Climate change projections for the Otago Region

Prepared for Otago Regional Council

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Executive summary

Otago's climate is changing, and these changes will continue for the foreseeable future. It is internationally accepted that human greenhouse gas emissions are the dominant cause of recent global climate change, and that further changes will result from increasing amounts of greenhouse gases in the atmosphere. The rate of future climate change depends on how fast greenhouse gas concentrations increase.

Otago Regional Council commissioned NIWA to analyse projected climate changes for the Otago Region. This report addresses expected changes for various climate variables out to 2100, drawing heavily on climate model simulations from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. In addition, hydrological impacts of climate change were assessed. The following bullet points outline some key findings of this report:

- The projected Otago temperature changes increase with time and emission scenario. Future annual average warming spans a wide range: 0.5-1.5°C by 2040, and 0.5-3.5°C by 2090. Diurnal temperature range (i.e., difference between minimum and maximum temperature of a given day) is expected to increase with time and emission scenarios.
- The average number of extreme hot days (days >30°C) is expected to increase with time and emission scenario, with considerable variability between coastal and southernmost parts of Otago compared to Central Otago. The number of extreme hot days in Central Otago are projected to increase by 30-40 days by 2090 under RCP8.5. The number of frost days (days <0°C) is expected to decrease throughout the region. Largest decreases are expected in inland areas; 10-15 fewer frost days per year by 2040, and 20-40 fewer frost days per year by 2090.
- Annual rainfall in Otago is expected to increase slightly by mid-century (0-10%), while the increase spans 10-20% (with a larger increase in the western part of the region) at the end of the century. Seasonally the largest increases are projected during winter, with 20-40% increases expected by 2090 under RCP8.5.
- Extreme, rare rainfall events are projected to become more severe in the future under all four climate change scenarios. The depth of a current 1:100-year 1-hour duration rainfall event is projected to increase by approximately 35% by 2090 under RCP8.5.
- By the end of the century, a decrease in annual dry days of 2-6 days is projected for coastal and some central parts of Otago, with increases of 2-10 more dry days per year for many remaining parts of Otago.
- By the end of the century and with increased emissions, average annual flows are expected to increase across the region (above 50% across all Freshwater Management Units except headwaters of Taieri and North Otago). Floods (characterised by the Mean Annual Flood) are expected to become larger everywhere, with increases up to 100% in some locations by the end of the century.

1 Introduction

Climate change is already affecting New Zealand and Otago with downstream effects on our natural environment, the economy, and communities. In the coming decades, climate change is highly likely to increasingly pose challenges to New Zealanders' way of life.

Otago Regional Council commissioned the National Institute of Water and Atmospheric Research (NIWA) to undertake a review of climate change projections for the Otago region (Figure 1-1; following page). This work follows the publication of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report in 2013 and 2014, and the New Zealand climate change projections report published by the Ministry for the Environment; updated 2018 (Ministry for the Environment, 2018a). The contents of this technical report include analysis of climate projections for the Otago region in greater detail than the national-scale analysis. Regional-scale climate projection maps have been provided for various climate variables, and GIS data files have been provided to the Council.

This technical report describes changes which may occur over the 21st century to the climate of the Otago region. Consideration about future change incorporates knowledge of both natural variations in the climate and changes that may result from increasing global concentrations of greenhouse gases that are contributed to by human activities. Climatic variables discussed in this report include temperature, precipitation (rainfall, snow days and dry days), and wind. Projections for hydrological variables are also discussed.

Some of the information that underpins portions of this report resulted from academic studies based on the latest assessments of the Intergovernmental Panel on Climate Change (IPCC, 2013; 2014a; 2014b; 2014c). Details specific to Otago were based on scenarios for New Zealand that were generated by NIWA from downscaling of global climate model simulations. This effort utilised several IPCC representative concentration pathways for the future and this was achieved through NIWA's core-funded Regional Modelling Programme. The atmospheric climate change information presented in this report is consistent with recently-updated national-scale climate change guidance produced for the Ministry for the Environment (2018a), and the hydrological projections are consistent with similar reports produced by NIWA for the Ministry for the Environment (Ministry for the Environment, 2018b) and the Ministry for Primary Industries (Collins and Zammit, 2016).

The remainder of this chapter includes a brief introduction of global and New Zealand climate change, based on the IPCC Fifth Assessment Report. It includes an introduction to the climate change scenarios used in this report, and the methodology that explains the modelling approach for the climate change projections that are presented for Otago.

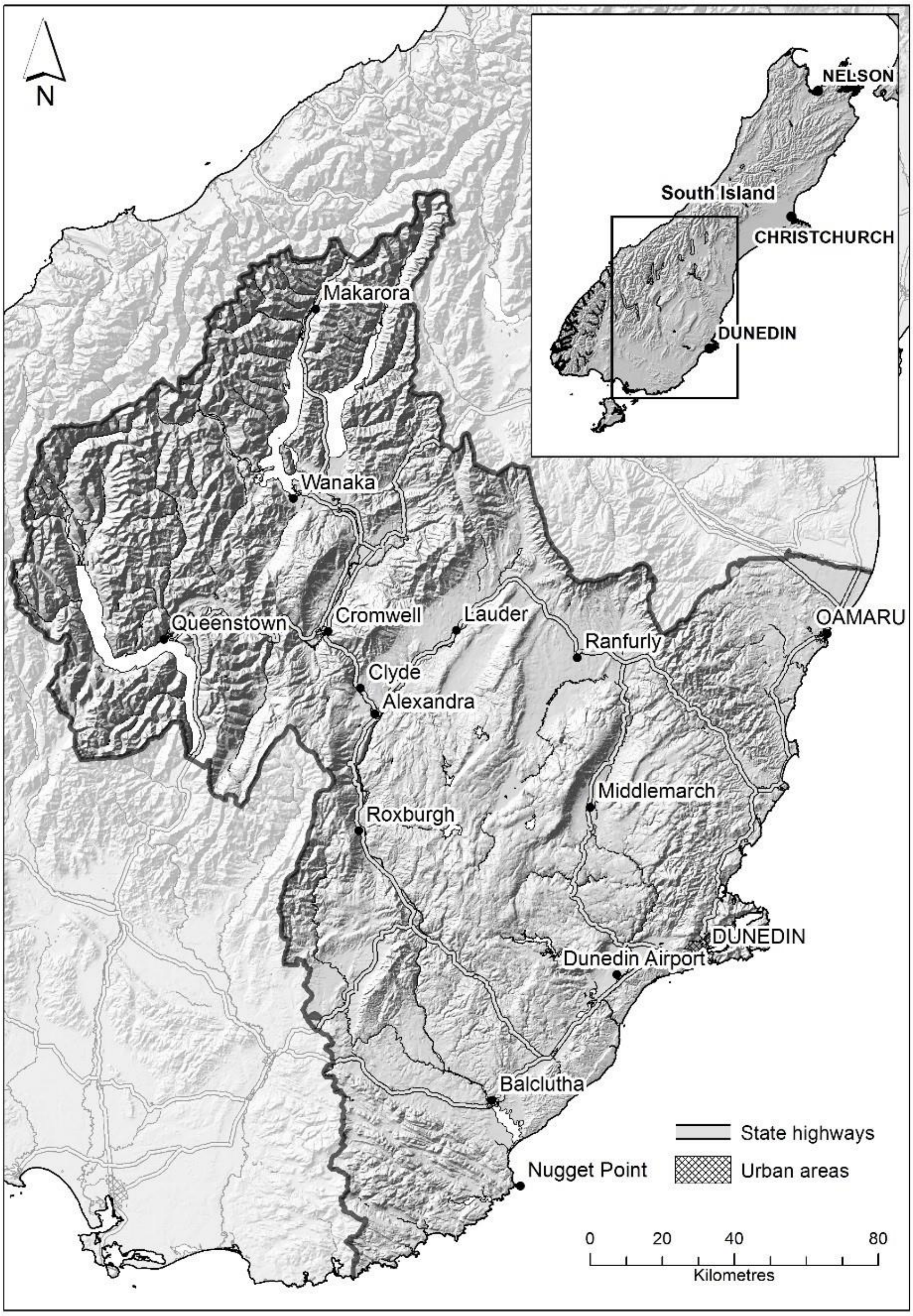


Figure 1-1: The Otago Region administered by the Otago Regional Council.

1.1 Global and New Zealand climate change

Key messages

- The global climate system is warming and many of the recently observed climate changes are unprecedented.
- Global mean sea level has risen over the past century at a rate of about 1.7 mm/year, and has very likely accelerated to 3.2 mm/year since 1993.
- Human activities (and associated greenhouse gas emissions) are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels.
- Estimated human-induced global warming is currently increasing at 0.2°C per decade due to past and ongoing emissions.
- Continued increases in greenhouse gas emissions will cause further warming and impacts on all parts of the global climate system.

Warming of the global climate system is unequivocal, and since the 1950s, many of the observed climate changes are unprecedented over short and long timescales (decades to millennia) (IPCC, 2013). These changes include warming of the atmosphere and ocean, diminishing of ice and snow, sea-level rise, and increases in the concentration of greenhouse gases in the atmosphere. Climate change is likely influencing the intensity and frequency of many extreme weather and climate events globally. The Earth's atmosphere has warmed by 0.85°C on average over the period 1880-2012. The rate of sea-level rise since the mid-19th century has been larger than the mean rate of change during the previous two millennia. Over the period 1901-2010, global mean sea level rose by 0.19 m.

The atmospheric concentrations of carbon dioxide have increased to levels unprecedented in at least the last 3 million years (Willeit et al., 2019). Carbon dioxide concentrations have increased by at least 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions (IPCC, 2013). In May 2019, the carbon dioxide concentration of the atmosphere reached 415 parts per million. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification. Due to the influence of greenhouse gases on the global climate system, it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century (IPCC, 2013, IPCC, 2018).

As global temperatures increase, it is virtually certain that there will be more hot and fewer cold temperature extremes over most land areas. It is very likely that heat waves will occur with a higher frequency and duration. Furthermore, the contrast in rainfall between wet and dry regions and wet and dry seasons will increase. Along with increases in global mean temperature, mid-latitude and wet tropical regions will experience more intense and more frequent extreme rainfall events by the end of the 21st century. The global ocean will continue to warm during the 21st century, influencing ocean circulation and sea ice extent.

Published information about the expected impacts of climate change on New Zealand is summarised and assessed in the Australasia chapter of the IPCC Working Group II assessment report (Reisinger et al., 2014) as well as a report published by the Royal Society of New Zealand (Royal Society of New Zealand, 2016). Key findings from these publications include:

The regional climate is changing. The Australasia region continues to demonstrate long-term trends toward higher surface air and sea surface temperatures, more hot extremes and fewer cold extremes, and changed rainfall patterns. Over the past 50 years, increasing greenhouse gas concentrations have contributed to rising average temperatures in New Zealand. Changing precipitation patterns have resulted in increases in rainfall for the south and west of the South Island and west of the North Island and decreases in the northeast of the South Island and the east and north of the North Island. Some heavy rainfall events already carry the fingerprint of a changed climate, in that they have become more intense due to higher temperatures allowing the atmosphere to carry more moisture (Dean et al., 2013). Cold extremes have become rarer and hot extremes have become more common.

The region has exhibited warming to the present and is virtually certain to continue to do so. New Zealand's mean annual temperature has increased, on average, by 1.00°C (± 0.25°C) per century since 1909 (Figure 1-2).

