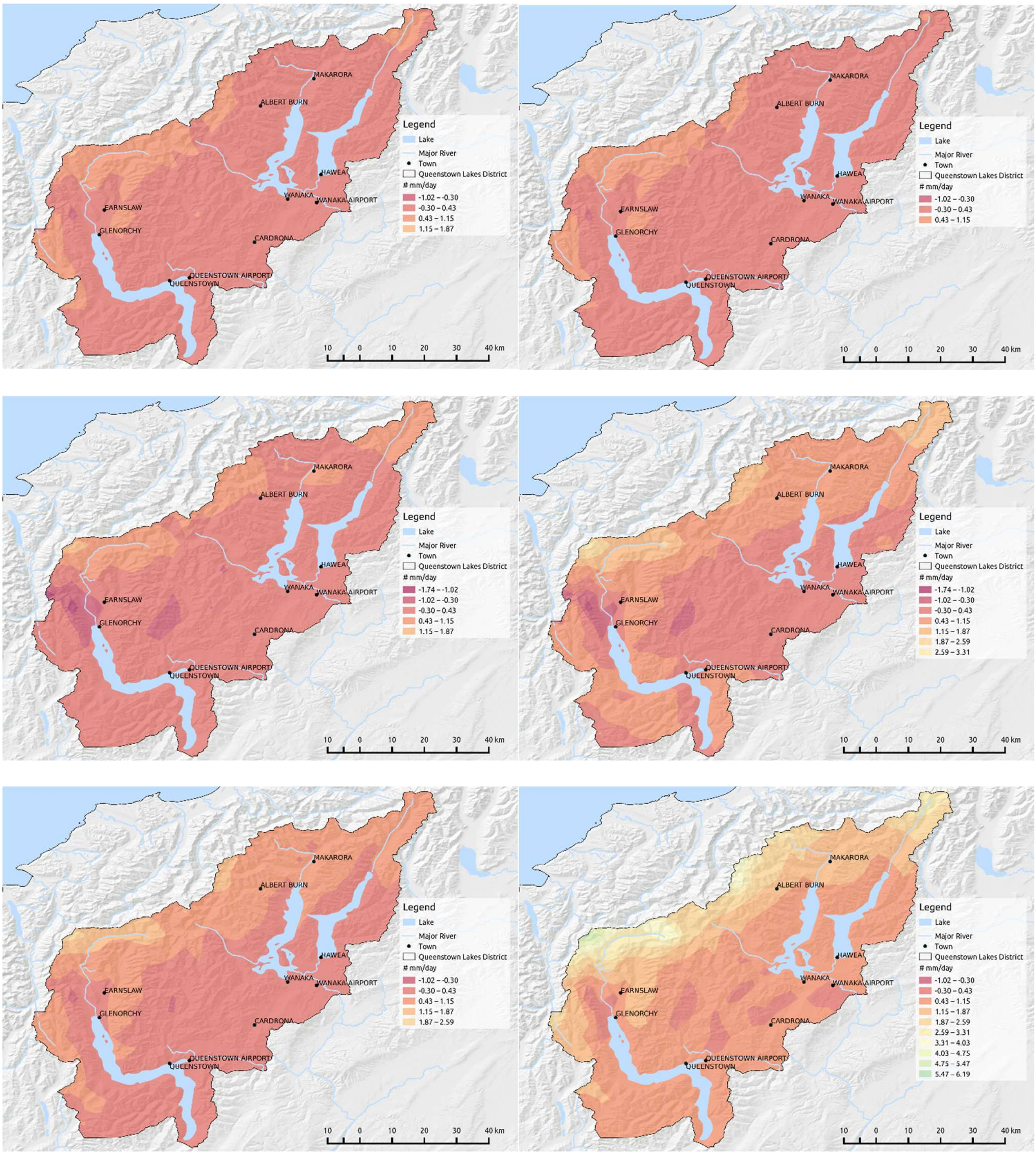

Figure C8: Change in precipitation intensity under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

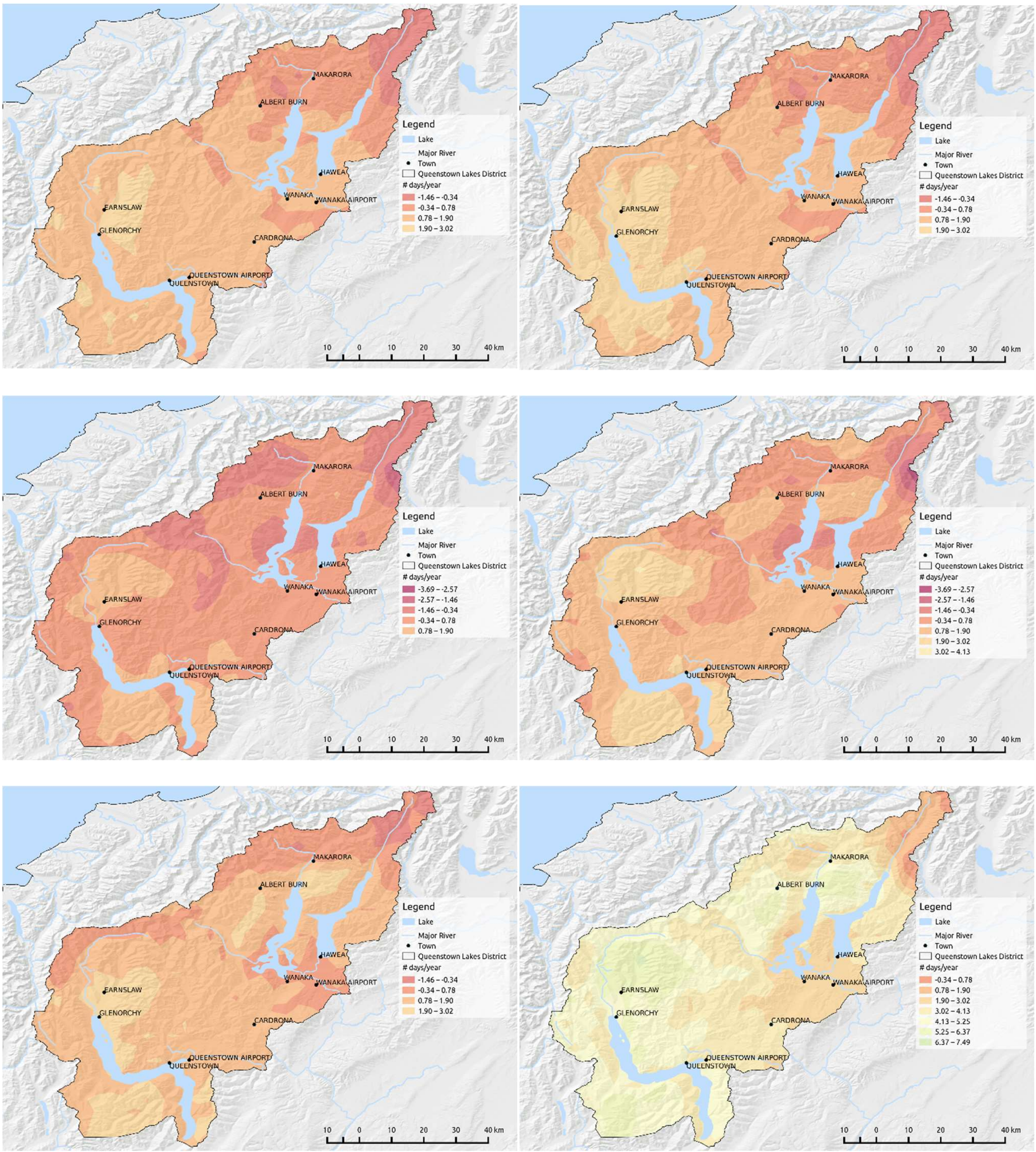

Figure C9: Change in heavy rainfall days under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

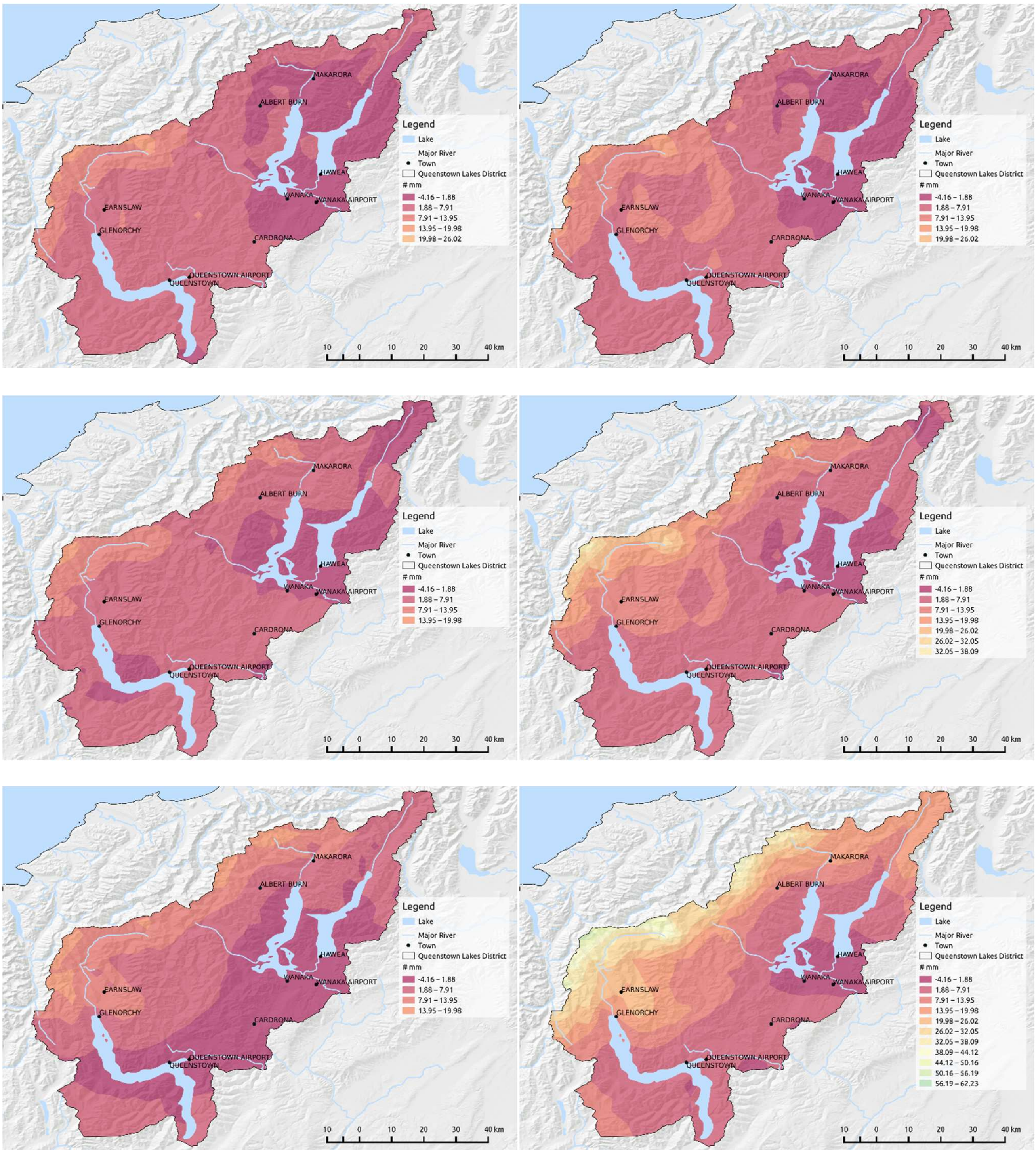

Figure C10: Change in maximum 1-day precipitation under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

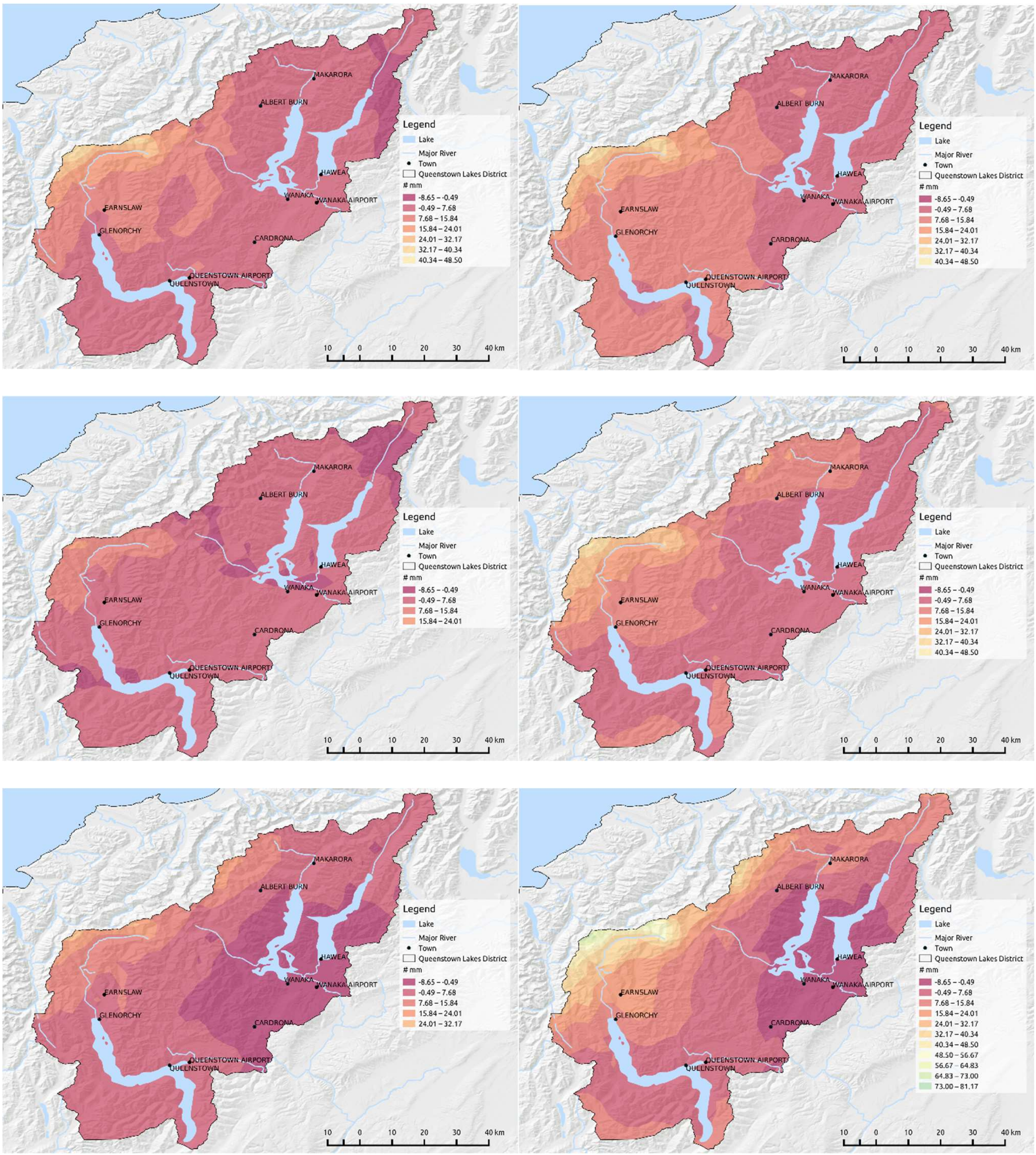

Figure C11: Change in maximum consecutive 5-day precipitation under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