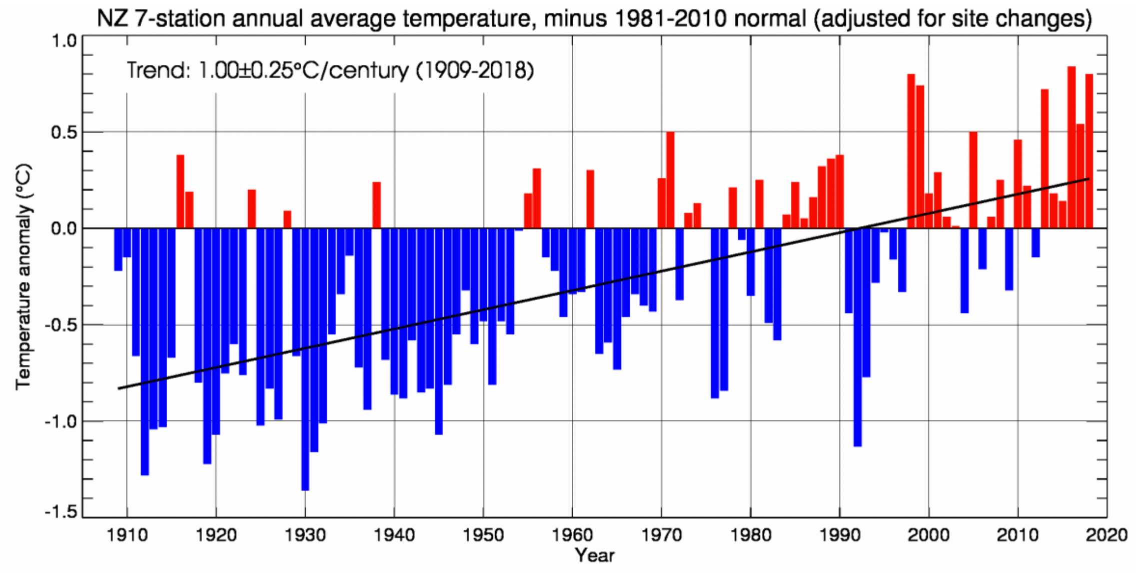


Figure 1-2: New Zealand national temperature series, 1909-2018. More information about the New Zealand seven-station temperature series can be found at https://www.niwa.co.nz/our-science/climate/information-and-resources/nz-temp-record/seven-station-series-temperature-data

Warming is projected to continue through the 21st century along with other changes in climate. Warming is expected to be associated with rising snow lines, more frequent hot extremes, less frequent cold extremes, and increasing extreme rainfall. Annual average rainfall is expected to decrease in the northeast South Island and north and east of the North Island, and to increase in other parts of New Zealand. Fire hazard is projected to increase in many parts of New Zealand. Regional sea level rise will very likely exceed the historical rate, consistent with global mean trends.

Impacts and vulnerability: Without adaptation, further climate-related changes are projected to have substantial impacts on water resources, coastal ecosystems, infrastructure, health, agriculture, and biodiversity. However, uncertainty in projected rainfall changes and other climate-related changes remains large for many parts of New Zealand, which creates significant challenges for adaptation.

Additional information about recent New Zealand climate change can be found in Ministry for the Environment (2018a).

1.2 Representative Concentration Pathways

Key messages

- Future climate change projections are considered under four emission scenarios, called Representative Concentration Pathways (RCPs) by the IPCC.
- The four RCPs project different climate futures based on future greenhouse gas concentrations, determined by economic, political and social developments during the 21st century.
- RCP2.6 is a mitigation scenario requiring significant reduction in greenhouse gas emissions, RCP4.5 and RCP6.0 are mid-range scenarios where greenhouse gas concentrations stabilise by 2100, and RCP8.5 is a 'business as usual' scenario with greenhouse gas emissions continuing at current rates.
- Projections for the future climate in Otago are presented for RCP4.5 and RCP8.5 in this report.

Assessing possible changes for our future climate due to human activity is difficult because climate projections depend strongly on estimates for future greenhouse gas concentrations. Those concentrations depend on global greenhouse gas emissions that are driven by factors such as economic activity, population changes, technological advances and policies for sustainable resource use. In addition, for a specific future trajectory of global greenhouse gas emissions, different climate model simulations produced somewhat different results for future climate change.

This range of uncertainty has been dealt with by the IPCC through consideration of 'scenarios' that describe concentrations of greenhouse gases in the atmosphere. The wide range of scenarios are associated with possible economic, political, and social developments during the 21st century, and via consideration of results from several different climate models for any given scenario. In the 2013 IPCC Fifth Assessment Report, the atmospheric greenhouse gas concentration components of these scenarios are called Representative Concentrations Pathways (RCPs). These are abbreviated as RCP2.6, RCP4.5, RP6.0, and RCP8.5, in order of increasing radiative forcing by greenhouse gases (i.e. the change in energy in the atmosphere due to greenhouse gas emissions). RCP2.6 leads to low anthropogenic greenhouse gas concentrations (requiring removal of CO_2 from the atmosphere, also called the 'mitigation' scenario), RCP4.5 and RCP6.0 are two 'stabilisation' scenarios (where greenhouse gas emissions and therefore radiative forcing stabilises by 2100) and RCP8.5 has very high greenhouse gas concentrations (the 'business as usual' scenario). Therefore, the RCPs represent a range of 21st century climate policies. Table 1-1 shows the projected global mean surface air temperature for each RCP.

Table 1-1: Projected change in global mean surface air temperature for the mid- and late- 21st century relative to the reference period of 1986-2005 for different RCPs. After IPCC (2013).

Scenario	Alternative name	2046-2065 (mid-century)		2081-2100 (end-century)	
		Mean	Likely range	Mean	Likely range
RCP2.6	Mitigation scenario	1.0	0.4 to 1.6	1.0	0.3 to 1.7
RCP4.5	Stabilisation scenario	1.4	0.9 to 2.0	1.8	1.1 to 2.6
RCP6.0	Stabilisation scenario	1.3	0.8 to 1.8	2.2	1.4 to 3.1
RCP8.5	Business as usual scenario	2.0	1.4 to 2.6	3.7	2.6 to 4.8

The full range of projected globally-averaged temperature increases for all scenarios for 2081-2100 (relative to 1986-2005) is 0.3 to 4.8°C (Figure 1-3). Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit inter-annual-to-decadal variability and will not be regionally uniform.

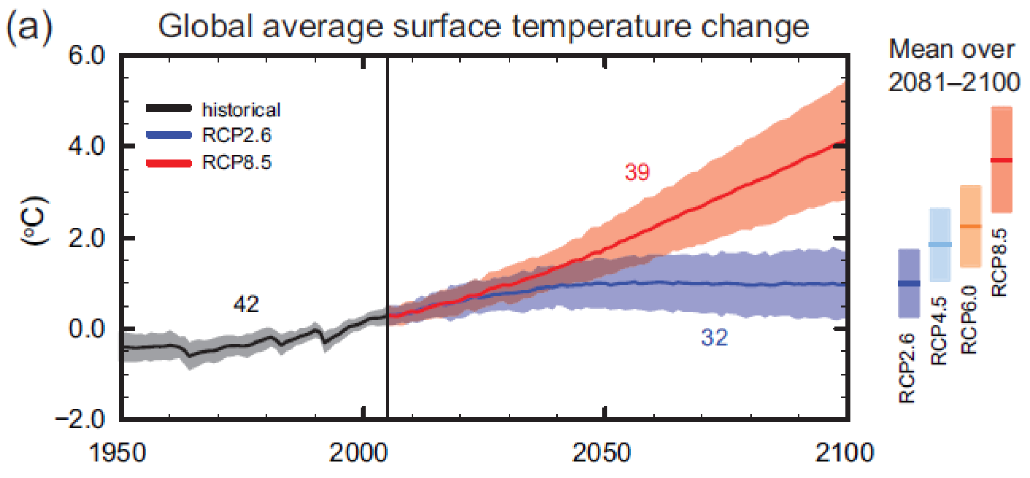


Figure 1-3: CMIP5 multi-model simulated time series from 1950-2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as coloured vertical bars to the right of the graph (the mean projection is the solid line in the middle of the bars). The numbers of CMIP5 models used to calculate the multi-model mean is indicated on the graph. From IPCC (2013).

Cumulative CO_2 emissions will largely determine global mean surface warming by the late 21st century and beyond. Even if emissions are stopped, the inertia of many global climate changes will continue for many centuries to come. This represents a substantial multi-century climate change commitment created by past, present, and future emissions of CO_2.

In this report, global climate model outputs based on two RCPs (RCP4.5 and RCP8.5) have been downscaled by NIWA to produce future climate projections for the Otago Region. The rationale for choosing these two scenarios was to present a 'business-as-usual' scenario if greenhouse gas emissions continue at current rates (RCP8.5) and a scenario which could be realistic if global action is taken towards mitigating climate change, for example the Paris climate change agreement (RCP4.5). In addition, the global model outputs based on all RCPs (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) have been utilised for the hydrological modelling component of this report.

1.3 Year to year climate variability and climate change

Key messages

- Natural variability is an important consideration in addition to the underlying climate change signal.
- El Niño-Southern Oscillation is the most dominant mode of inter-annual climate variability and it impacts New Zealand primarily through changing wind, temperature and rainfall patterns.
- The Interdecadal Pacific Oscillation affects New Zealand through drier conditions in the east and wetter conditions in the west during the positive phase, the opposite in the negative phase.
- The Southern Annular Mode affects New Zealand through higher temperatures and settled weather during the positive phase and lower temperatures and unsettled weather during the negative phase.
- Natural variability will continue to affect the year-to-year climate of New Zealand into the future, and thus introduce some uncertainty in the 20-year averages presented.

Much of the material in this report focuses on the projected impact on the climate of Otago over the coming century due to increases in global anthropogenic greenhouse gas concentrations. However, natural variations will also continue to occur. Much of the variation in New Zealand's climate is random and lasts for only a short period, but longer term, quasi-cyclic variations in climate can be attributed to different factors. Three large-scale oscillations that influence climate in New Zealand are the El Niño-Southern Oscillation, the Interdecadal Pacific Oscillation, and the Southern Annular Mode (Ministry for the Environment, 2008). Those involved in (or planning for) climate-sensitive activities in the Otago region will need to cope with the sum of both anthropogenic change and natural variability.

1.3.1 The effect of El Niño and La Niña

El Niño-Southern Oscillation (ENSO) is a natural mode of climate variability that has wide-ranging impacts around the Pacific Basin (Ministry for the Environment, 2008). ENSO involves a movement of warm ocean water from one side of the equatorial Pacific to the other, changing atmospheric circulation patterns in the tropics and subtropics, with corresponding shifts for rainfall across the Pacific.

During El Niño, easterly trade winds weaken and warm water 'spills' eastward across the equatorial Pacific, accompanied by higher rainfall than normal in the central-east Pacific. La Niña produces opposite effects and is typified by an intensification of easterly trade winds, and retention of warm ocean waters over the western Pacific. ENSO events occur on average three to seven years apart, typically becoming established in April or May and persisting for about a year thereafter.

During El Niño events, the weakened trade winds cause New Zealand to experience a stronger than normal south-westerly airflow. This generally brings lower seasonal temperatures to the country and drier than normal conditions to the north and east of New Zealand (Salinger and Mullan, 1999). During La Niña conditions, the strengthened trade winds cause New Zealand to experience more north-easterly airflow than normal, higher-than-normal temperatures (especially during summer), and generally drier conditions in the west and south of the South Island, including Otago (Figure 1-4).

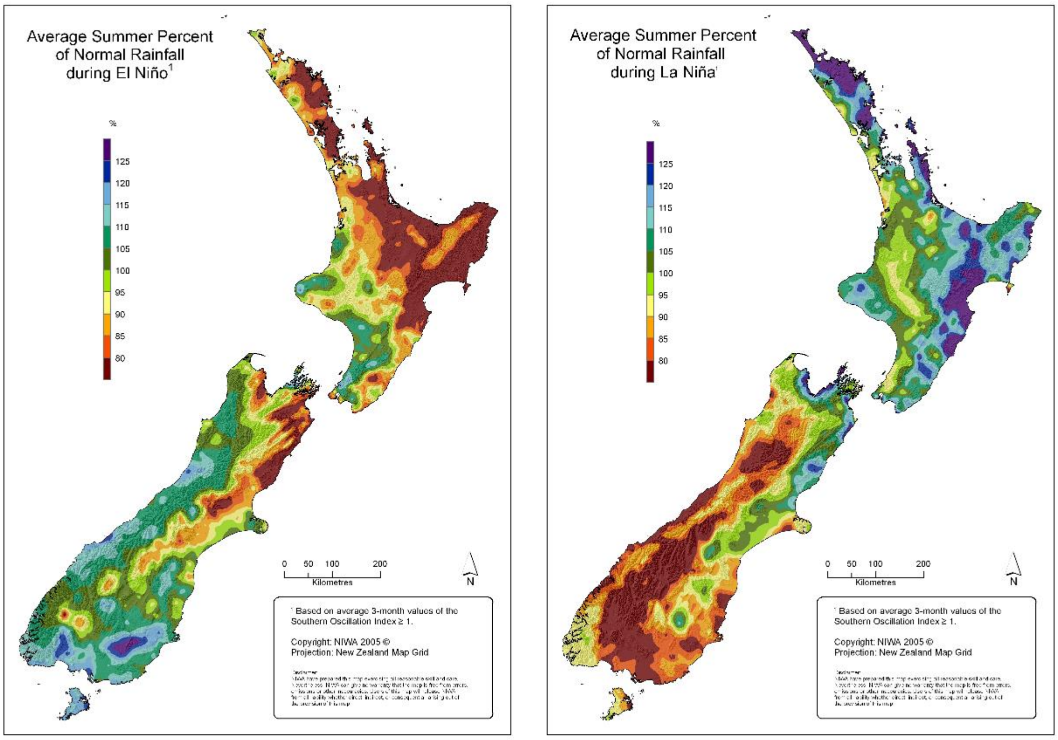


Figure 1-4: Average summer percentage of normal rainfall during El Niño (left) and La Niña (right). El Niño composite uses the following summers: 1963/64, 1965/66, 1968/69, 1969/70, 1972/73, 1976/77, 1977/78, 1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98, 2002/03. La Niña composite uses the following summers: 1964/65, 1970/71, 1973/74, 1975/76, 1983/84, 1984/85, 1988/89, 1995/96, 1998/99, 1999/2000, 2000/01. This figure was last updated in 2005. © NIWA.

According to IPCC (2013), ENSO is highly likely to remain the dominant mode of natural climate variability in the 21st century, and that rainfall variability relating to ENSO is likely to increase. However, there is uncertainty about future changes to the amplitude and spatial pattern of ENSO.

1.3.2 The effect of the Interdecadal Pacific Oscillation

The Interdecadal Pacific Oscillation (IPO) is a large-scale, long-period oscillation that influences climate variability over the Pacific Basin including New Zealand (Salinger et al., 2001). The IPO operates at a multi-decadal scale, with phases lasting around 20 to 30 years. During the positive phase of the IPO, sea surface temperatures around New Zealand tend to be lower, and westerly winds stronger, resulting in drier conditions for eastern areas of both North and South Islands. The opposite occurs in the negative phase. The IPO can modify New Zealand's connection to ENSO, and it also positively reinforces the impacts of El Niño (during IPO+ phases) and La Niña (during IPO-phases).

1.3.3 The effect of the Southern Annular Mode

The Southern Annular Mode (SAM) represents the variability of circumpolar atmospheric jets that encircle the Southern Hemisphere that extend out to the latitudes of New Zealand. The SAM is often coupled with ENSO, and both phenomena affect New Zealand's climate in terms of westerly wind strength and storm occurrence (Renwick and Thompson, 2006). In its positive phase, the SAM is associated with relatively light winds and more settled weather over New Zealand, with stronger westerly winds further south towards Antarctica. In contrast, the negative phase of the SAM is associated with unsettled weather and stronger westerly winds over New Zealand, whereas wind and storms decrease towards Antarctica.

The phase and strength of the SAM is influenced by the size of the ozone hole, giving rise to positive trends in the past during spring and summer. In the future other drivers are likely to have an impact on SAM behaviour, for example changing temperature gradients between the equator and the high southern latitudes would have an impact on westerly wind strength in the mid-high latitudes.

1.3.4 The influence of natural variability on climate change projections

It is important to consider human-induced climate change in the context of natural climate variability. An example of this for temperature is shown in Figure 1-5. The solid black line on the left-hand side represents the observed annual average temperature for New Zealand[1], and the dashed black line represents the 1909-2014 trend of 0.92 °C/century extrapolated to 2100. All the other line plots and shading refer to the modelled air temperature averaged over the New Zealand region. Post-2014, the two line plots show the annual temperature changes for the New Zealand region under RCP8.5 (orange) and RCP2.6 (blue); a single model is selected to illustrate the inter-annual variability. The shading shows the range across all IPCC AR5 models for both historical and future periods.

Over the 1900-2014 historical period, the New Zealand observed temperature curve lies within the simulations of all models (purple shading). For the future 2015-2100 period, the RCP2.6 models (blue shading) show very little warming trend after about 2030, whereas the RCP8.5 models (orange shading) 'take off' to be anywhere between +2°C and +5°C by 2100.

Figure 1-5 should not be interpreted as a set of specific predictions for individual years. However, it illustrates that although we expect a long term overall upward trend in temperatures (at least for RCP8.5), there will still be some relatively cool years. For this example, a year which is unusually warm under our present climate could become the norm by about 2050, and an "unusually warm" year in 30-50 years' time (under the higher emission scenarios) is likely to be warmer than anything we currently experience.

[1] https://www.niwa.co.nz/our-science/climate/information-and-resources/nz-temp-record/seven-station-series-temperature-data

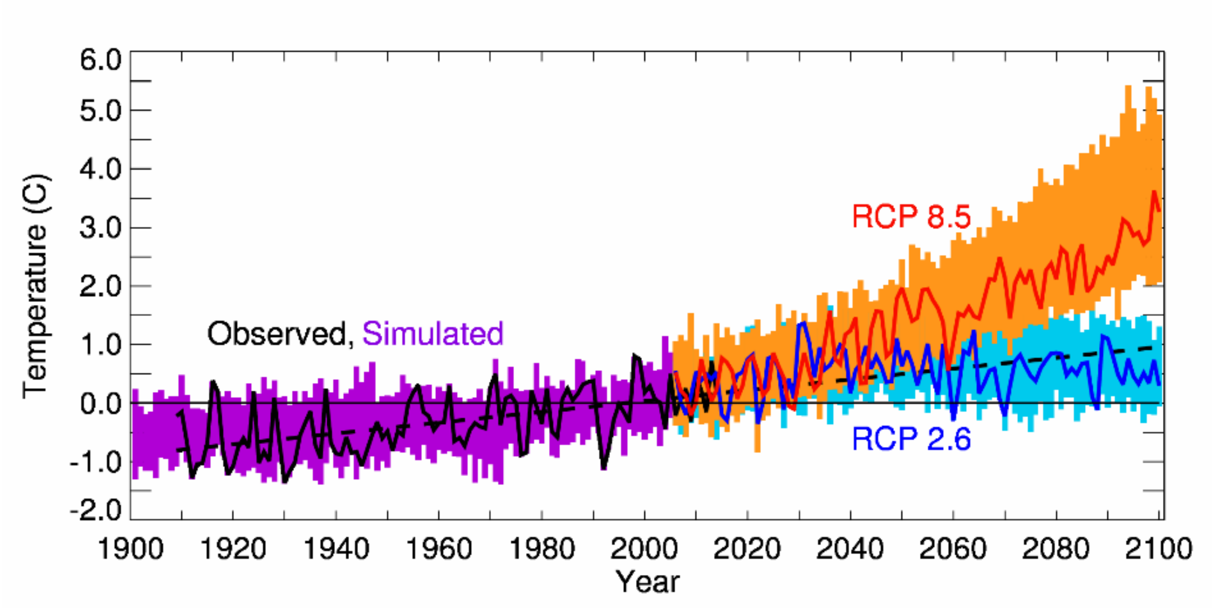


Figure 1-5: New Zealand Temperature - historical record and an illustrative schematic projection illustrating future year-to-year variability. (See text for full explanation). From Ministry for the Environment (2018).

For rainfall, multi-decadal variability associated with the IPO can enhance or counter the impacts of anthropogenic climate change. This influence may generate either slightly above normal or below normal rainfall for parts of New Zealand during summer. For the present period, IPO-negative conditions coupled with more frequent La Niña episodes could increase rainfall during spring and summer, essentially in the opposite direction as expected from anthropogenic factors (i.e. a potential reduction in spring and summer rainfall). A subsequent further reversal of the IPO in 10-20 years' time could have the opposite effect, enhancing part of the anthropogenic (drying) trend in rainfall for a few decades.

The message from this section is *not* that anthropogenic trends in climate can be ignored because of natural variability. In the projections, we have discussed these anthropogenic trends because they become the dominant factor locally as the century progresses. Nevertheless, we need to bear in mind that at some times natural variability will be adding to the human-induced trends, while at others it may be offsetting part of the anthropogenic effect.

1.4 Climate modelling methodology

Key messages

- Climate model simulation data from the IPCC Fifth Assessment has been used to produce climate projections for New Zealand.
- Six climate models were chosen by NIWA for dynamical downscaling. These models were chosen because they produced the most accurate results when compared to historical climate and circulation patterns in the New Zealand and southwest Pacific region.
- Downscaled climate change projections are at a 5 km x 5 km resolution over New Zealand.
- Climate projection and historic baseline maps and tables present the average of the six downscaled models.
- Climate projections are presented as a 20-year average for two future periods: 2031-2050 (termed '2040') and 2081-2100 (termed '2090'). All maps show changes relative to the baseline climate of 1986-2005 (termed '1995').
- More details about the methods used in climate change modelling are found in Appendix A.

1.5 Hydrological modelling methodology

Key messages

- NIWA's TopNet model has been used in this study. TopNet is a spatially semi-distributed, time-stepping model of water balance. The model is driven by time-series of precipitation and temperature, and additional weather elements (e.g. wind) where available.
- TopNet was run continuously from 1971 to 2100, with the spin-up period 1971 excluded from the analysis. The climate inputs were stochastically disaggregated from daily to hourly time steps.
- The simulation results comprise time-series of modelled river flow for each computational sub-catchment, and for each of the six GCMs and four RCPs considered.
- Hydrological projections are presented as the average for two future periods: 2036-2056 (termed 'mid-century') and 2086-2099 (termed 'late-century'). All maps show changes relative to the baseline climate (1986-2005 average).
- More details about the methods used in hydrological modelling are found in Appendix B.

2 Current and future climate of the Otago Region

The topography of the South Island has a profound effect on the weather of the Otago Region. The Southern Alps act as a barrier to the prevailing westerly winds over the region, separating New Zealand's wettest region (the West Coast) from Central Otago - New Zealand's driest region. As a result, a steep precipitation gradient exists eastward from the western ranges. In Central Otago, hot dry summers and cold dry winters approximate a semi-arid 'continental' climate. In coastal areas of eastern Otago, conditions are tempered by relatively cool sea surface temperatures nearby, and by the absence of shelter from airflows moving over the area from the south and southwest. More information about the present climate of Otago, outside of the information in this report, can be found in Chappell (2013).

The following sections (3-6) present climate change projections for the Otago Region.

3 Temperature

3.1 Mean temperature

Key messages

- Projected Otago temperature changes increase with time and emission scenario. Future annual average warming spans a wide range: 0.5-1.5°C by 2040, and 0.5-3.5°C by 2090.
- Seasonal mean temperatures are projected to increase by 0.5-1.0°C across much of Otago (by 2040 under RCP4.5,). By 2090 under RCP8.5, projected increases of 1.5-2.5°C in coastal areas of Otago, with increases of 2.0-3.5°C for inland parts of the region.

Present-day (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for mean temperature are shown in this section. The present-day maps show annual and seasonal mean temperature in units of degrees Celsius (°C) and the future projection maps show the change in mean temperature compared with the present day, in units of °C. Note that the present-day maps are on a different colour scale to the future projection maps.