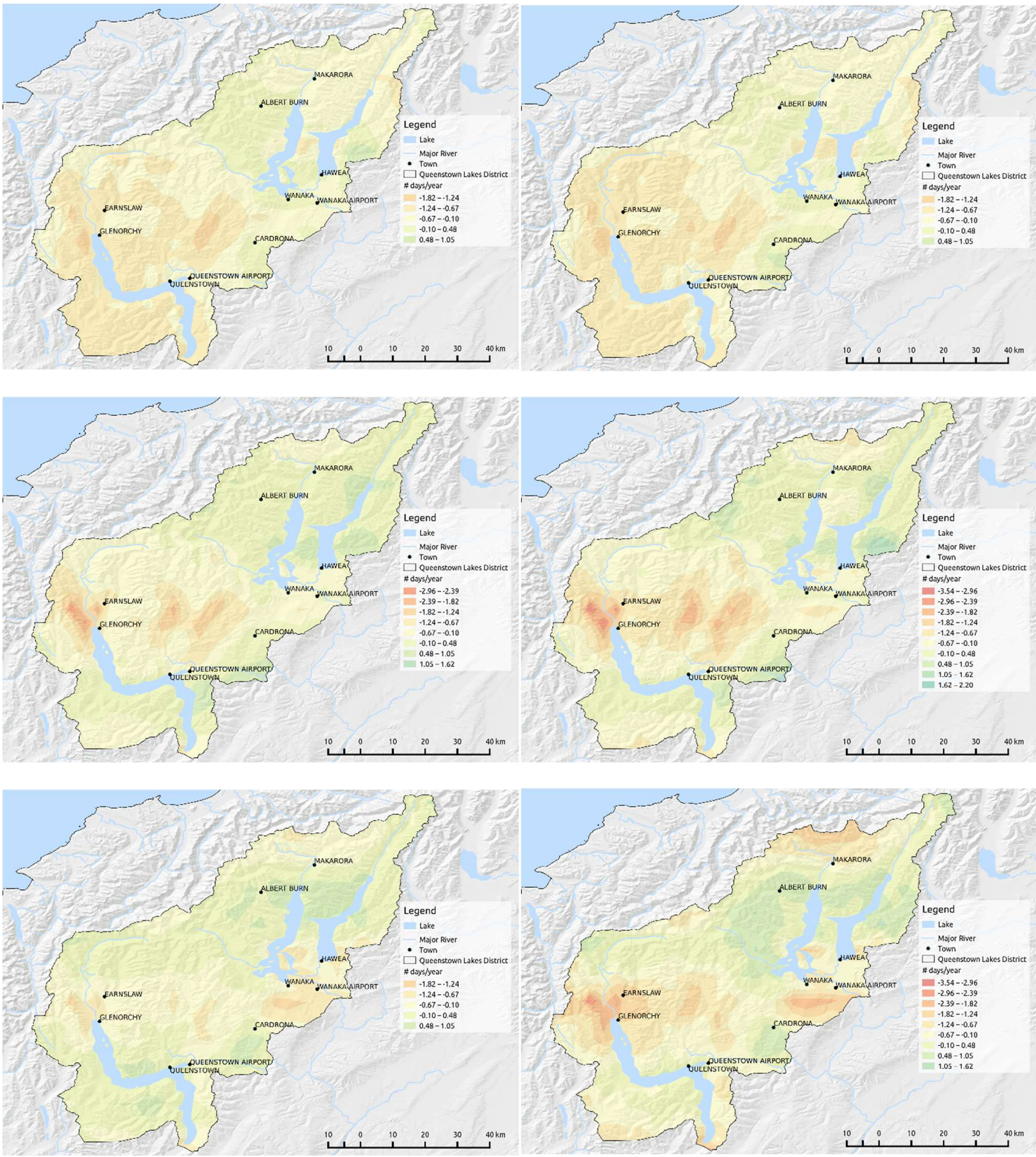

Figure C12: Change in the length of a dry spell under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

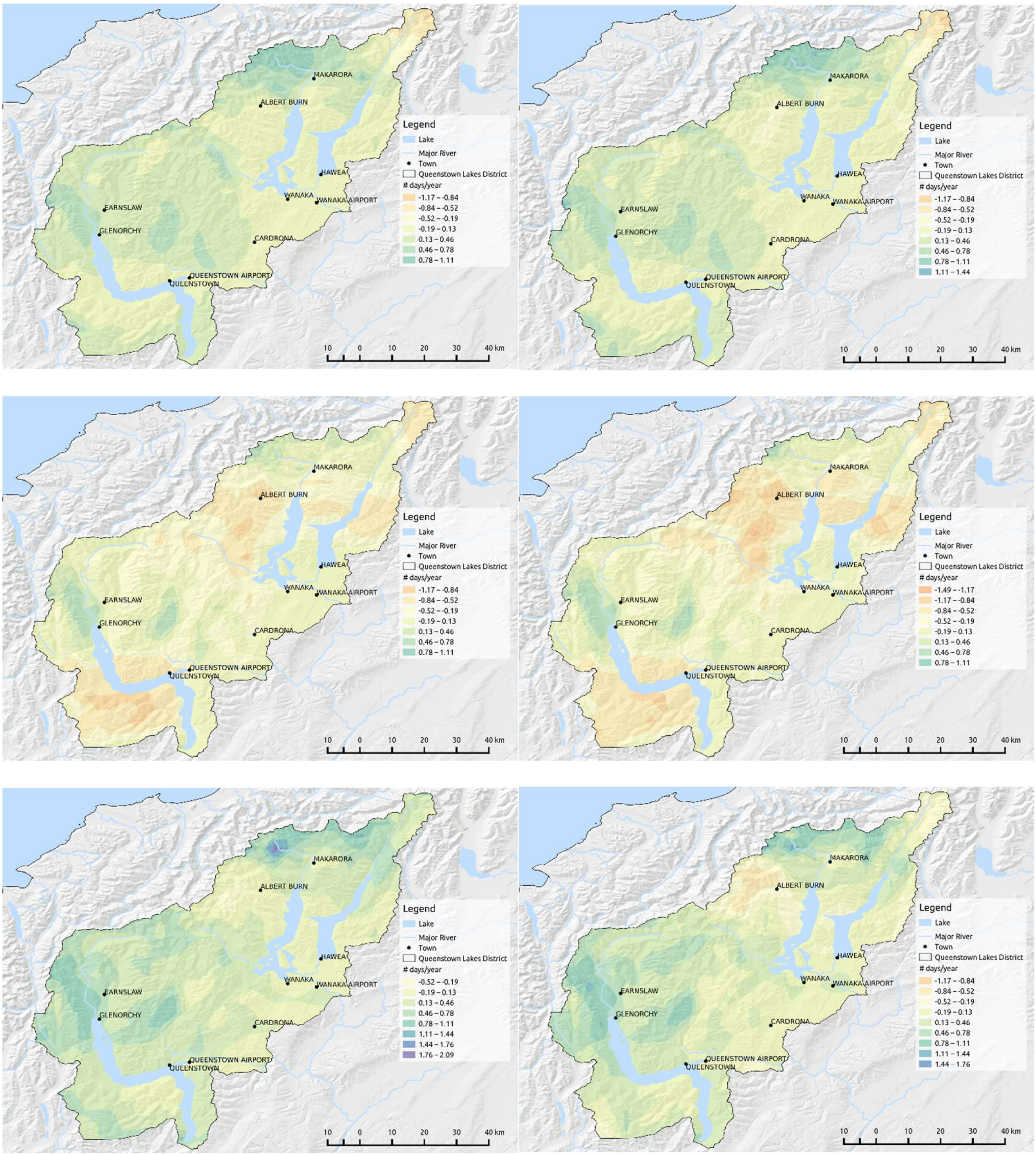

Figure C13: Change in the length of a wet spell under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

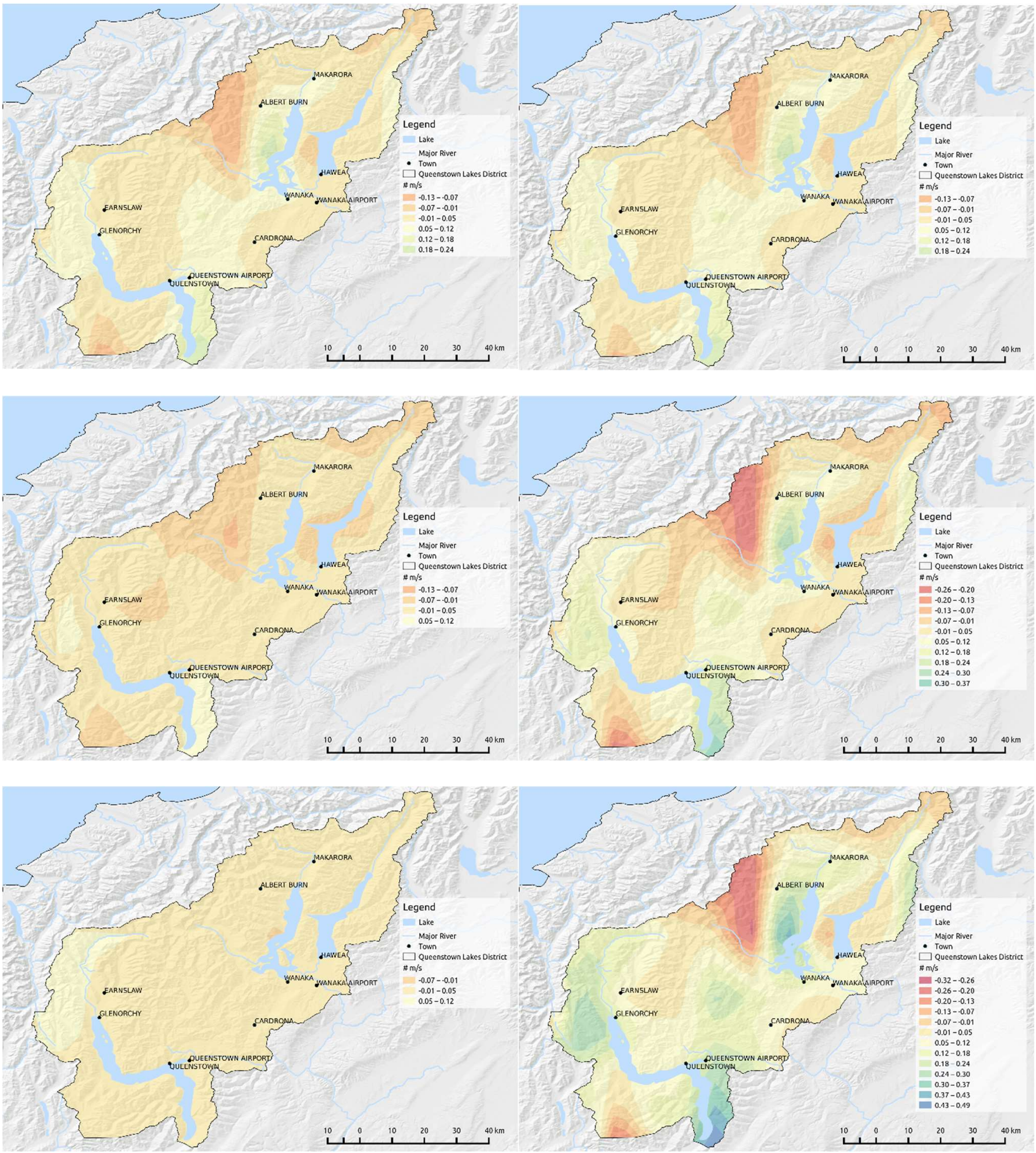

Figure C14: Change in average wind-speed under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

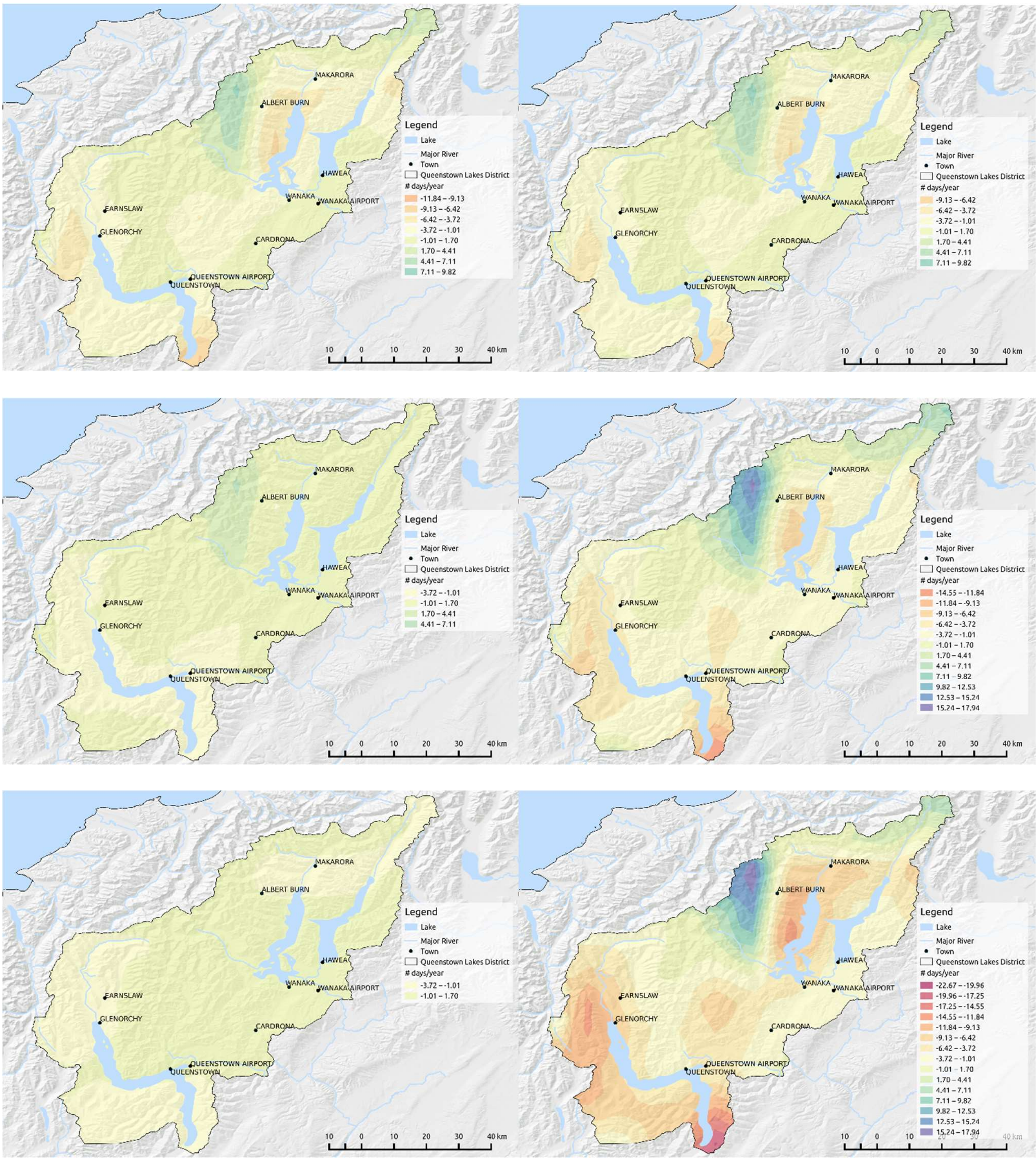

Figure C15: Change in the number of light wind days under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

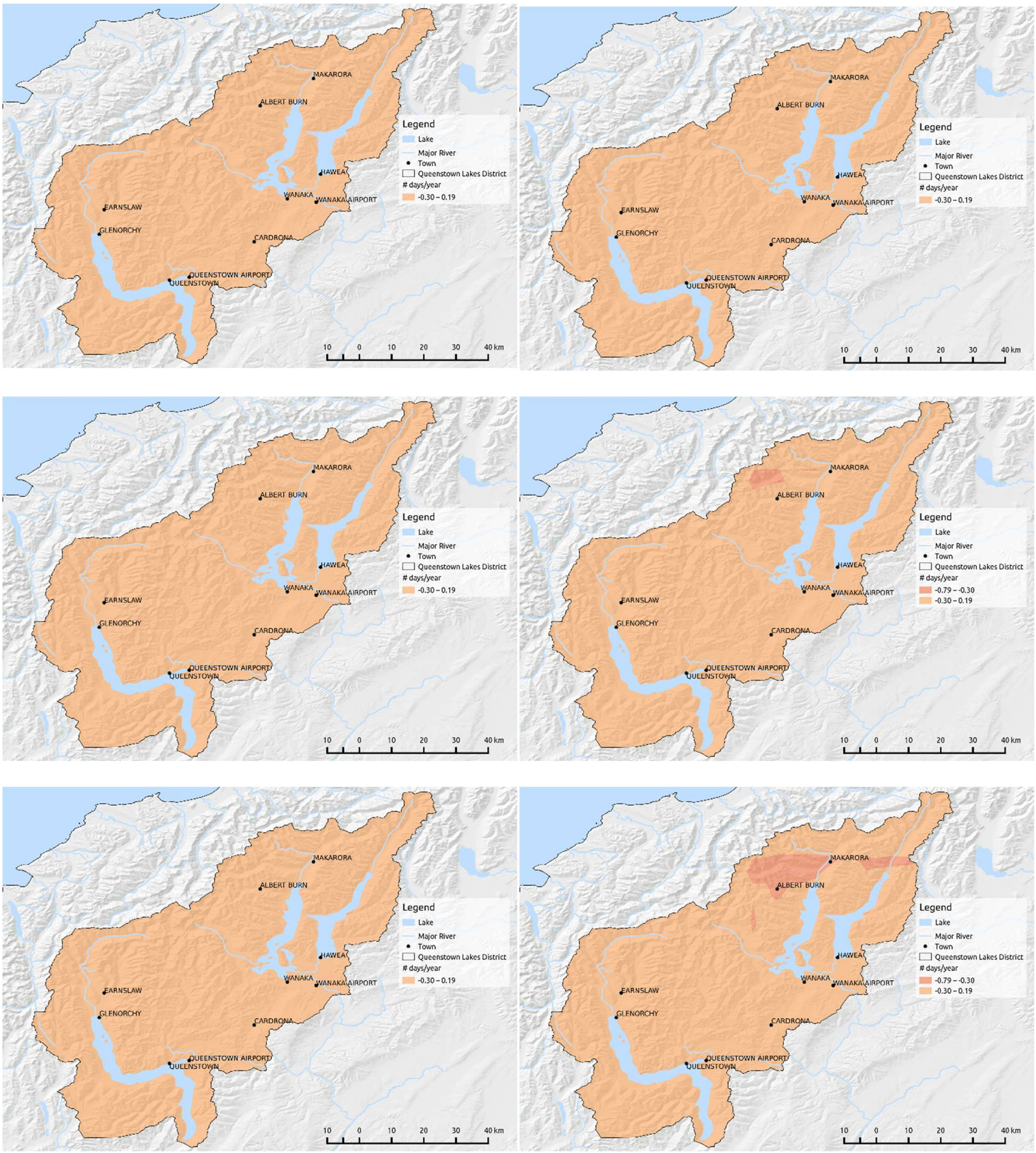

Figure C16: Change in the number of strong wind days under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

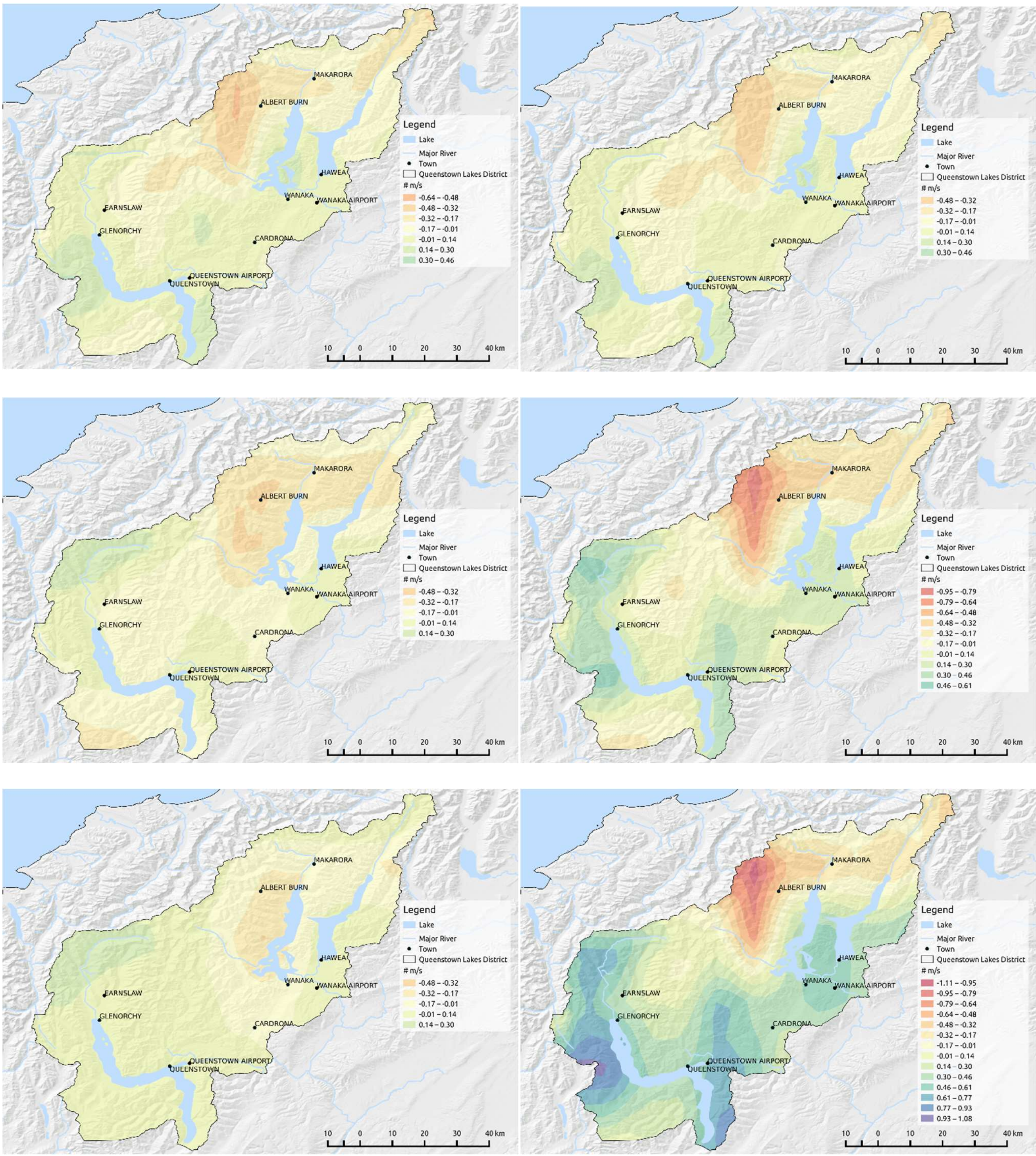

Figure C17: Change in the maximum wind-speed under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

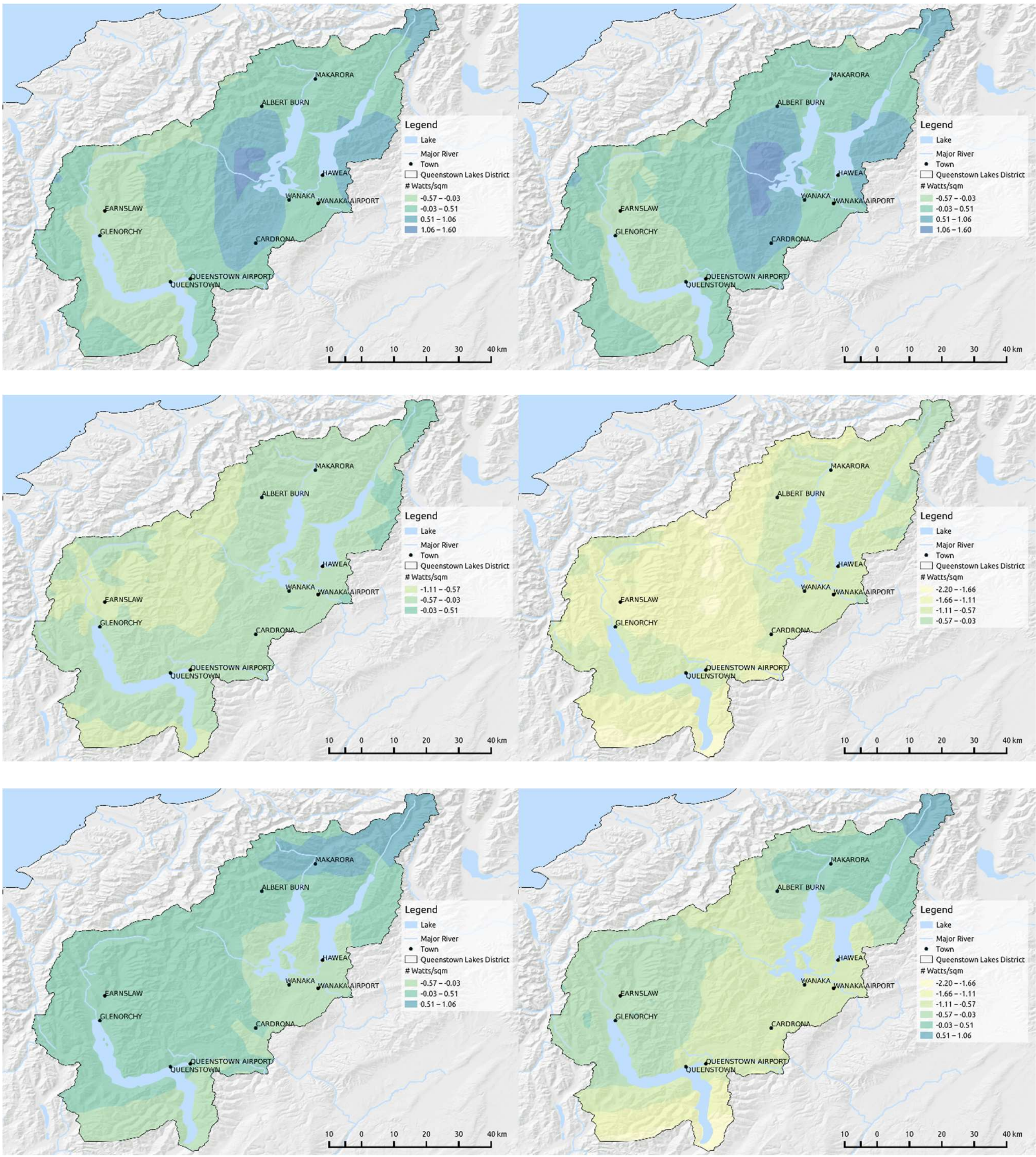

Figure C18: Change in average solar insolation under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

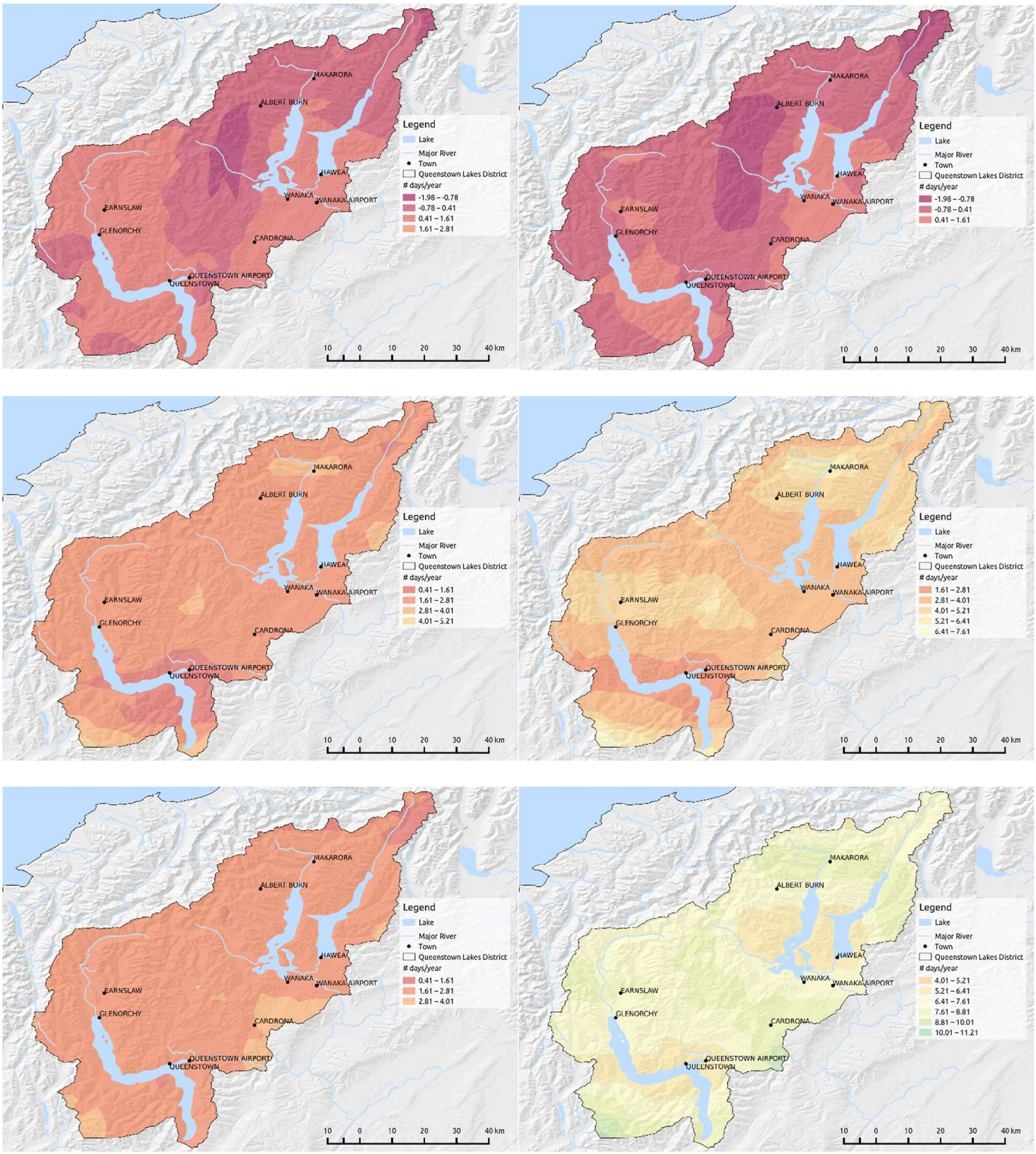

Figure C19: Change in the number of low solar insolation days under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