At present, annual mean temperatures range between 8-12°C for most coastal and inland low-elevation locations of Otago (Figure 3-1). Seasonal mean temperatures are influenced by a proximity to the sea, such that coastal locations are typically cooler in summer and warmer in winter compared to inland parts of the region (Figure 3-3). For coastal areas of Otago including Dunedin, summer mean temperatures range between 12-16°C, and winter mean temperatures range between 6-8°C. For inland low-elevation locations, summer mean temperatures range between 16-18°C, and winter mean temperatures range between 2-6°C. Mean temperatures at high-elevation mountainous areas of Otago remain several degrees Celsius colder than the remainder of the region throughout the year.

Annual mean temperature is projected to increase by 0.5-1.5°C by 2040 under RCP4.5 and RCP8.5 (Figure 3-2). By 2090, annual mean temperature increases of 0.5-2.0°C (RCP4.5) and 1.5-3.5°C (RCP8.5) are projected. Seasonal projections of mean temperature change are shown for RCP4.5 by 2040 (Figure 3-4) and 2090 (Figure 3-6), and RCP8.5 by 2040 (Figure 3-5) and 2090 (Figure 3-7). Seasonal mean temperatures are projected to increase by 0.5-1.0°C across much of Otago by 2040 under RCP4.5, and by 0.5-1.5°C under RCP8.5. By 2090 under RCP4.5, seasonal mean temperatures are projected to increase by 0.5-1.5°C for most of Otago and 1.5-2.5°C for western high elevations areas. Under RCP8.5, seasonal mean temperatures are projected to increase by 1.5-2.5°C in coastal areas of Otago, with increases of 2.0-3.5°C projected for inland parts of the region.

Modelled seasonal and annual mean temperature data have been generated for 16 Otago locations, and these are presented in Table 3-1.

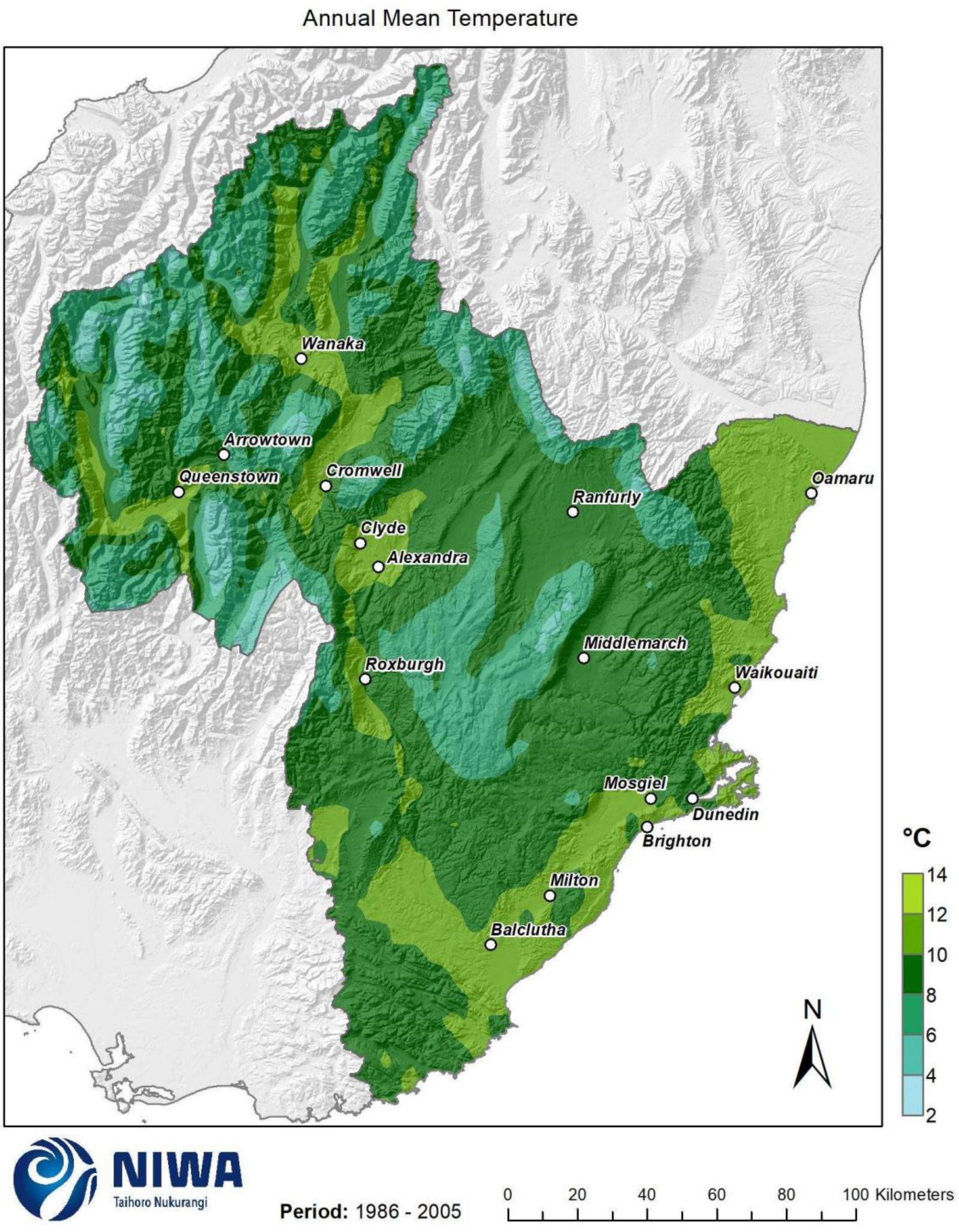


Figure 3-1: Modelled annual mean temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

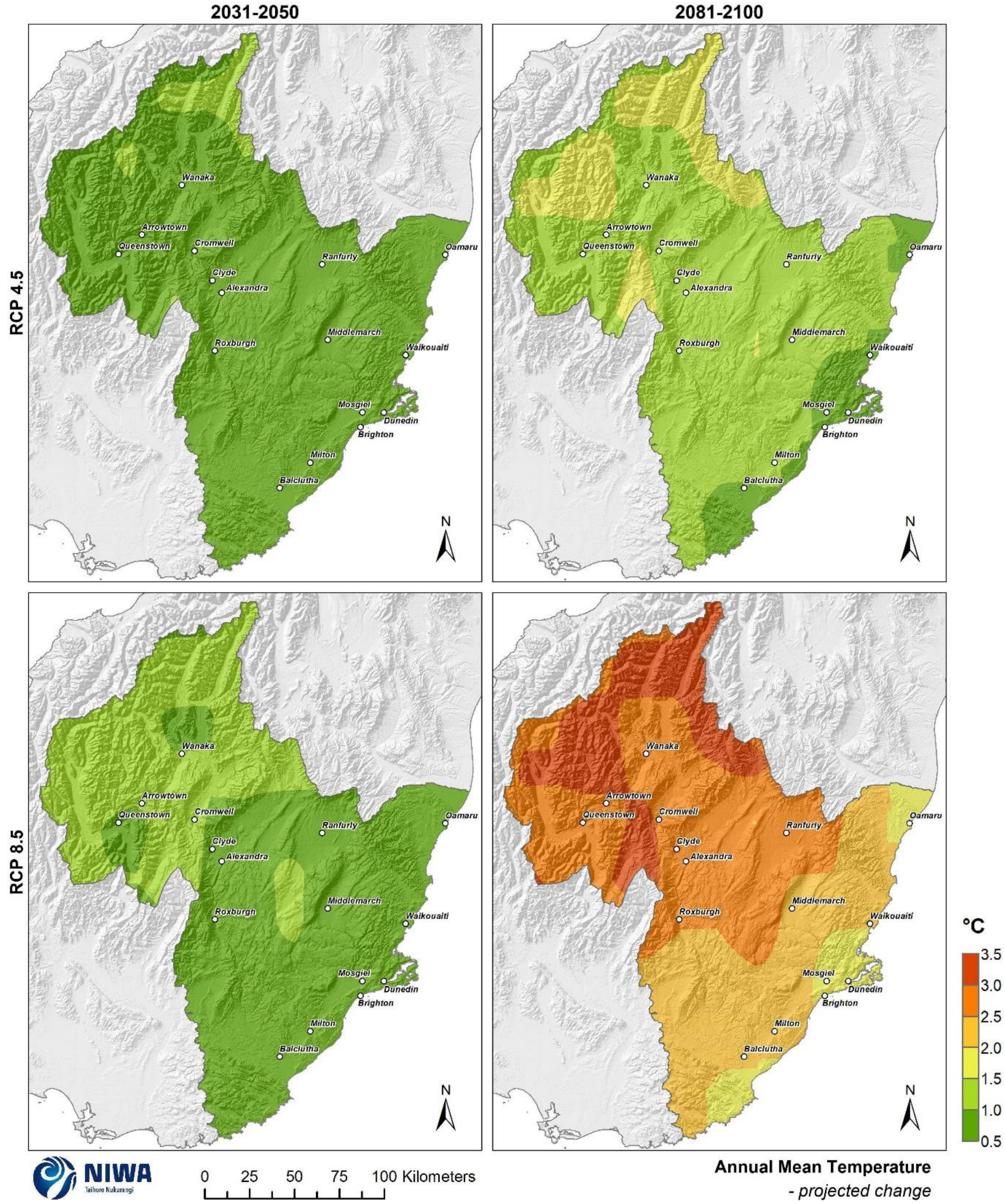


Figure 3-2: Projected annual mean temperature changes by 2040 and 2090, under RCP4.5 and RCP8.5. Climate change scenarios: RCP4.5 (top panels) and RCP8.5 (bottom panels). Time periods: mid-century (2031-2050; "2040" – panels on left) and end-century (2081-2100; "2090" – panels on right). Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

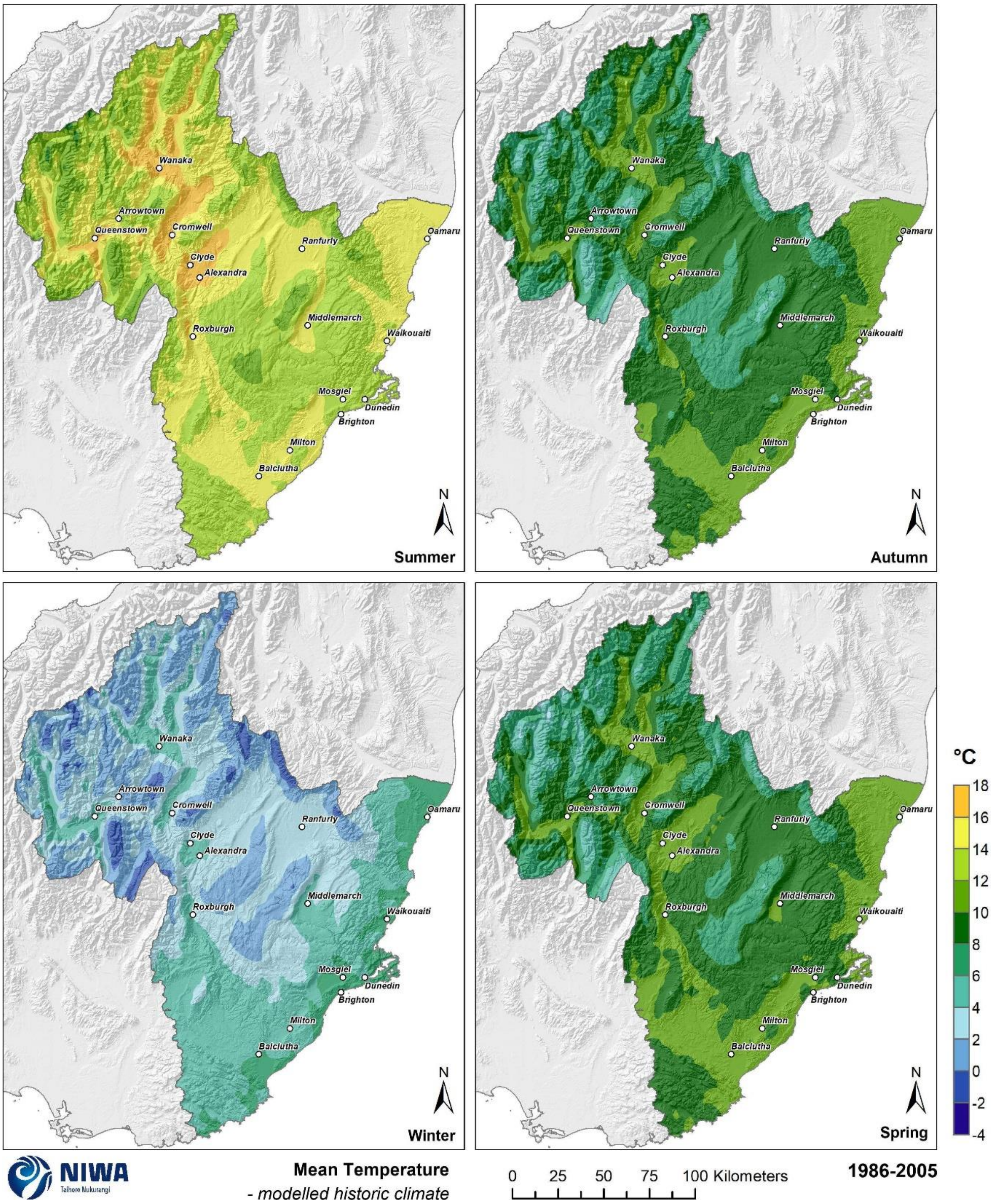


Figure 3-3: Modelled seasonal mean temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