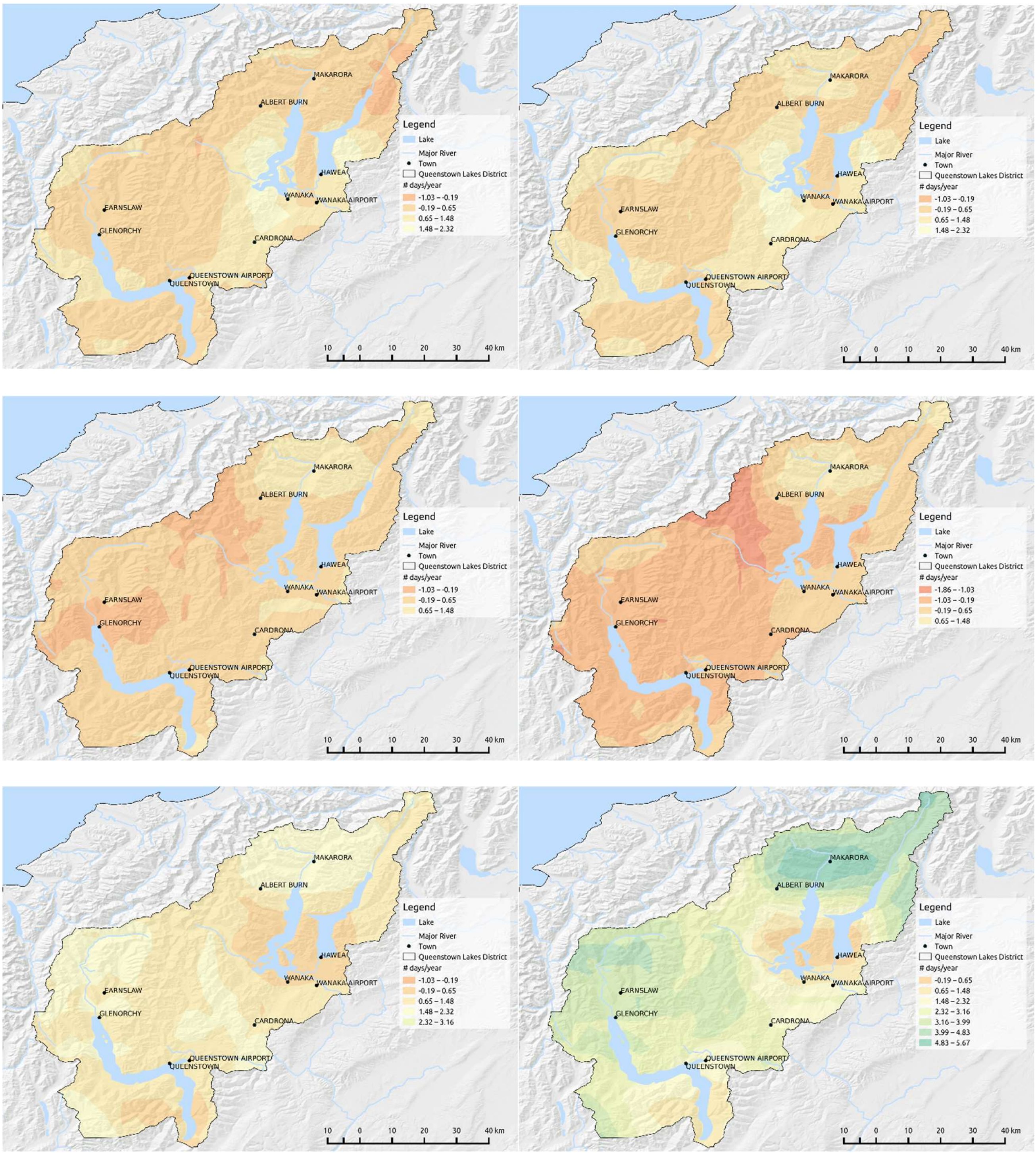

Figure C20: Change in the number of high solar insolation days under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

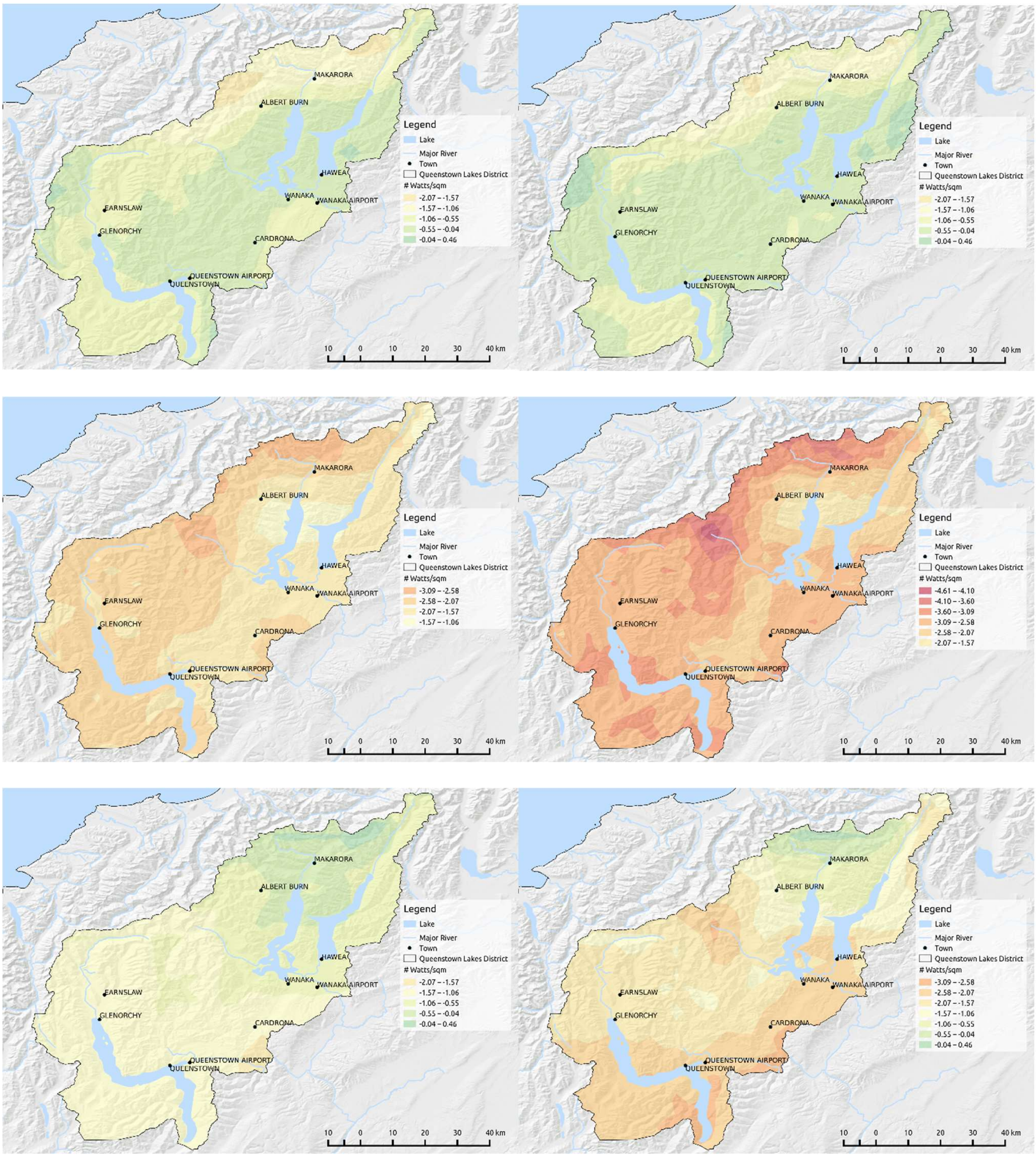

Figure C21: Change in maximum solar insolation under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

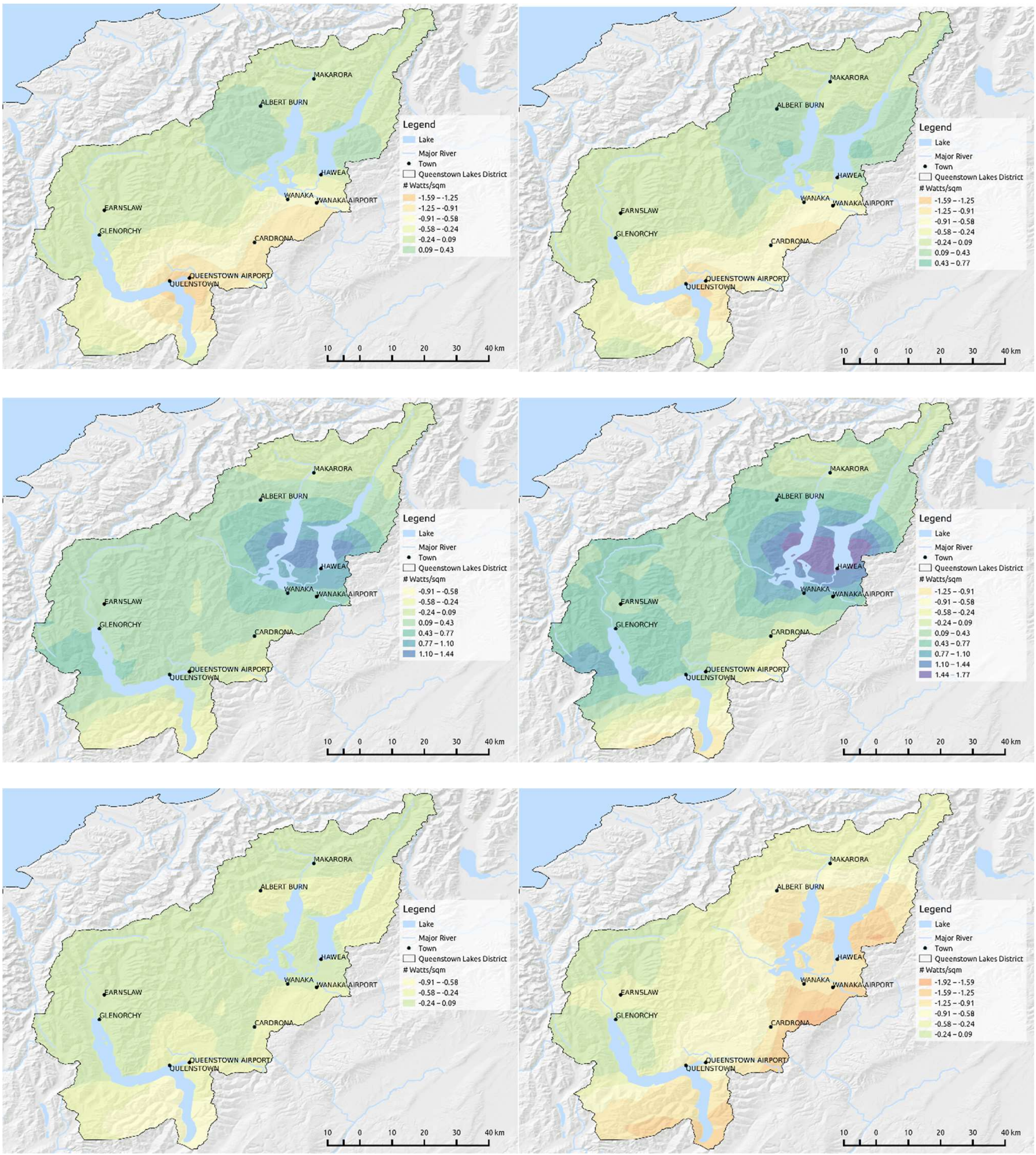

Figure C22: Change in minimum solar insolation under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

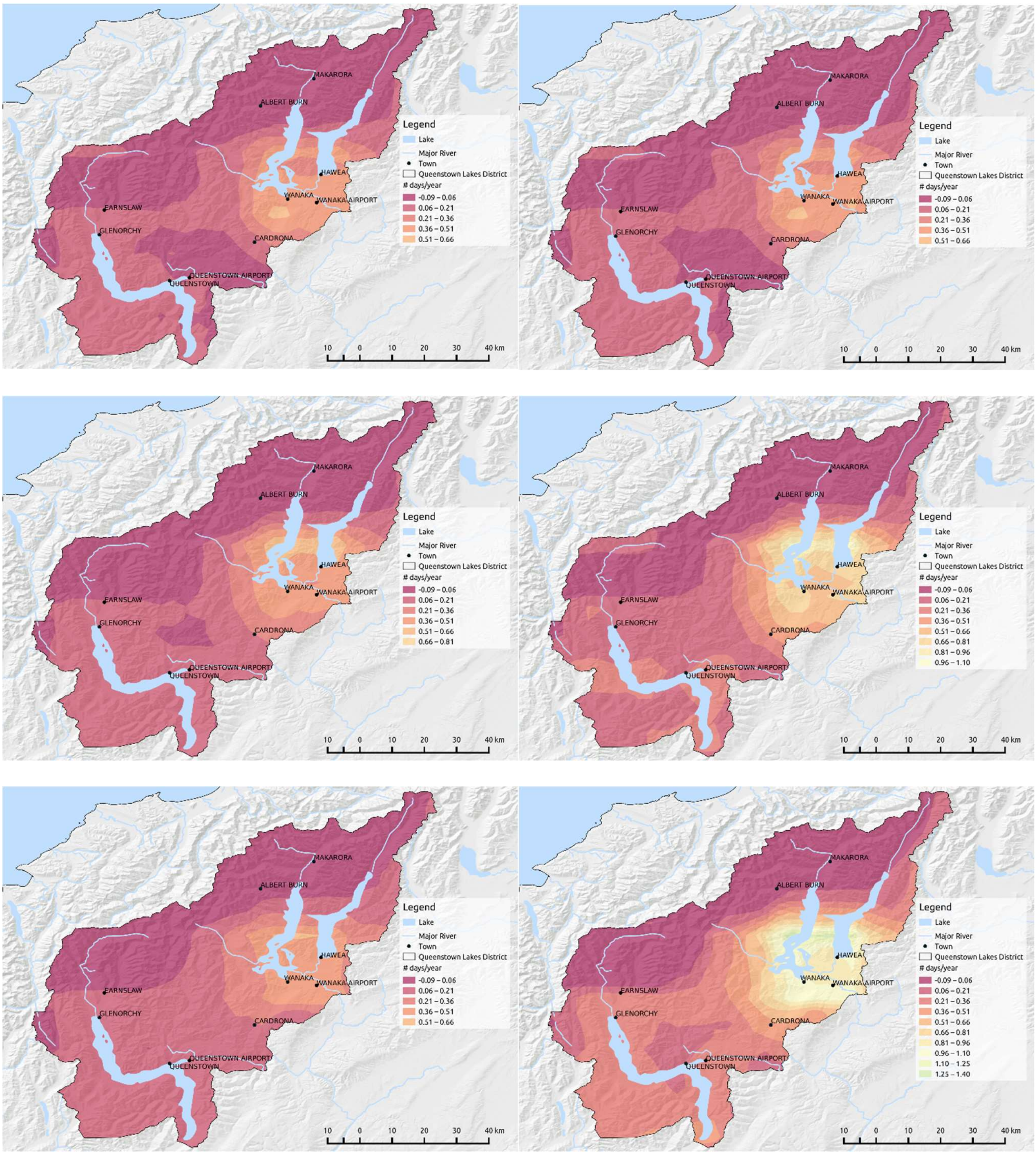

Figure C23: Change in the number of low relative humidity days under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

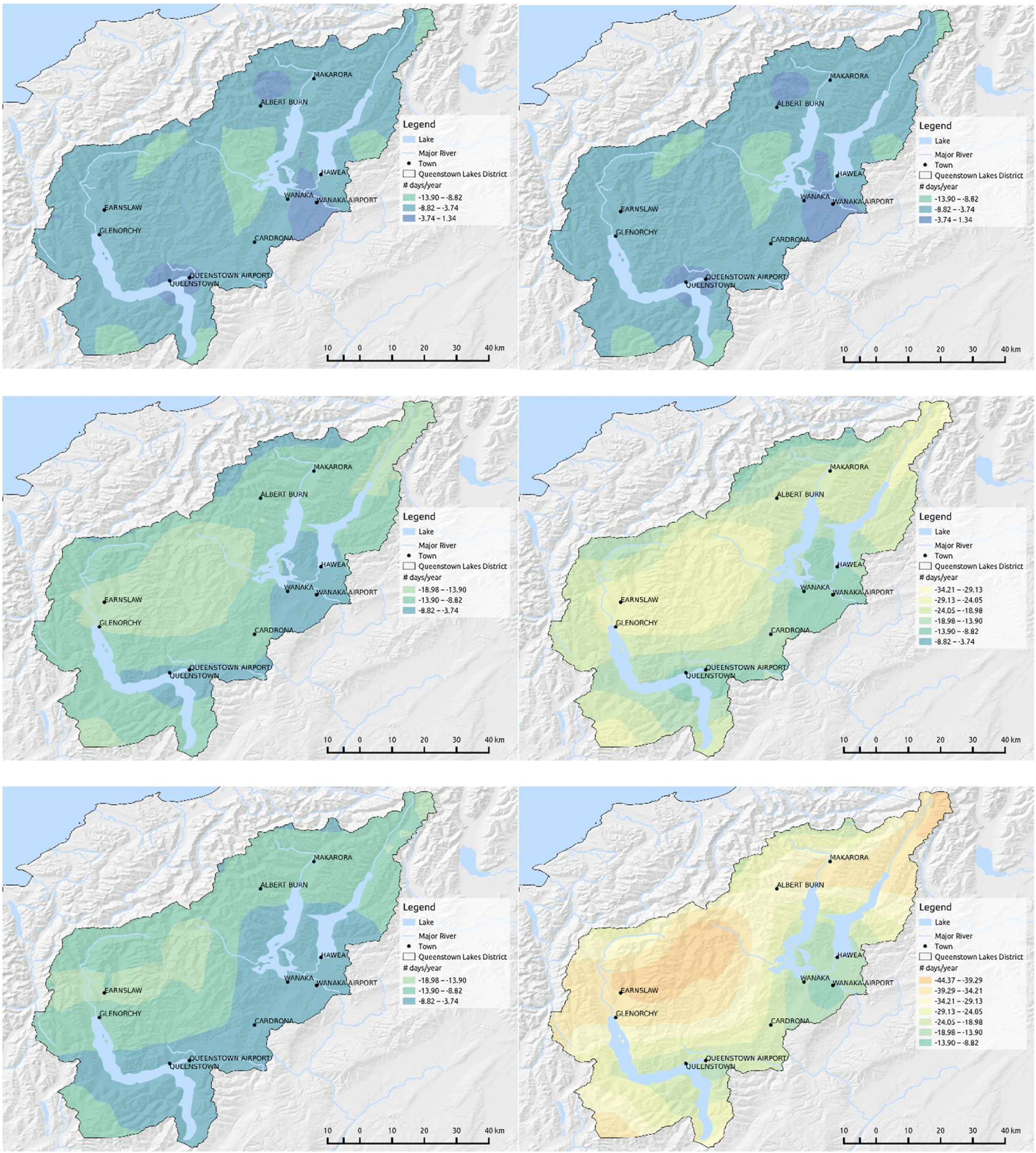

Figure C24: Change in the number of high relative humidity days under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

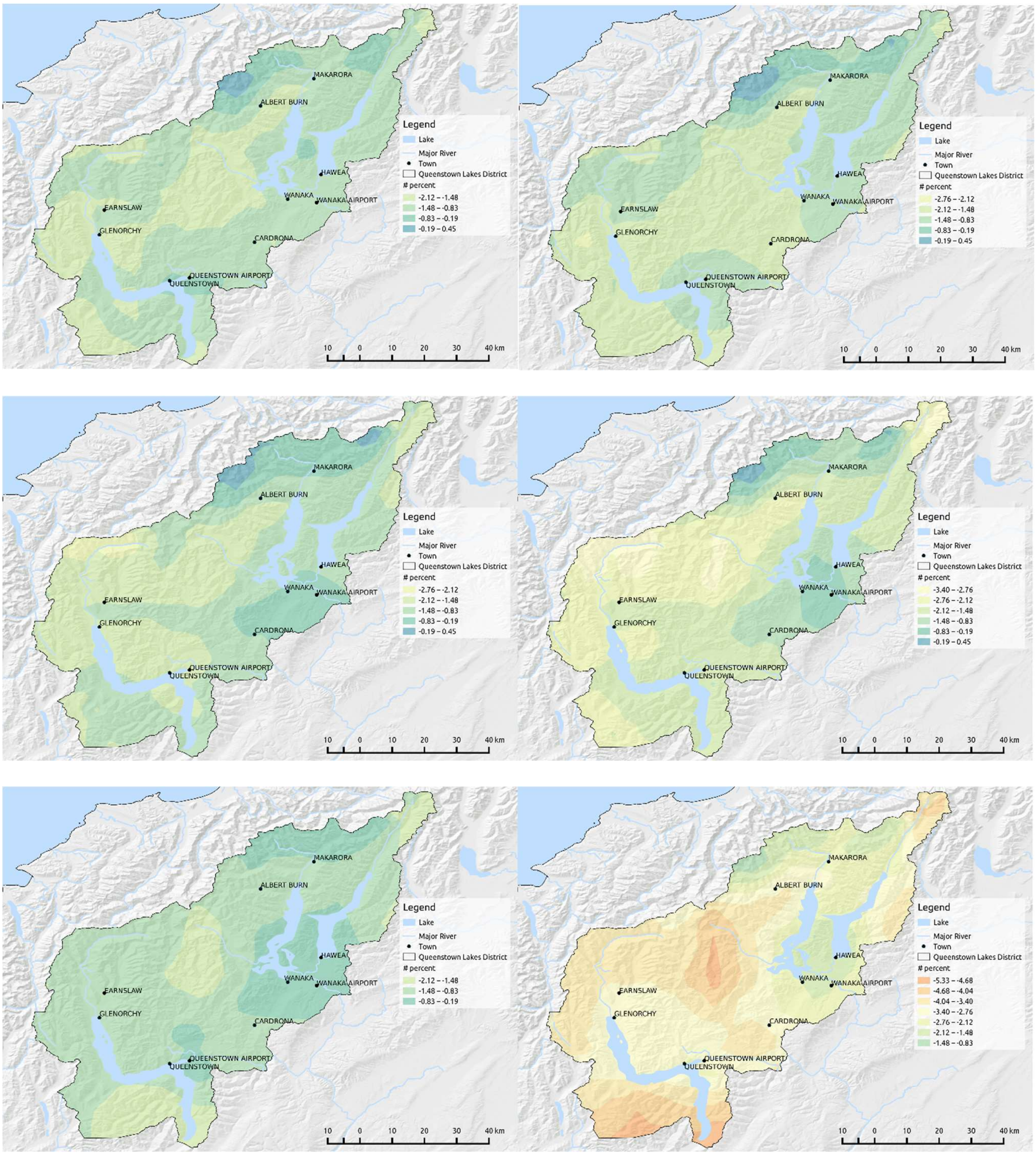

Figure C25: Change in the minimum relative humidity under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

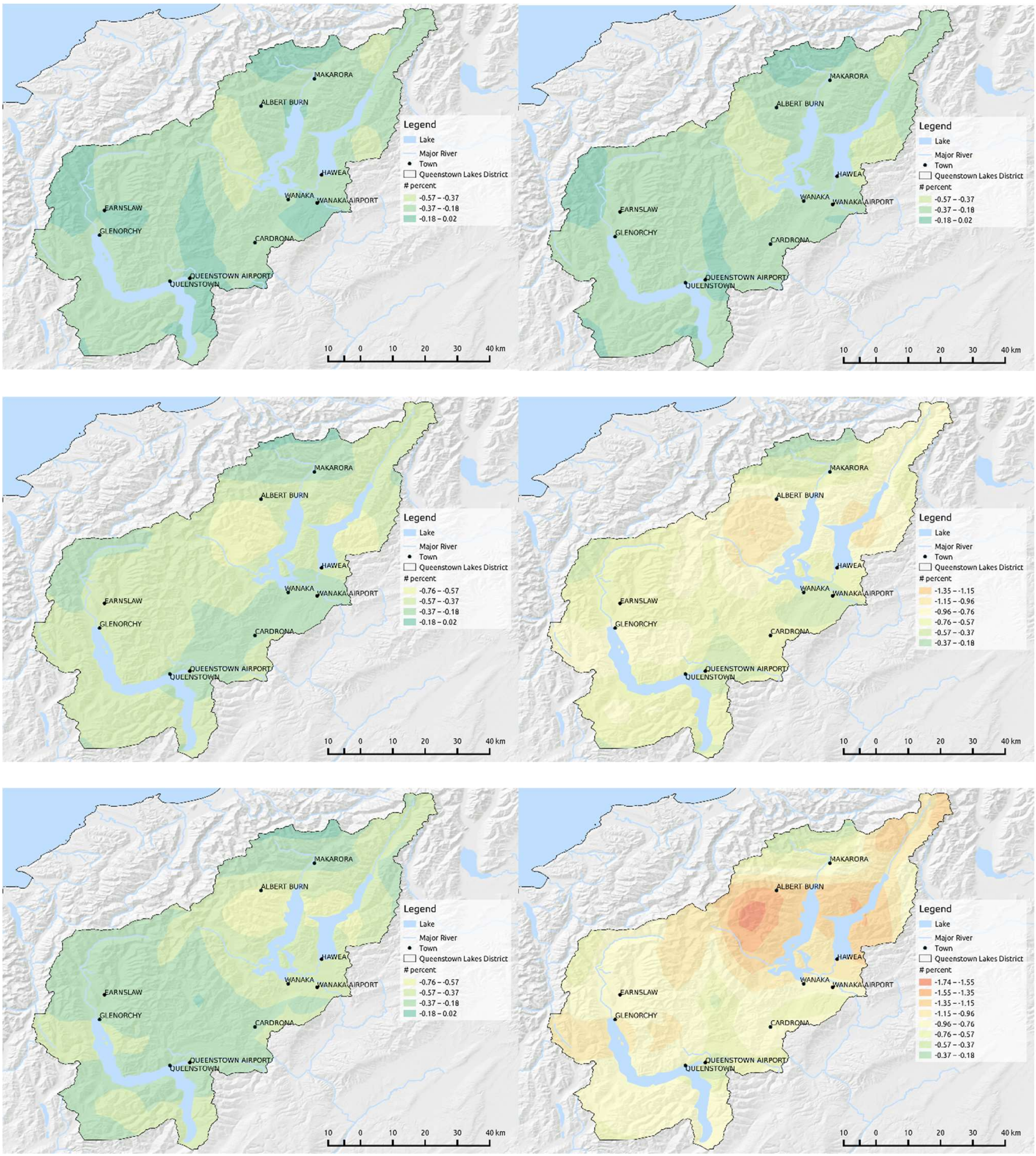

Figure C26: Change in the maximum relative humidity under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

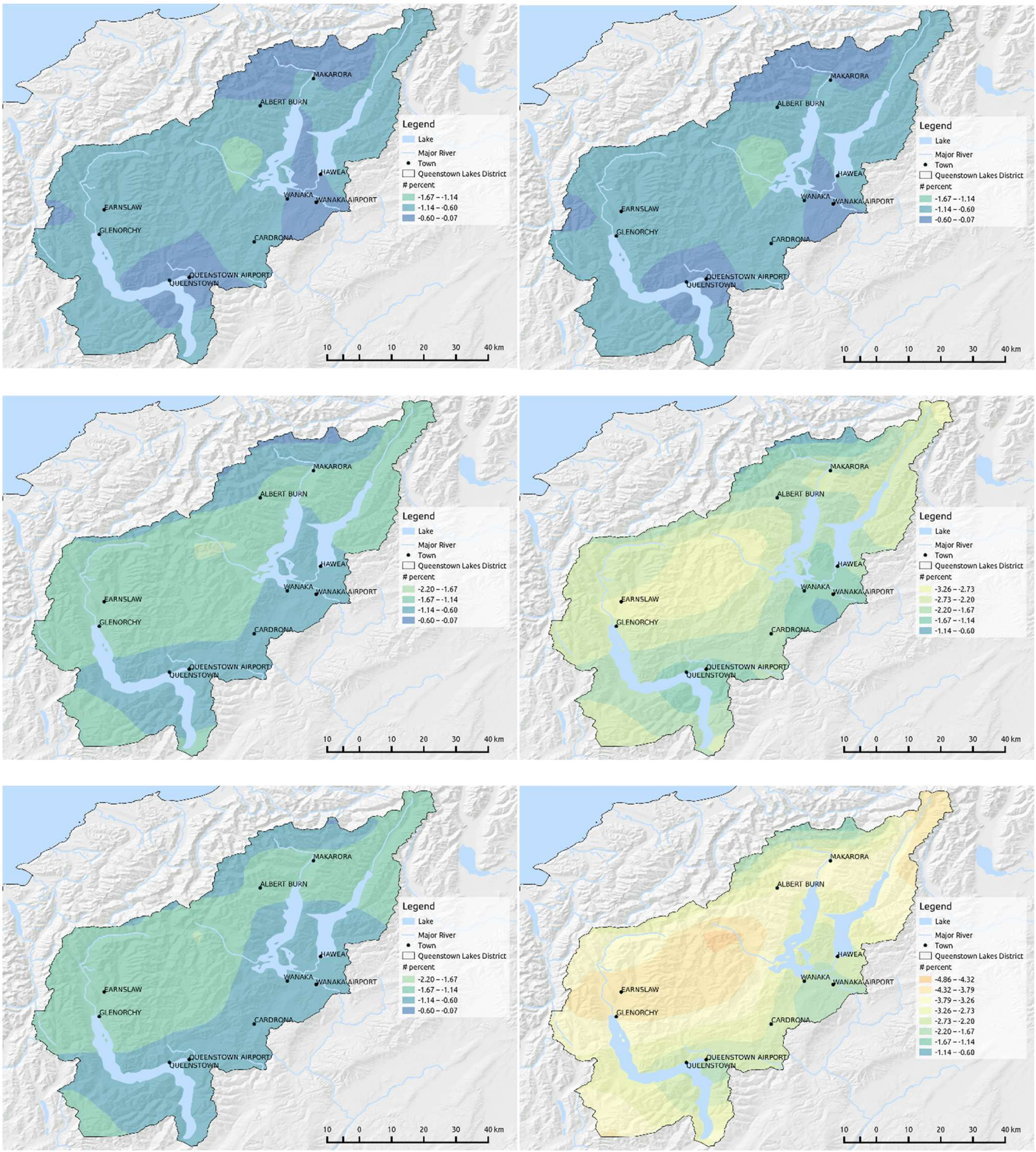

Figure C27: Change in average relative humidity under RCP2.6, RCP4.5 and RCP6.0 (top to bottom) for mid-century (left column) and end of century (right column).

Appendix D – Snow cover duration with RCP scenario

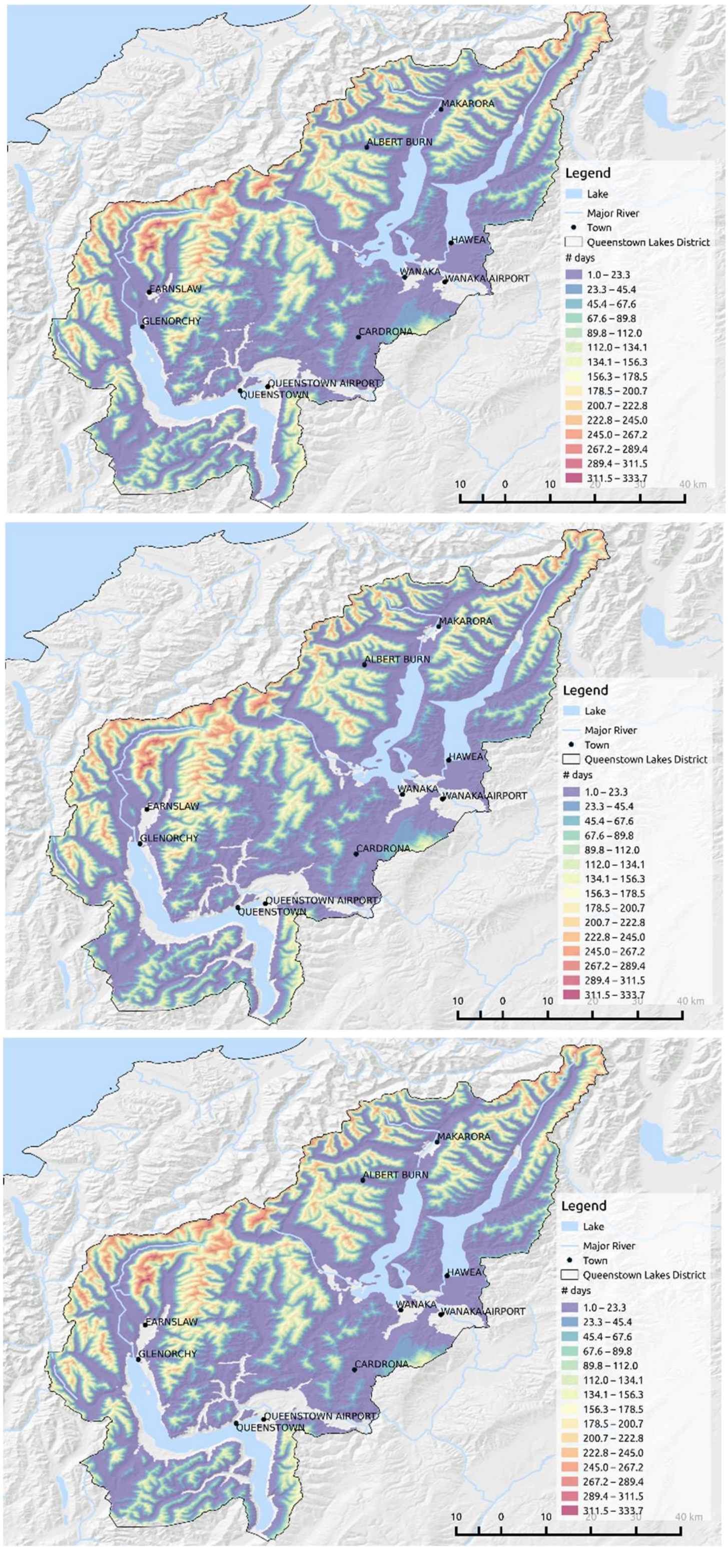

Figure D1: Snow cover duration at the beginning of the century (top), and under RCP2.6 for mid-century (middle), and end of century (bottom).