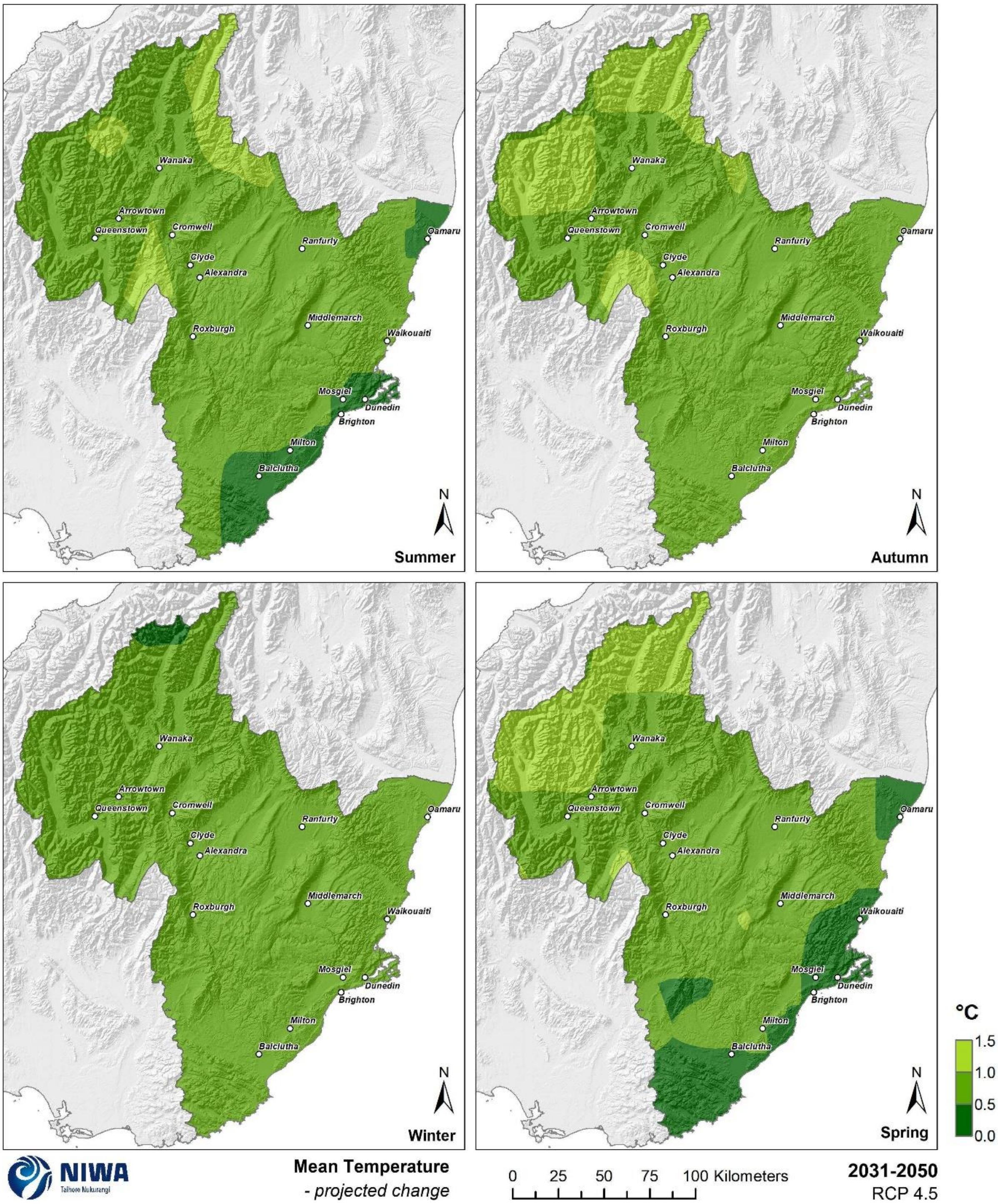


Figure 3-4: Projected seasonal mean temperature changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

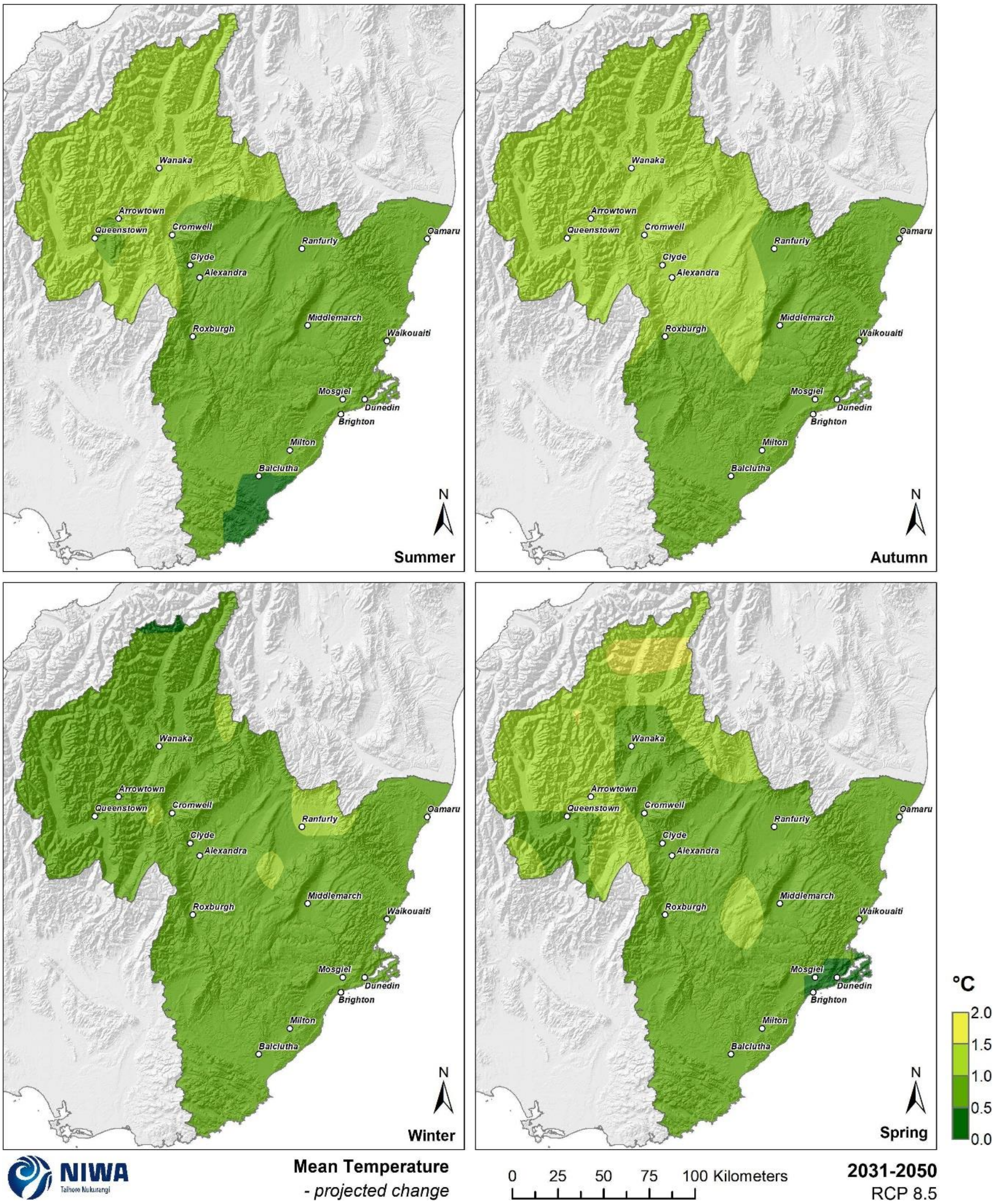


Figure 3-5: Projected seasonal mean temperature changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

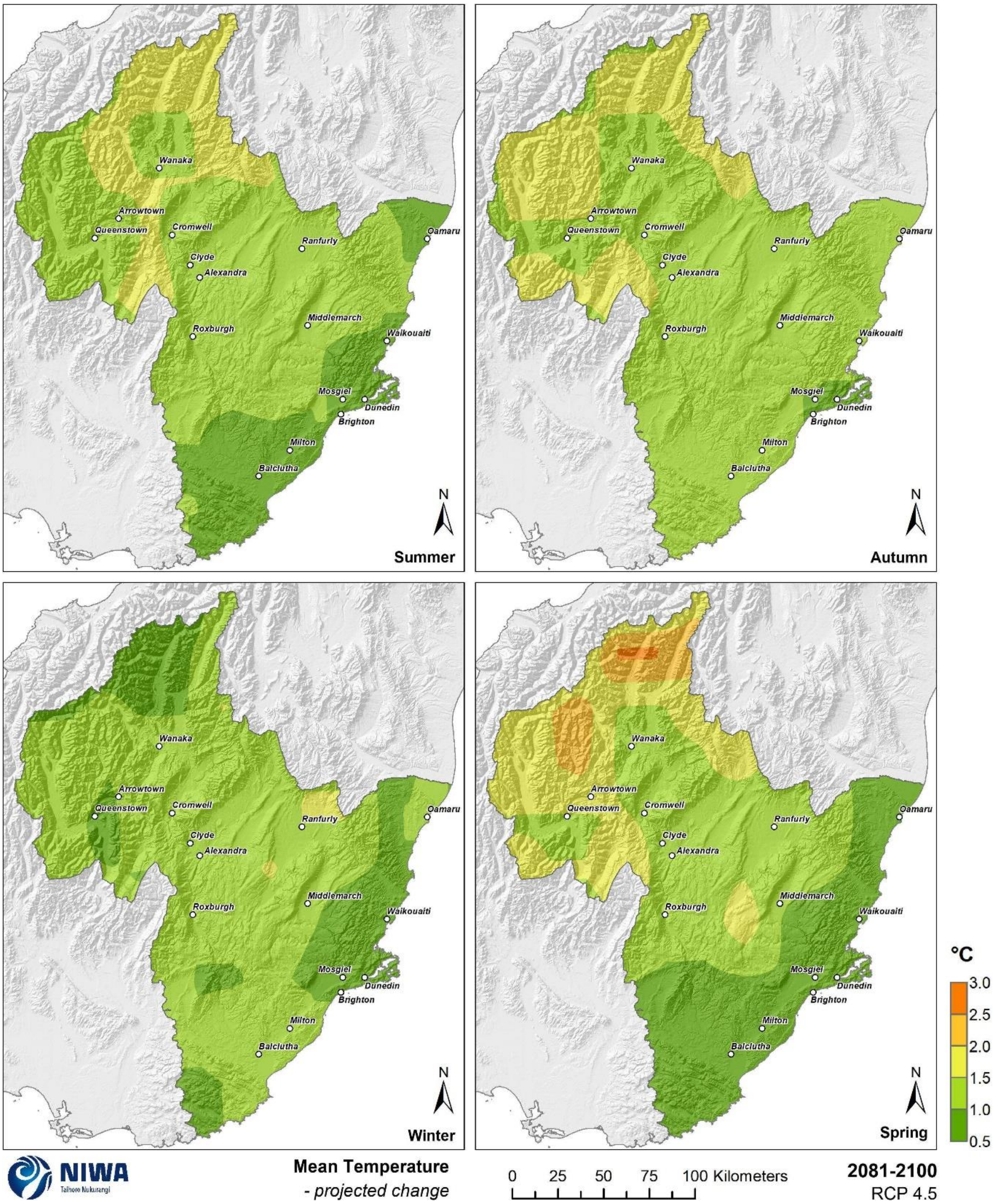


Figure 3-6: Projected seasonal mean temperature changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