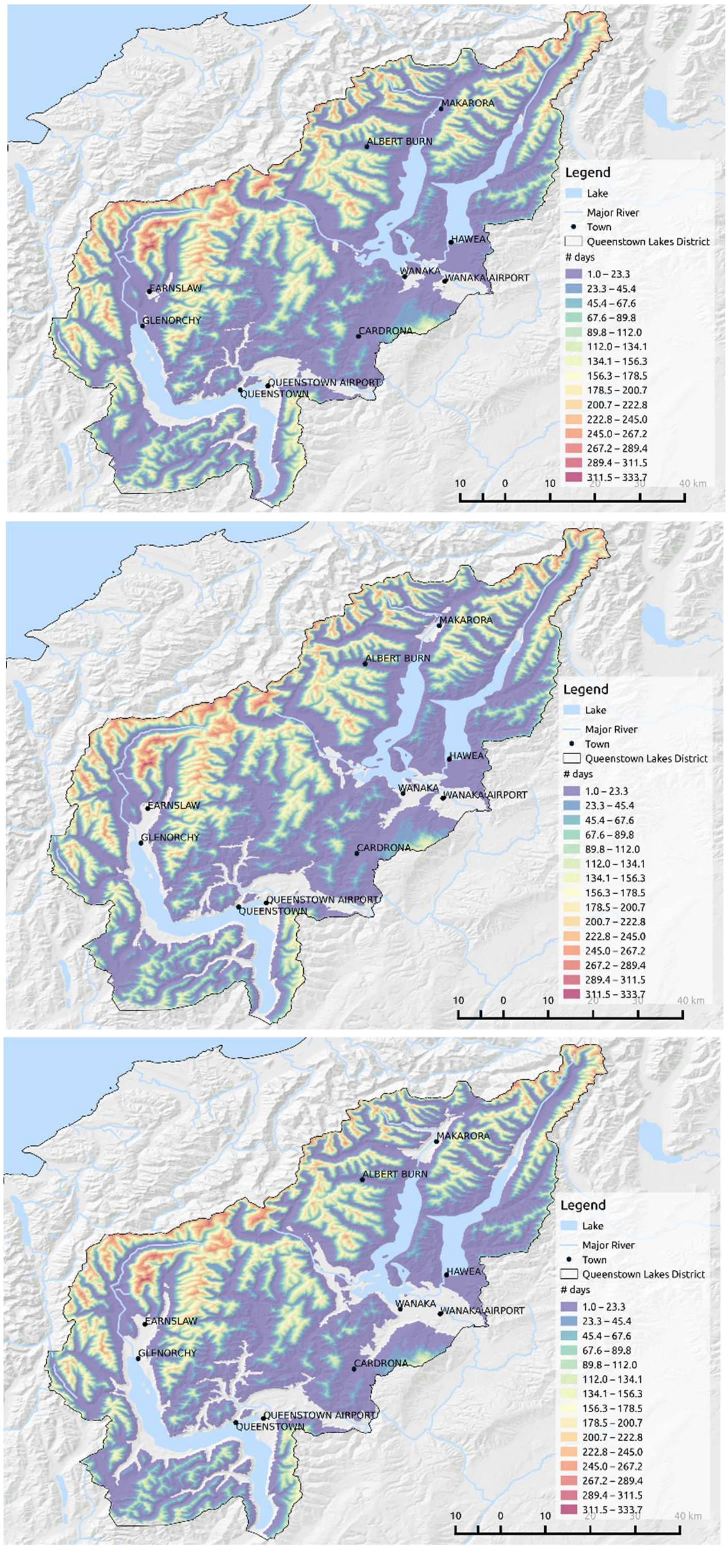

Figure D2: Snow cover duration at the beginning of the century (top), and under RCP4.5 for mid-century (middle), and end of century (bottom).

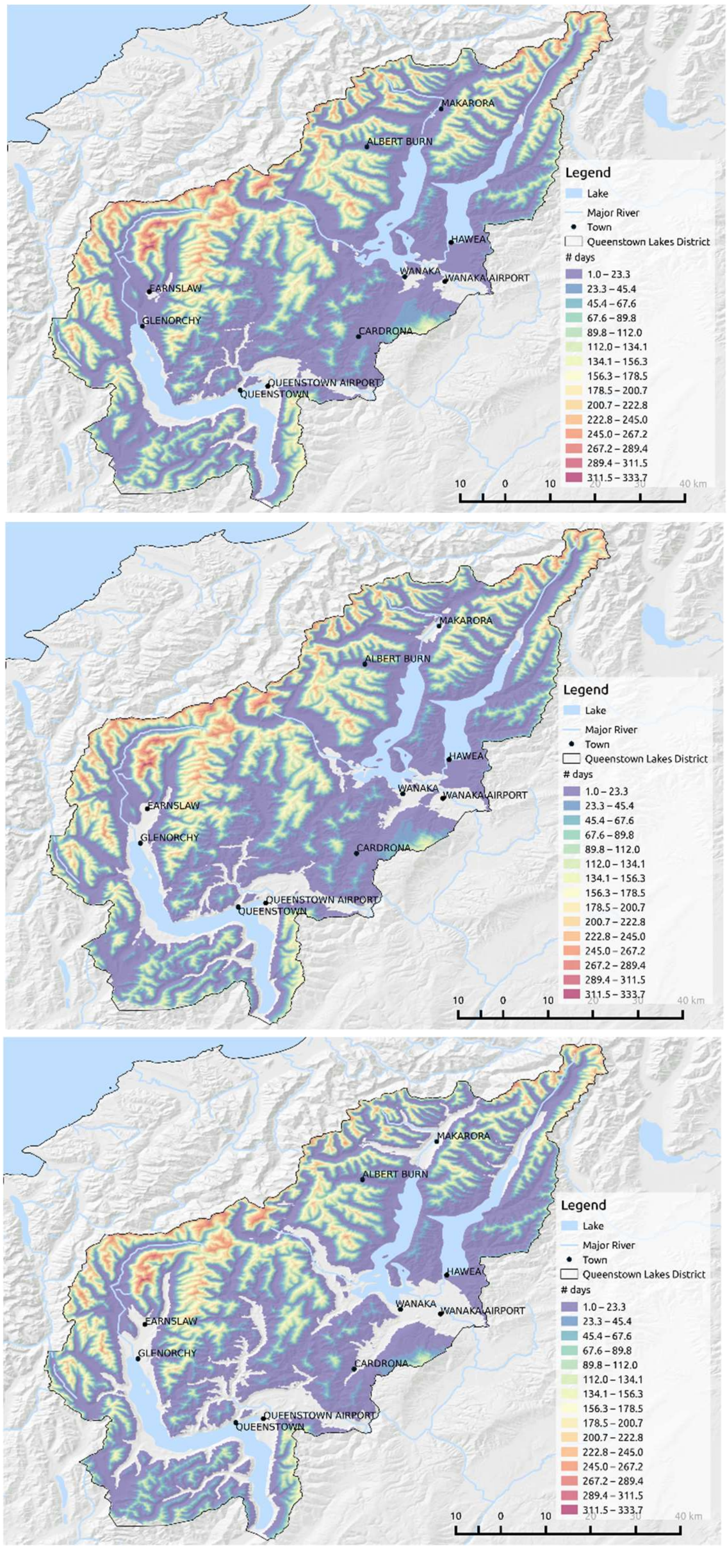

Figure D3: Snow cover duration at the beginning of the century (top), and under RCP6.0 for mid-century (middle), and end of century (bottom).

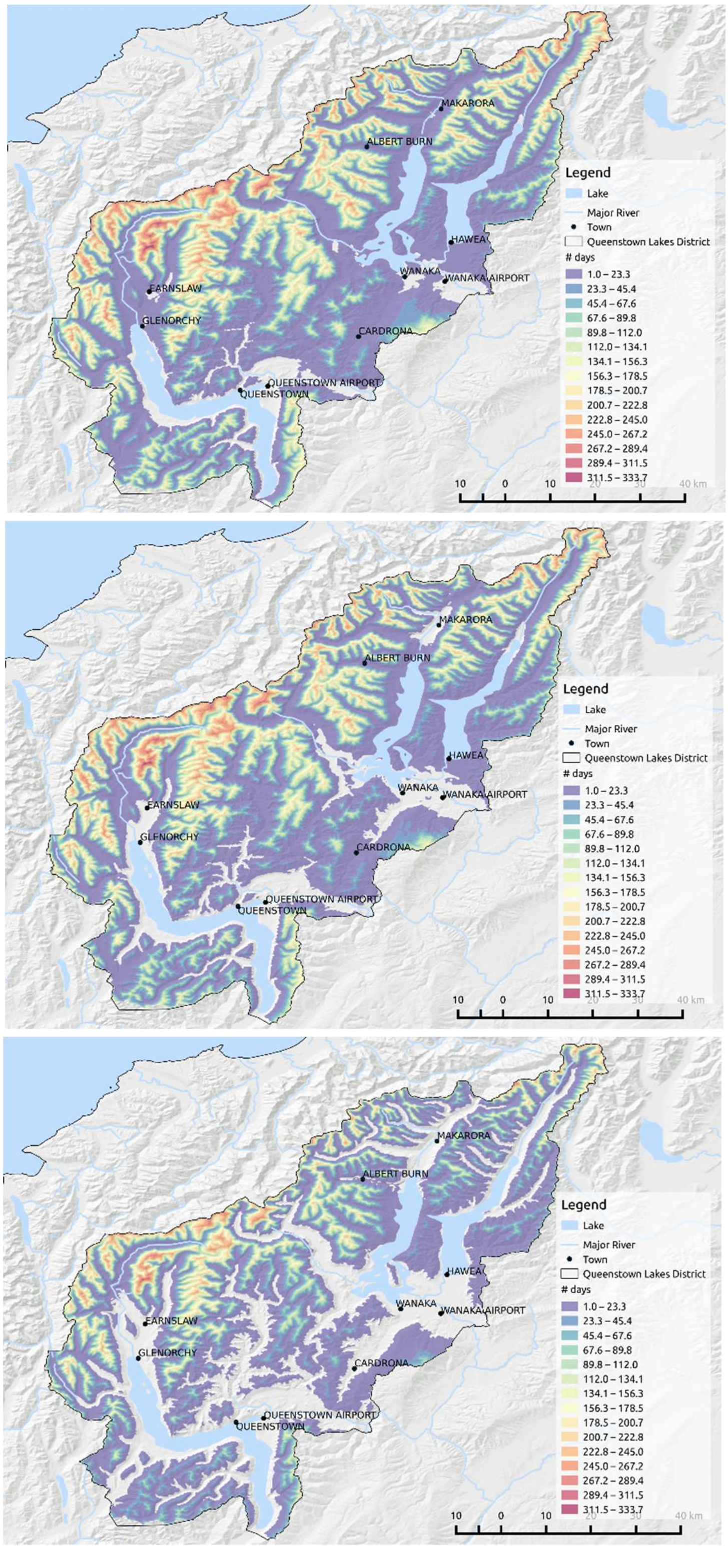

Figure D4: Snow cover duration at the beginning of the century (top), and under RCP8.5 for mid-century (middle), and end of century (bottom).

Appendix E – Projections of seasonal change

Additional figures are provided here for the seasonal change in selected temperature and precipitation indices for four locations (Queenstown, Glenorchy, Albert Burn and Wanaka) across the District and for each of the projected decadal periods (2040s, 2090s). The results presented below are decadal means over all 188 simulations for the emissions scenario of interest and season and the error bar represents 1σ (i.e., 68% of the simulations fall within that projected range). The seasonal metrics examined here are:

- Highest maximum temperature
- Lowest minimum temperature
- Precipitation total
- Standardised Daily Intensity Index.

From this analysis we can determine changes in the seasonality of hotter periods (e.g., is there a greater likelihood for hotter weather in summer?) and for both wet and dry periods (e.g., is there a shift in the timing of high rainfall periods?).

Queenstown

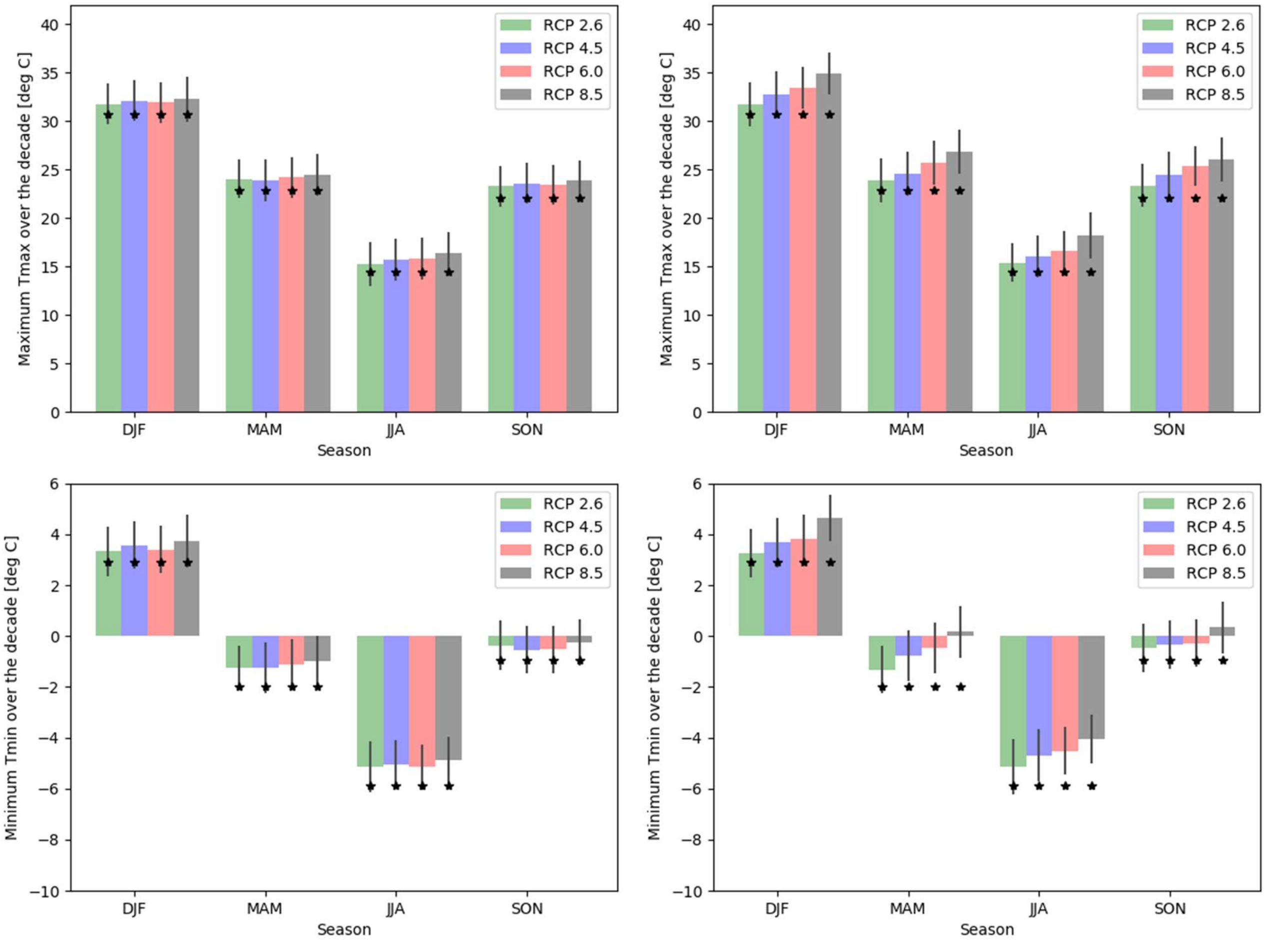

Figure E1: Average maximum temperature (top) and average minimum temperature (bottom) reached over the 2040 to 2049 decade (left) and 2090 to 2099 decade (right) for all four emissions scenarios for Queenstown. The black stars show the baseline values (i.e., the mean value over 2000-2009) and the error bars represent 1σ. If the black star falls outside the 1σ range, the results indicate that the change in temperature is statistically significantly different from the baseline value at the 1σ level.