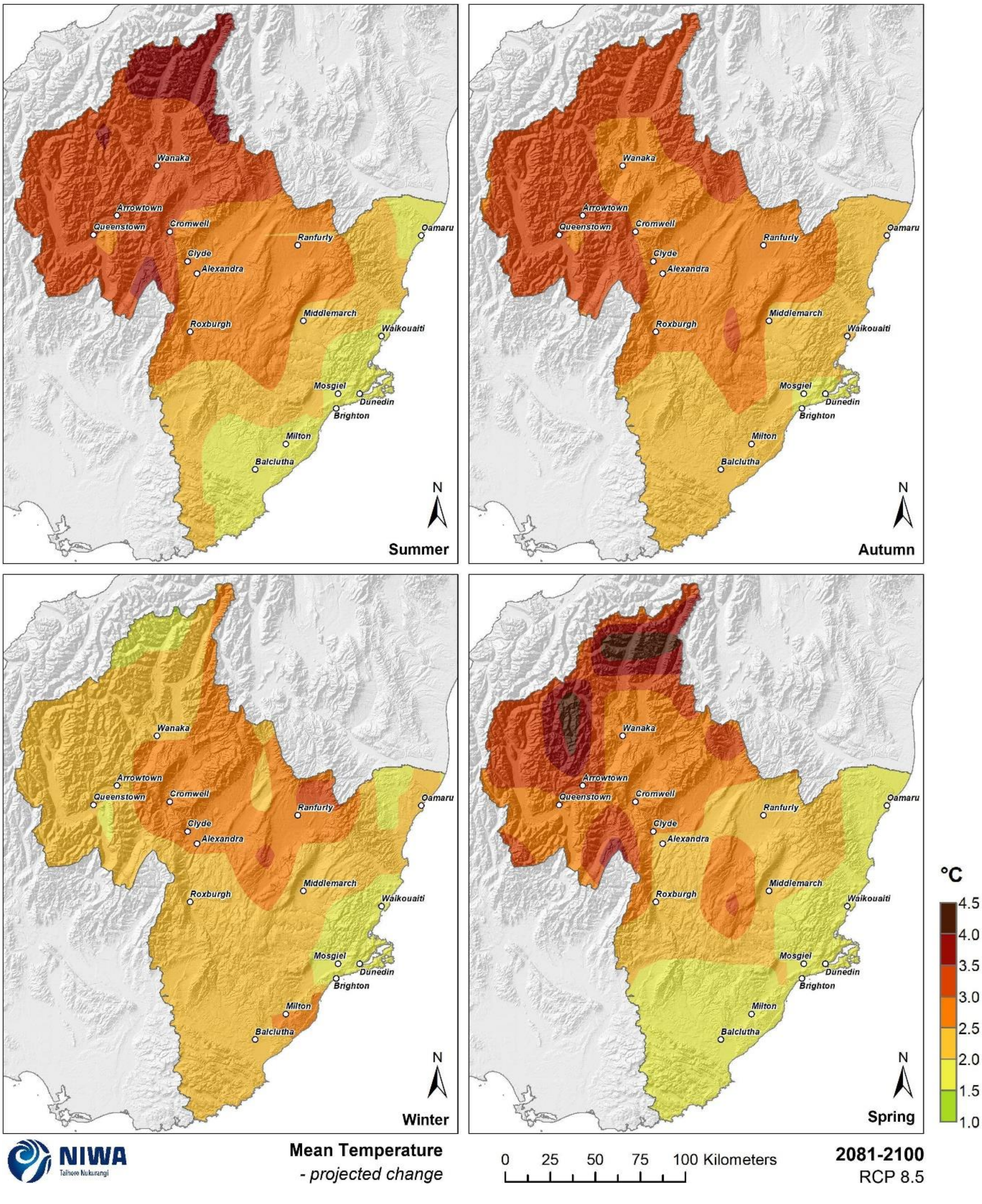


Figure 3-7: Projected seasonal mean temperature changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 3-1: Modelled seasonal and annual mean temperature for present and two climate change scenarios (RCP4.5 and RCP8.5) at two future time periods. Time periods: present (1986-2005), mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models. Annual ("Ann"); Seasons: summer ("Sum"), autumn ("Aut"), winter ("Win") and spring ("Spr").

	PRESENT				
	Sum	Aut	Win	Spr	Ann
Alexandra	16.9	10.7	4.4	11.4	10.8
Arrowtown	15.0	9.3	3.2	9.1	9.1
Balclutha	14.2	10.3	5.8	10.4	10.2
Brighton	13.1	10.2	6.2	9.6	9.7
Clyde	16.7	10.5	4.1	11.2	10.6
Cromwell	17.5	11.3	4.7	11.8	11.3
Dunedin	13.6	10.6	6.6	10.0	10.2
Middlemarch	14.7	9.8	4.7	10.2	9.8
Milton	14.5	10.5	6.0	10.6	10.4
Mosgiel	14.0	11.1	7.0	10.5	10.6
Oamaru	15.0	10.9	6.3	10.8	10.7
Queenstown	14.8	9.5	3.7	9.4	9.3
Ranfurly	14.7	9.3	3.2	9.7	9.2
Roxburgh	16.3	10.8	5.1	11.3	10.8
Waikouaiti	14.1	10.3	6.0	10.3	10.2
Wanaka	16.9	11.0	4.6	10.9	10.8

		2040					2090				
		Sum	Aut	Win	Spr	Ann	Sum	Aut	Win	Spr	Ann
Alexandra	RCP4.5	+0.9	+1.0	+0.7	+0.7	+0.8	+1.3	+1.4	+1.2	+1.2	+1.3
	RCP8.5	+0.9	+1.1	+0.8	+0.8	+0.9	+2.7	+2.9	+2.6	+2.5	+2.7
Arrowtown	RCP4.5	+0.9	+1.0	+0.6	+1.0	+0.9	+1.4	+1.5	+1.0	+1.7	+1.5
	RCP8.5	+1.0	+1.2	+0.7	+1.1	+1.0	+3.2	+3.1	+2.2	+3.3	+3.0
Balclutha	RCP4.5	+0.5	+0.7	+0.6	+0.5	+0.6	+0.8	+1.1	+1.1	+0.9	+1.0
	RCP8.5	+0.5	+0.8	+0.7	+0.6	+0.7	+1.7	+2.2	+2.4	+1.9	+2.1
Brighton	RCP4.5	+0.5	+0.6	+0.6	+0.4	+0.5	+0.8	+0.9	+0.9	+0.7	+0.9
	RCP8.5	+0.5	+0.7	+0.6	+0.5	+0.6	+1.6	+1.9	+1.9	+1.6	+1.8
Clyde	RCP4.5	+0.9	+1.0	+0.7	+0.7	+0.8	+1.3	+1.4	+1.2	+1.2	+1.3
	RCP8.5	+0.9	+1.1	+0.8	+0.8	+0.9	+2.8	+2.9	+2.7	+2.5	+2.7
Cromwell	RCP4.5	+0.9	+1.0	+0.9	+0.8	+0.9	+1.4	+1.4	+1.4	+1.4	+1.4
	RCP8.5	+1.0	+1.1	+1.0	+0.9	+1.0	+3.0	+3.0	+2.8	+2.8	+2.9
Dunedin	RCP4.5	+0.5	+0.6	+0.6	+0.4	+0.5	+0.8	+0.9	+0.9	+0.7	+0.9
	RCP8.5	+0.5	+0.7	+0.6	+0.5	+0.6	+1.6	+1.9	+1.9	+1.6	+1.8
Middlemarch	RCP4.5	+0.7	+0.8	+0.6	+0.6	+0.7	+1.1	+1.2	+1.0	+1.0	+1.1
	RCP8.5	+0.8	+0.9	+0.7	+0.7	+0.8	+2.3	+2.4	+2.2	+2.1	+2.3
Milton	RCP4.5	+0.5	+0.7	+0.7	+0.5	+0.6	+0.8	+1.1	+1.1	+0.9	+1.0
	RCP8.5	+0.5	+0.8	+0.8	+0.6	+0.7	+1.7	+2.3	+2.5	+1.9	+2.1
Mosgiel	RCP4.5	+0.5	+0.6	+0.6	+0.4	+0.5	+0.8	+0.9	+0.9	+0.7	+0.9
	RCP8.5	+0.5	+0.7	+0.6	+0.5	+0.6	+1.6	+1.9	+1.9	+1.6	+1.8
Oamaru	RCP4.5	+0.4	+0.7	+0.7	+0.5	+0.6	+0.8	+1.2	+1.1	+0.8	+1.0
	RCP8.5	+0.5	+0.8	+0.7	+0.6	+0.7	+1.5	+2.2	+2.0	+1.7	+1.9
Queenstown	RCP4.5	+0.9	+1.0	+0.6	+0.8	+0.9	+1.4	+1.5	+1.0	+1.5	+1.4
	RCP8.5	+1.0	+1.1	+0.7	+1.0	+1.0	+3.0	+3.0	+2.1	+2.9	+2.8
Ranfurly	RCP4.5	+0.8	+0.8	+0.9	+0.7	+0.8	+1.2	+1.3	+1.4	+1.2	+1.3
	RCP8.5	+0.8	+1.0	+1.0	+0.8	+0.9	+2.6	+2.6	+2.9	+2.3	+2.6
Roxburgh	RCP4.5	+0.8	+0.9	+0.6	+0.6	+0.8	+1.2	+1.3	+1.1	+1.2	+1.2
	RCP8.5	+0.9	+1.0	+0.8	+0.8	+0.9	+2.7	+2.7	+2.3	+2.4	+2.5
Waikouaiti	RCP4.5	+0.6	+0.8	+0.6	+0.5	+0.6	+1.0	+1.2	+0.9	+0.8	+1.0
	RCP8.5	+0.6	+0.8	+0.6	+0.5	+0.7	+2.0	+2.4	+1.9	+1.8	+2.0
Wanaka	RCP4.5	+1.0	+0.9	+0.7	+0.8	+0.9	+1.5	+1.4	+1.2	+1.4	+1.4
	RCP8.5	+1.1	+1.1	+0.8	+0.9	+1.0	+3.2	+2.9	+2.5	+2.8	+2.9

3.1.1 Model confidence

Key message

- The complete range of model projections (as shown in this section) demonstrate the difference with season and RCP, allowing interpretation of the range of model uncertainty.
- For mean temperature, all models at 2040 project warming, so this direction of change has high certainty.
- By 2090, the model spread is quite large within the scenarios, so the actual value of temperature change is less certain. However, all models for RCP4.5, 6.0 and 8.5 project warming, with higher greenhouse gas concentrations generally projecting more warming.

The climate change projections in other sections of this report show the average of six dynamically downscaled climate models. This is useful as the average is the 'best estimate' of future conditions, but these results taken alone do not allow for communication of uncertainty or range in potential future outcomes within the different scenarios and time periods. This section presents the full range of model results for mean temperature, to help the reader understand that there is no 'single answer' in terms of future projections.