For Queenstown, the model simulations project that under the high emissions scenario, maximum temperatures reached in all seasons would increase, with statistical significance, by about 6°C by the end of this century compared to the start of the century (Figure E1, top right panel). Seasonal changes in maximum temperature in Queenstown for the mid-century period are not statistically significant at the 1σ level across all RCP scenarios (Figure E1, top left panel).

Statistically significant changes in the minimum seasonal temperatures in Queenstown are projected to occur by the end of this century under the high emissions scenarios (Figure E1, lower right panel), particularly notable are the changes projected for the Autumn and Winter seasons – both increases of around 3°C.

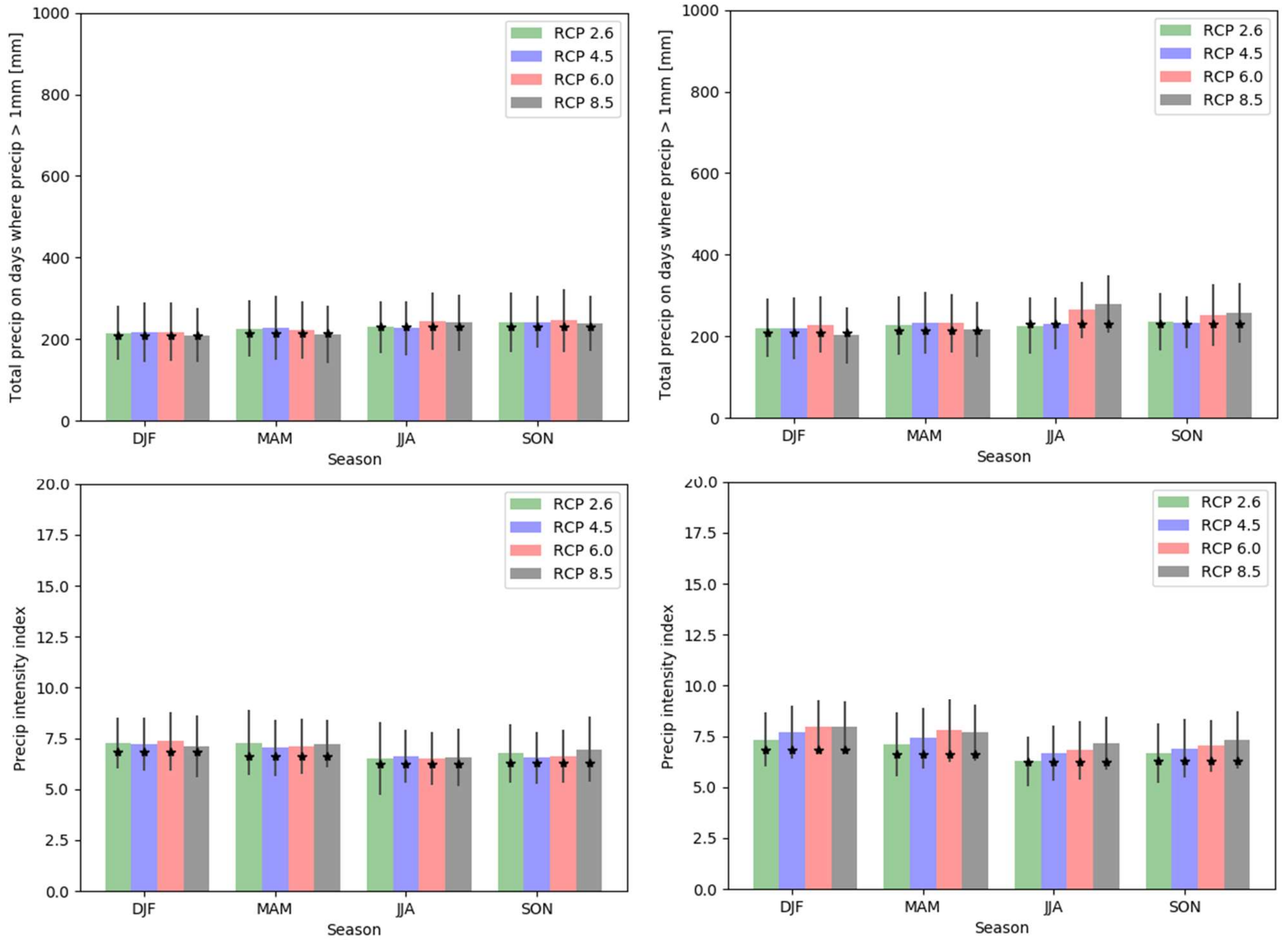

Figure E2: Average total precipitation (top) and Standardised Daily Intensity Index (bottom) reached over the 2040 to 2049 decade (left) and 2090 to 2099 decade (right) for all four emissions scenarios for Queenstown. The black stars show the baseline values (i.e., the mean value over 2000-2009) and the error bars represent 1σ. If the black star falls outside the 1σ range, the results indicate that the change in temperature is statistically significantly different from the baseline value at the 1σ level.

Seasonal changes in precipitation and its intensity for Queenstown are likely to be limited by the middle of the century (Figure E2, left two panels). However, by the end of the century, there is the potential for both higher total precipitation and higher rainfall intensity during the winter months (Figure E2, right two panels) – though note that this trend is close to the level of non-significance.

Glenorchy

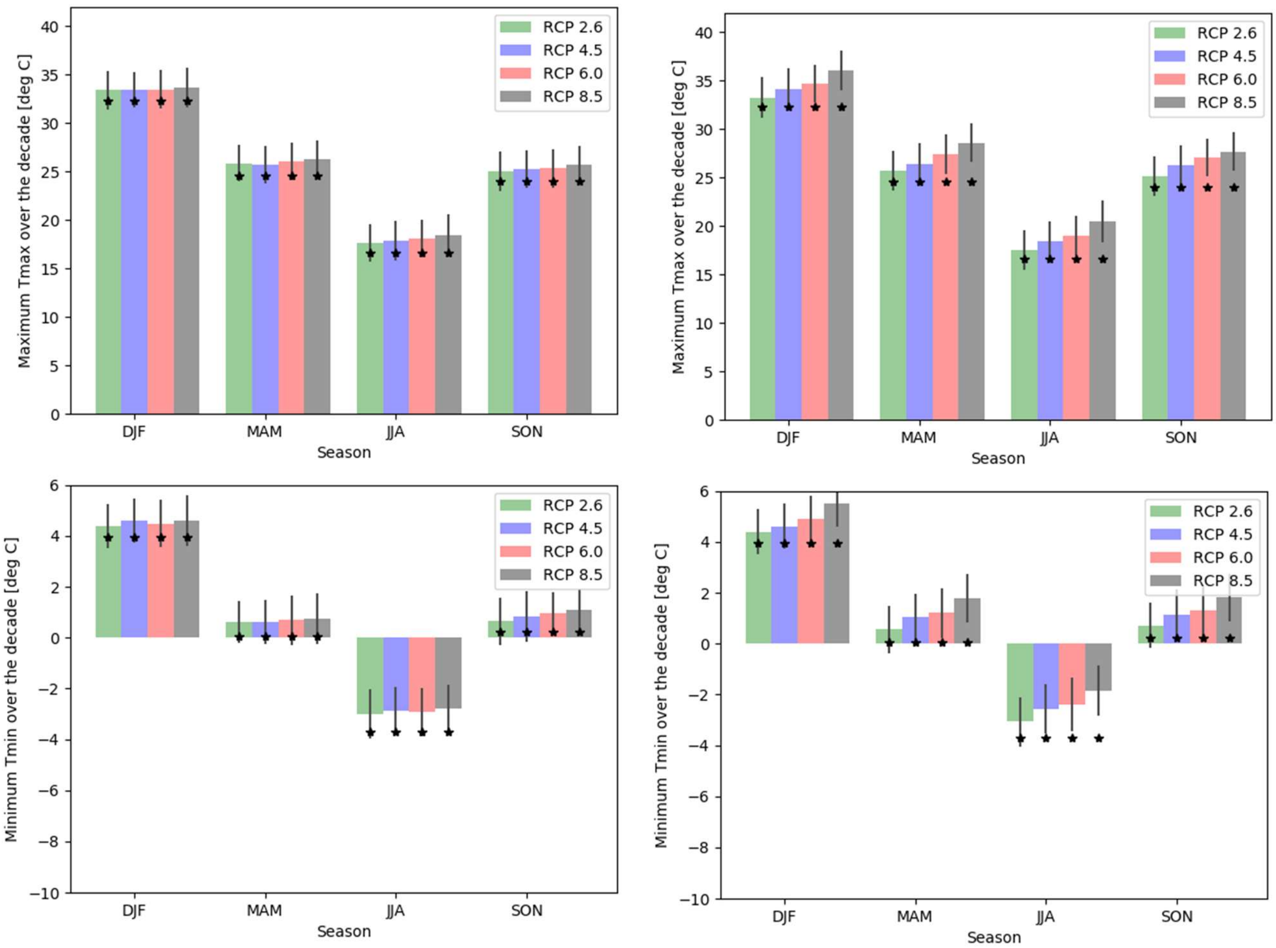

Figure E3: Same as Figure D1 but for Glenorchy.

As for Queenstown, we see that Glenorchy is projected to experience similar levels of warming in maximum temperatures across all seasons – in this case about 5^{o}C (Figure E3, top right panel). The pattern for minimum seasonal temperatures also follows that of Queenstown, where the high emissions scenario (Figure E3, lower right panel) has the greatest changes projected for the Autumn and Winter seasons – both increases of around 3^{o}C.

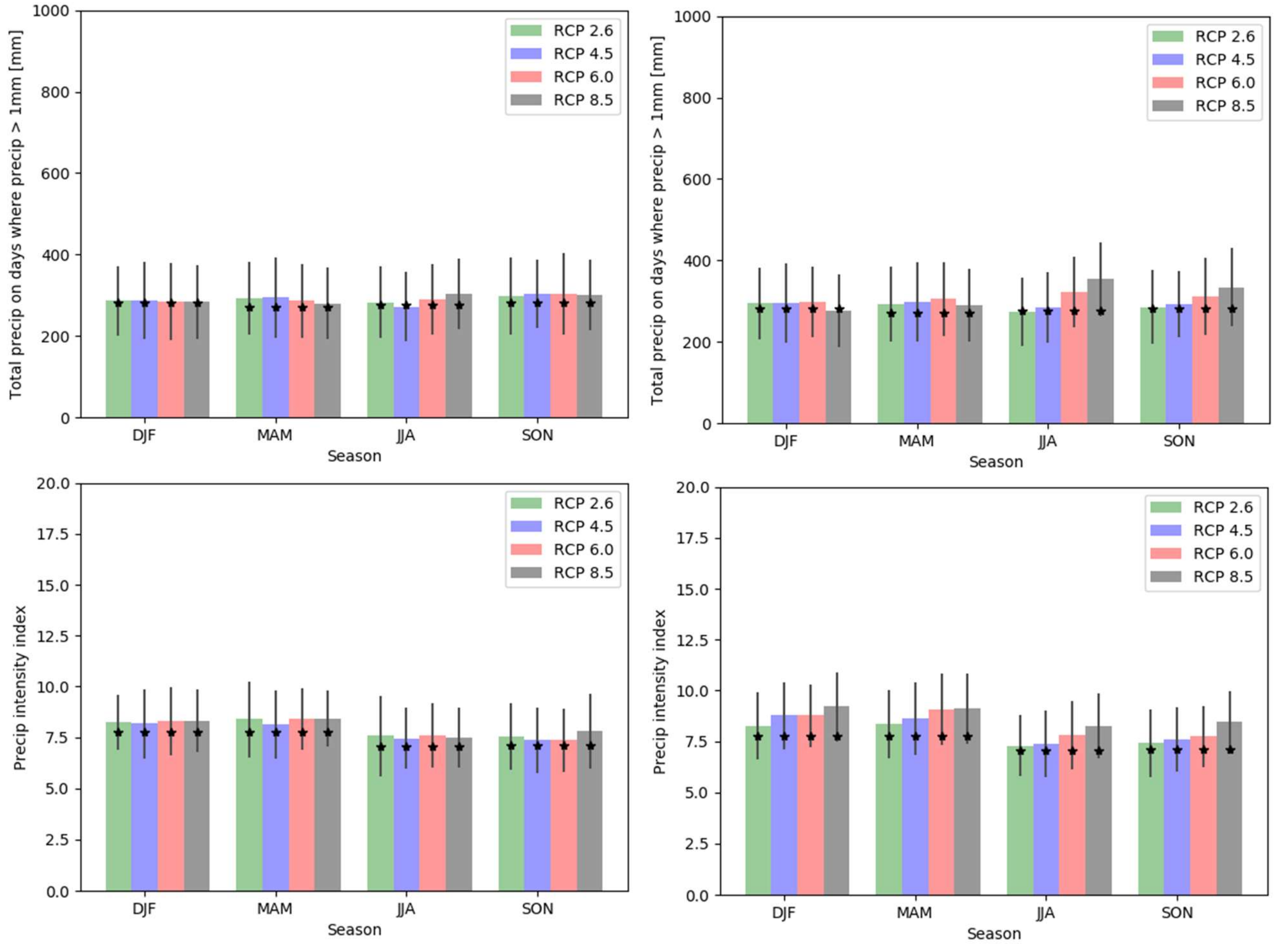

Figure E4: Same as Figure D2 but for Glenorchy.

Glenorchy again sees no significant seasonal changes in precipitation volume or intensity by mid-century (Figure E4, left two panels). At the end of the century there is the possibility of significant increases in precipitation volume and intensity during the winter months (Figure E4, right two panels) – though note that again this trend is close to the level of non-significance.