Projected changes in seasonal and annual mean temperature are shown for the Otago region overall in Table 3-2 (i.e. the average of all grid points within Otago). Note that data in this table was derived from additional IPCC Fifth Assessment Report models than are presented in the maps in this report (the maps are the average of six dynamically downscaled models, whereas the data here are from ~40 statistically downscaled models), in order to enable an assessment of the range of temperature change projected for Otago by 2040 and 2090 under RCP4.5 and RCP8.5. The difference between dynamical and statistical downscaling is explained in Appendix A.

Figure 3-8 and Figure 3-9 illustrate the seasonal and annual temperature projections for each RCP, for the two time periods of 2040 and 2090, respectively. The temperature changes are averaged over all grid-points within the Otago region. The coloured vertical bars, and inset stars, show all the individual models, so the complete range is displayed (unlike Table 3-2 where the 5th to 95th percentile range has been calculated). These figures are an excellent way of not only demonstrating the difference between the models for each season and RCP, but also the range of model sensitivity (i.e. how the different models predict future conditions under the same scenarios/greenhouse gas concentrations). The closer together the model outcomes are, it can be inferred that these projections have more certainty. The black stars within each vertical bar represent the results of the six RCM simulations selected for presentation in this report.

For 2040 projections (Figure 3-8 and Table 3-2), the average of all the models is similar between the different scenarios, indicated in the table and by the horizontal black line on each bar in the figure (averages between 0.7 and 1.0°C). The average projection for RCP8.5 is higher than the other RCPs. However, the range of model results for each scenario is quite different as seen by the size of the coloured bars and the numbers inside the parentheses in the table – some models project close to 0°C change under RCP2.6 and others over 2°C increase under RCP8.5. Although the models project a range of different outcomes, all the projections are for increases in temperature (i.e. >0°C) so there is high confidence that ongoing warming will be observed to the mid-century period.

For 2090 projections (Figure 3-9 and Table 3-2), there is a much larger range of model results within and between scenarios, indicated by the length of the coloured bars in the figure and the numbers in parentheses in the table. The average mean temperature of all the models (seasonal and annual), indicated by the horizontal black line, is also quite different between the scenarios (around 0.5°C for RCP2.6 for all seasons and annual, and around 2.5-3°C for RCP8.5 for all seasons and annual). This is a response of the models to the different greenhouse gas concentrations under each scenario by 2090 compared with similar concentrations between scenarios at 2040. The differences between the model results in the same scenario by 2090 indicates that there is less certainty about the actual value of projected temperatures by this time period. However, for RCP4.5, 6.0 and 8.5, all models project warming, so there is a high degree of certainty that warming will continue under those scenarios, and that higher greenhouse gas concentrations will result in more warming. For RCP2.6, one or two models project cooling by 2090, indicating that 2090 temperatures under this scenario are less certain whether it will be warmer or cooler than present, or about the same.

Table 3-2: Projected changes in seasonal and annual mean temperature (°C) between 1986-2005 and two climate change scenarios (RCP4.5 and RCP8.5) at two future time periods for Otago. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"). The values in each column represent the ensemble average, taken over 41 models (RCP8.5) and 37 models (RCP4.5). Bracketed values represent the range (5th percentile to 95th percentile) over all models within that ensemble. Changes averaged over the Otago region.

		Summer	Autumn	Winter	Spring	Annual
2040	RCP8.5	0.9 (0.3, 1.7)	1.0 (0.6, 1.5)	1.1 (0.7, 1.5)	0.8 (0.3, 1.3)	0.9 (0.6, 1.5)
	RCP4.5	0.8 (0.2, 1.4)	0.8 (0.3, 1.3)	0.9 (0.6, 1.4)	0.7 (0.3, 1.1)	0.8 (0.4, 1.2)
2090	RCP8.5	2.9 (1.8, 4.6)	2.9 (2.0, 4.3)	3.1 (2.3, 4.2)	2.5 (1.7, 3.4)	2.8 (2.1, 4.0)
	RCP4.5	1.2 (0.6, 2.6)	1.3 (0.8, 2.1)	1.5 (0.8, 2.2)	1.1 (0.6, 1.8)	1.3 (0.8, 2.1)

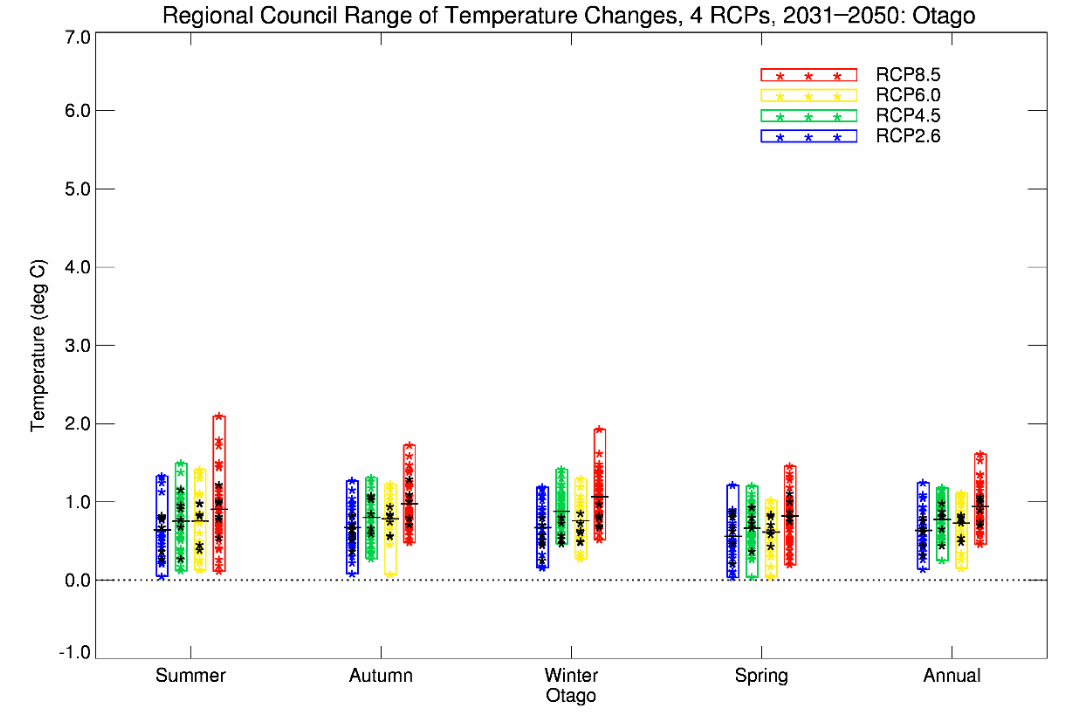


Figure 3-8: Projected seasonal and annual mean temperature change for Otago by 2040 (2031-2050). Coloured stars represent all models as derived by statistical downscaling. Black stars correspond to the six-model RCM-downscaling, and the horizontal bars are the average over all downscaled results (statistical and RCM).

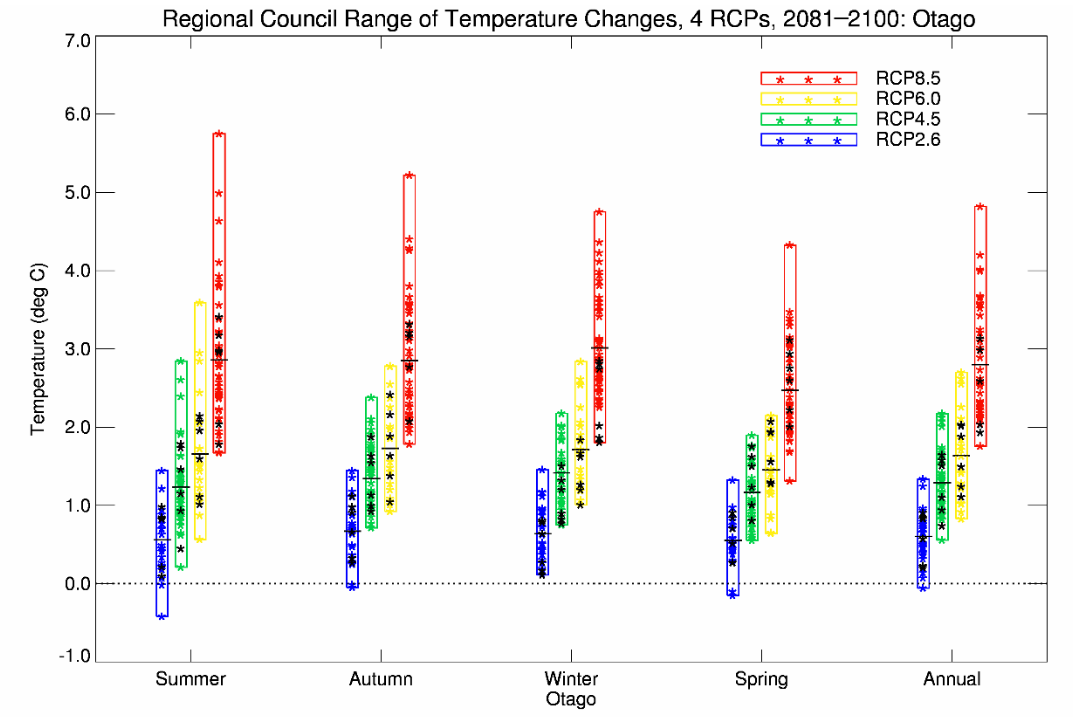


Figure 3-9: Projected seasonal and annual mean temperature change for Otago by 2090 (2081-2100). Coloured stars represent all models as derived by statistical downscaling. Black stars correspond to the six-model RCM-downscaling, and the horizontal bars are the average over all downscaled results (statistical and RCM).

3.2 Maximum temperature

Key messages

- Annual mean maximum temperature is projected to increase by 0.5-1.5°C by 2040 under RCP4.5 and RCP8.5.
- By 2090, annual mean maximum temperature increases of 1.0-2.0°C (RCP4.5) and 2.0-4.0°C (RCP8.5) are projected.
- Central and western parts of Otago are projected to observe a 4.0-5.0°C increase in summer mean maximum temperatures by 2090 under RCP8.5.

Maximum temperatures are generally recorded in the afternoon, and therefore are known as daytime temperatures. Present-day (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for mean maximum temperature are shown in this section. The present-day maps show annual and seasonal mean maximum temperature in units of degrees Celsius (°C) and the future projection maps show the change in mean temperature compared with the present day, in units of °C. Note that the present-day maps are on a different colour scale to the future projection maps.

Annual mean maximum temperatures range between 14-16°C for most coastal locations of Otago, compared to 16-18°C for much of the inland basins of Central and western Otago (Figure 3-10). For coastal areas of Otago, summer mean maximum temperatures range between 18-20°C, and winter mean maximum temperatures range between 10-12°C (Figure 3-12). For inland low-elevation locations, summer mean maximum temperatures range between 22-24°C, and winter mean maximum temperatures range between 8-10°C.

Annual mean maximum temperature is projected to increase by 0.5-1.5°C by 2040 under RCP4.5 and RCP8.5 (Figure 3-11). By 2090, annual mean maximum temperature increases of 1.0-2.0°C (RCP4.5) and 2.0-4.0°C (RCP8.5) are projected. Seasonal projections of mean maximum temperature change are shown for RCP4.5 by 2040 (Figure 3-13) and 2090 (Figure 3-15), and RCP8.5 by 2040 (Figure 3-14) and 2090 (Figure 3-16). By 2040 under RCP4.5, seasonal mean maximum temperatures are projected to increase by 0.5-1.5°C across much of Otago, and by 0.5-2.5°C under RCP8.5. By 2090 under RCP4.5, seasonal mean maximum temperatures are projected to increase by 1.0-3.0°C for most of Otago. Under RCP8.5 by 2090, seasonal mean maximum temperatures are projected to increase by 2.0-4.0°C for much of Otago. Notably, central and western parts of the region are projected to observe a 4.0-5.0°C increase in summer mean maximum temperatures by 2090 under RCP8.5.