Albert Burn

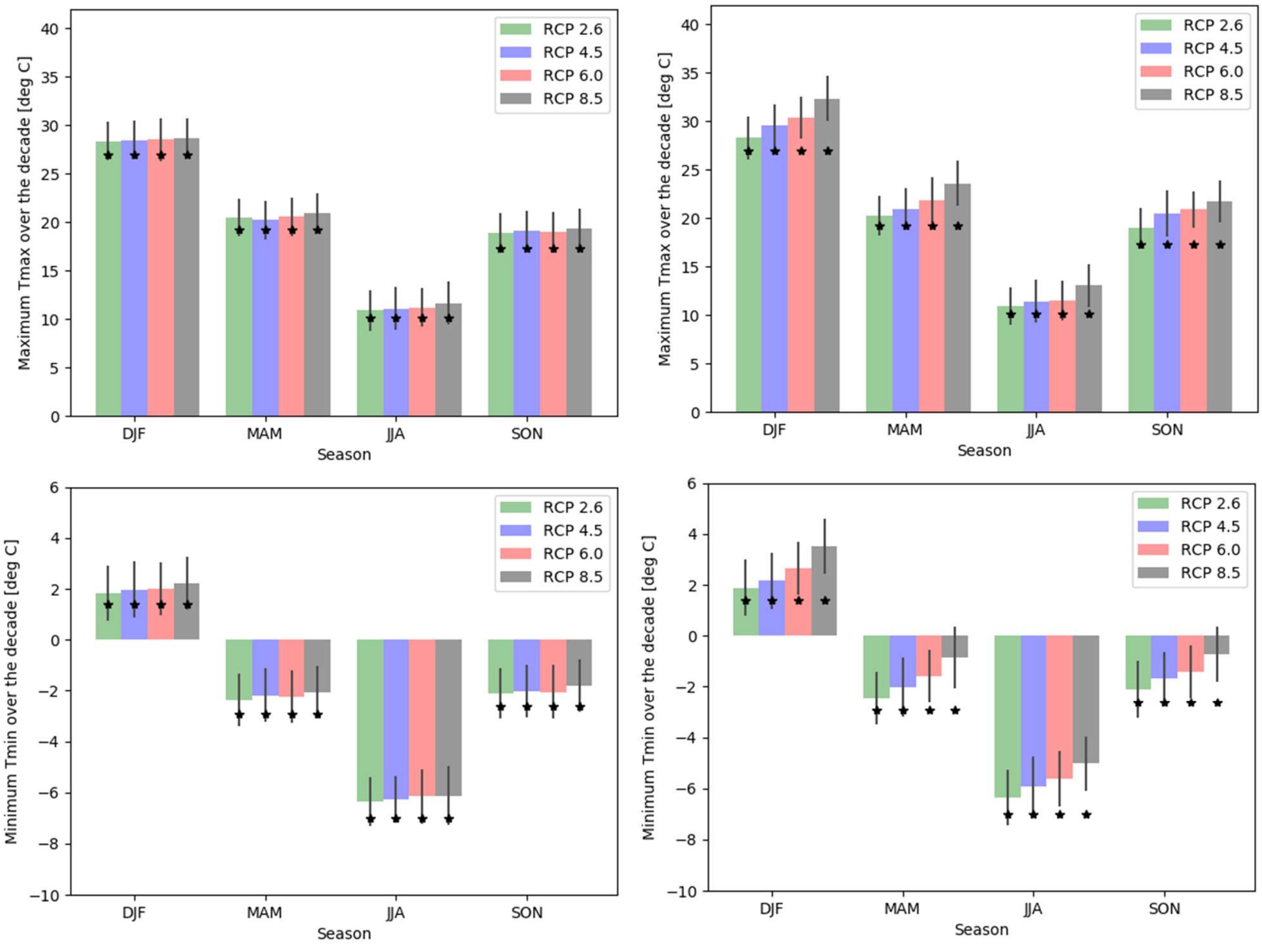

Figure E5: Same as Figure E1 but for Albert Burn.

Albert Burn is projected to experience the greatest increase in maximum temperatures – of around 8°C – in the summer season (Figure E5, top right panel), with lower increases in autumn and spring (both about 6°C) and the lowest increase in winter (around 5°C). Minimum seasonal temperatures appear likely to increase at about the same rate (around 3.5°C) for all seasons under the high emissions scenario (Figure E5, lower right panel) in Albert Burn.

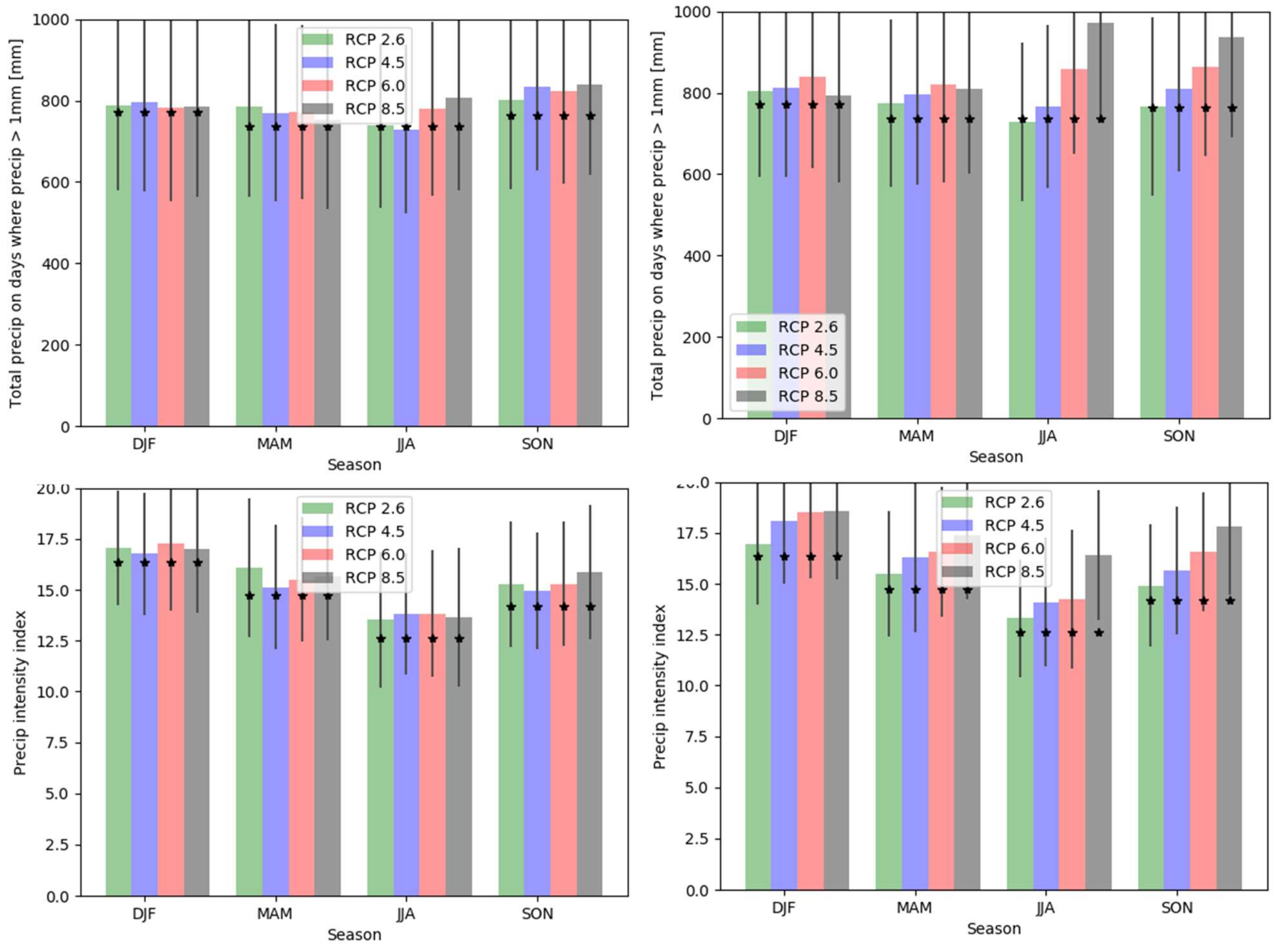

Figure E6: Same as Figure E2 but for Albert Burn.

Precipitation in Albert Burn has a wide range of uncertainty, reflecting high variation in that area. The only significant projected changes are seen in precipitation volume and intensity in the winter season, and in the precipitation intensity in the spring (Figure E6, right two panels).

Wanaka

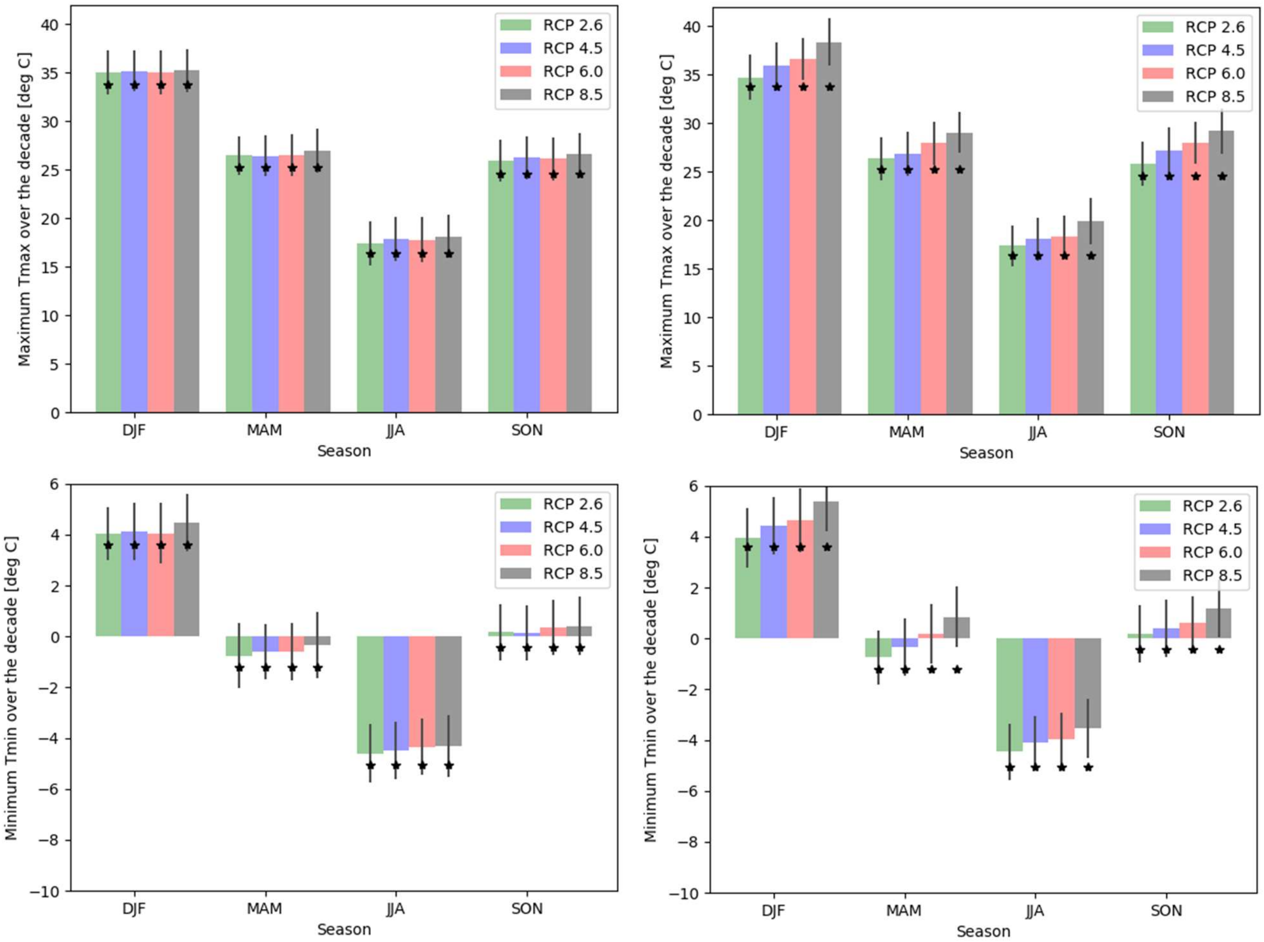

Figure E7: Same as Figure E1 but for Wanaka.

Under the high emissions scenario, projected maximum Wanaka temperatures in all seasons would increase by up to about 7°C by the end of this century (Figure E7, top right panel). Statistically significant increases in the minimum seasonal temperature are projected to occur by the end of this century under the high emissions scenarios (Figure E1, lower right panel), which as was found in Queenstown are particularly apparent in the Autumn and Winter months – both increases of around 3.5°C.

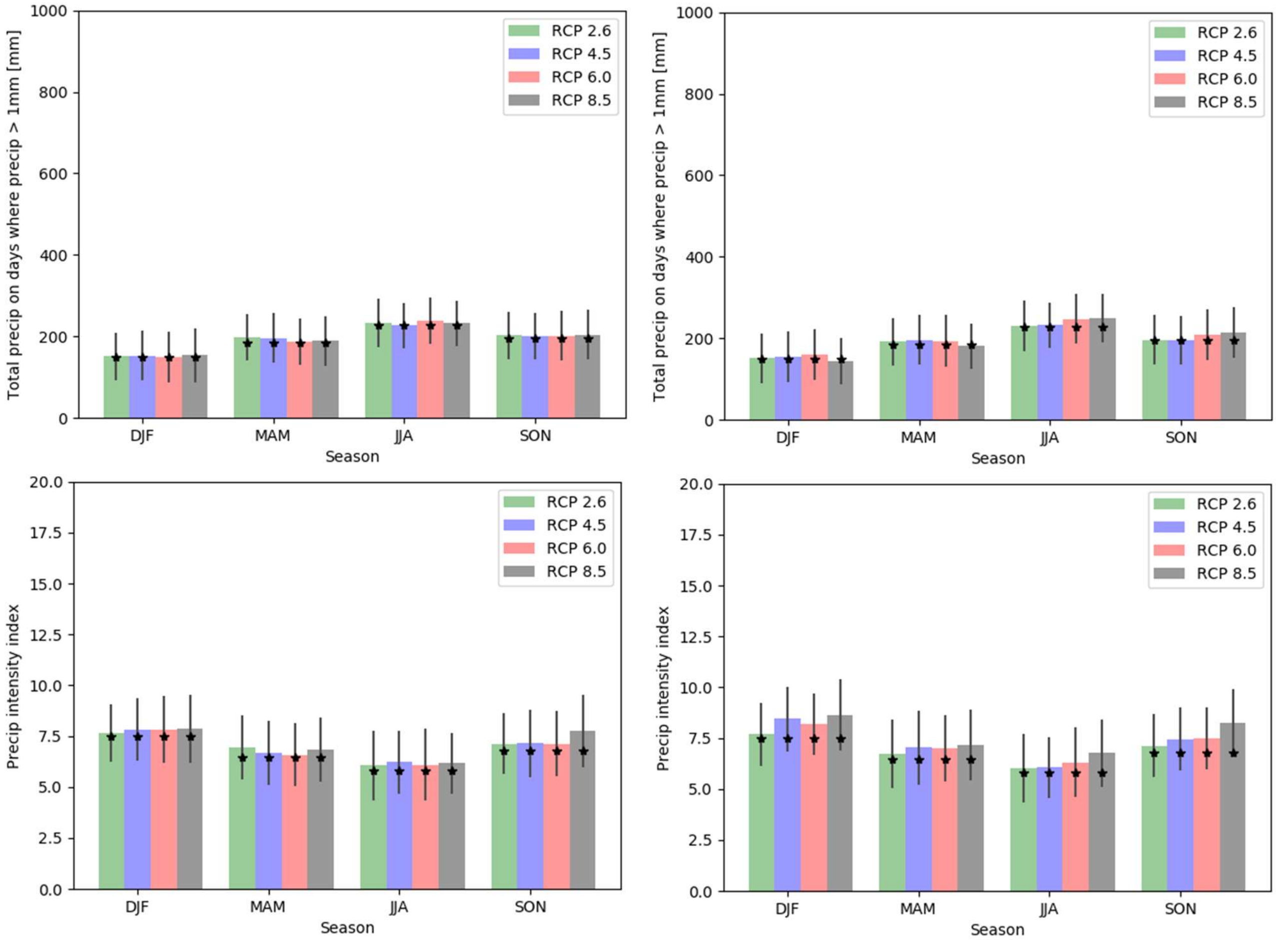

Figure E8: Same as Figure E2 but for Wanaka.

Wanaka is projected to have limited change in seasonal precipitation volume and intensity by either the middle (Figure E8, left two panels) or the end of the century (Figure E8, right two panels).

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