Modelled seasonal and annual mean maximum temperature data have been generated for 16 Otago locations, and these are presented in Table 3-3.

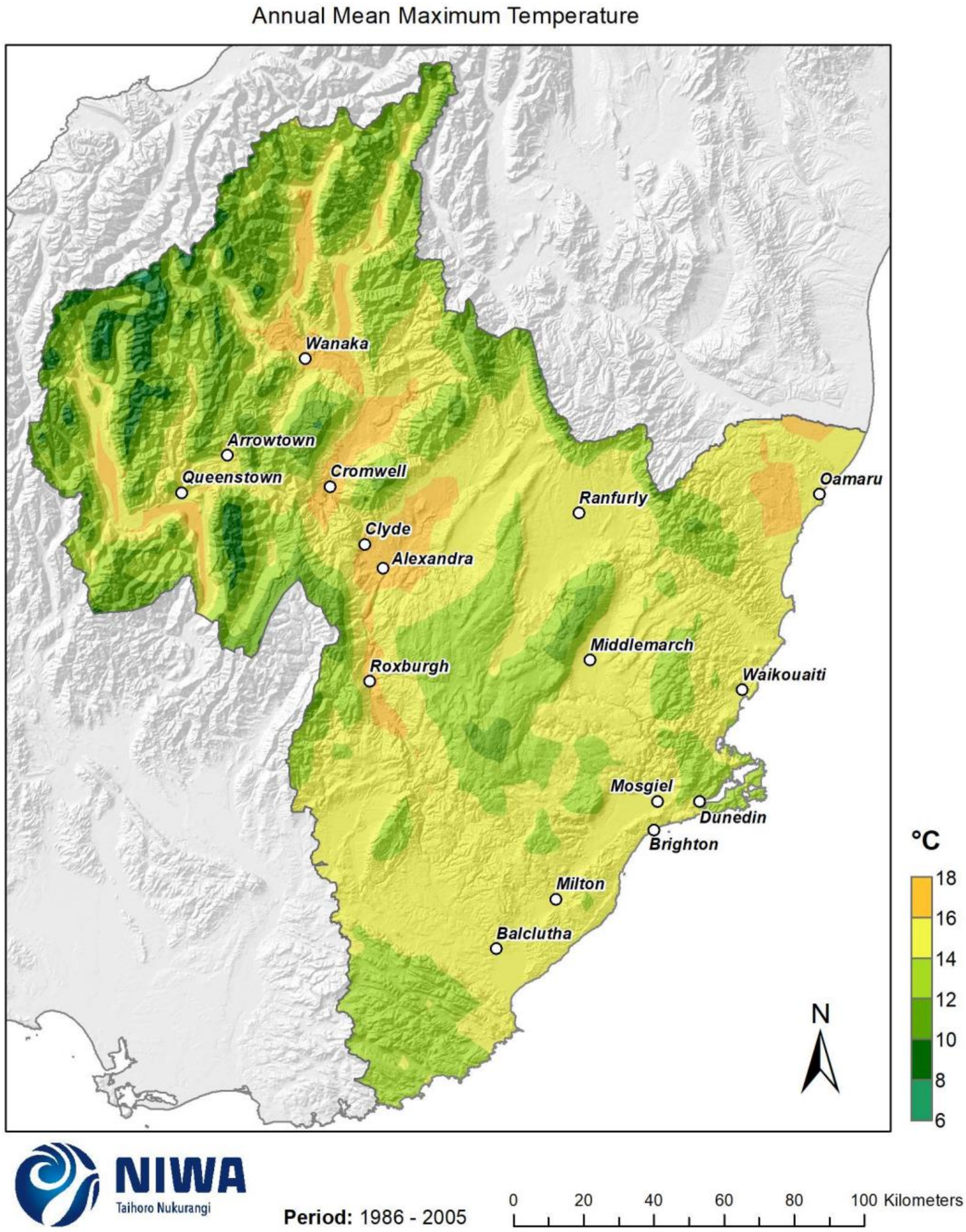


Figure 3-10: Modelled annual mean maximum temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

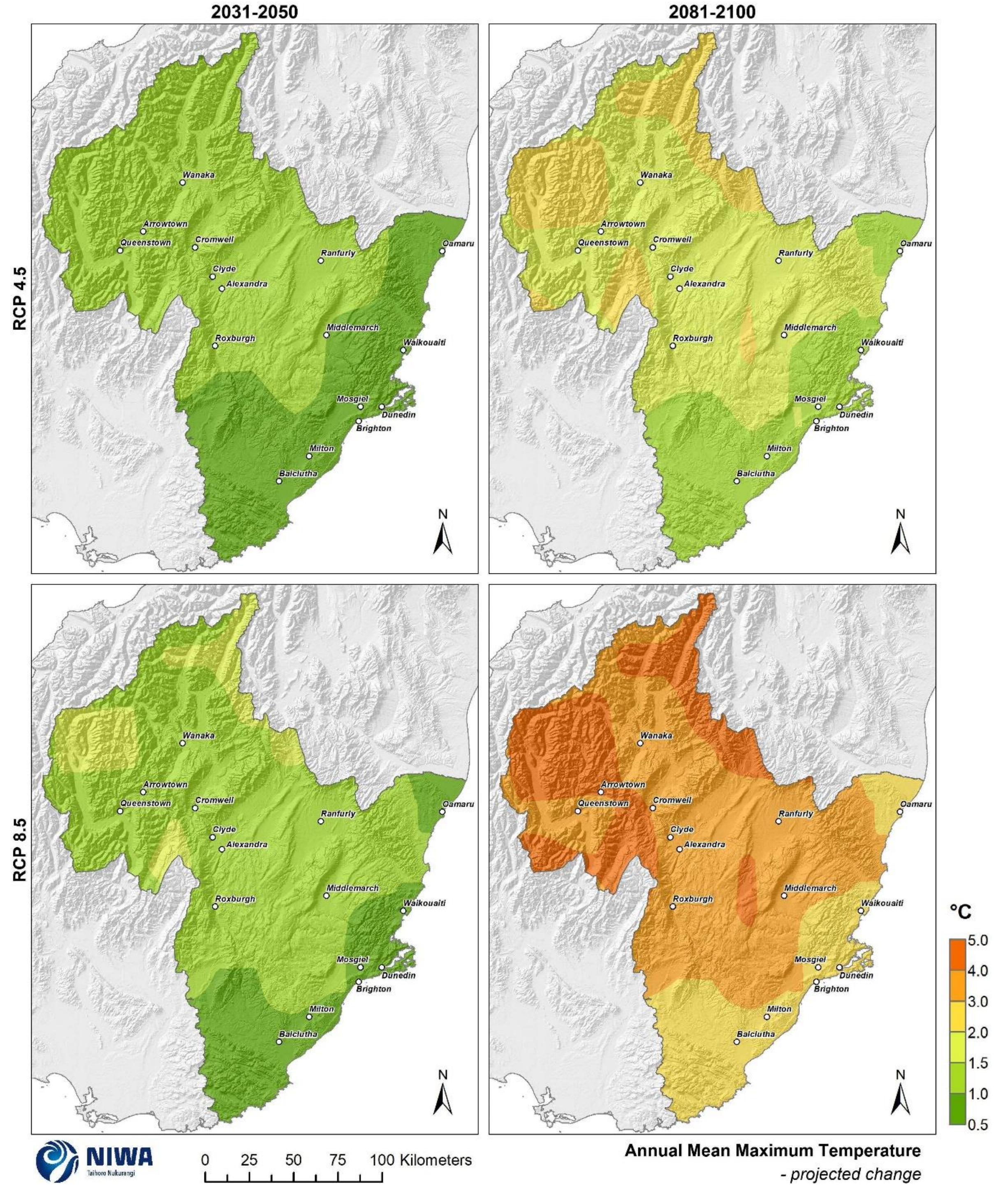


Figure 3-11: Projected annual mean maximum temperature changes by 2040 and 2090, under RCP4.5 and RCP8.5. Climate change scenarios: RCP4.5 (top panels) and RCP8.5 (bottom panels). Time periods: mid-century (2031-2050; "2040" – panels on left) and end-century (2081-2100; "2090" – panels on right). Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

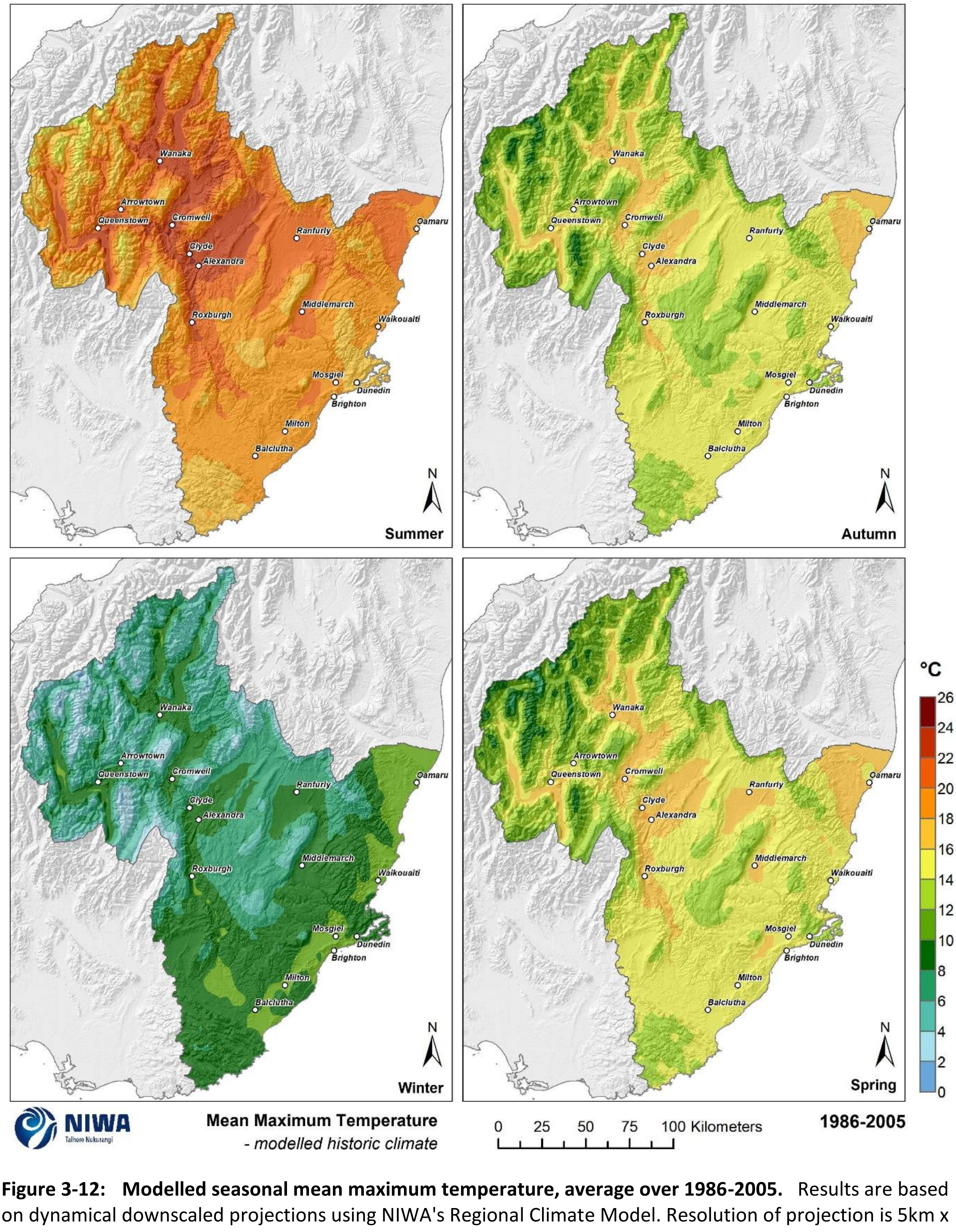


Figure 3-12: Modelled seasonal mean maximum temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

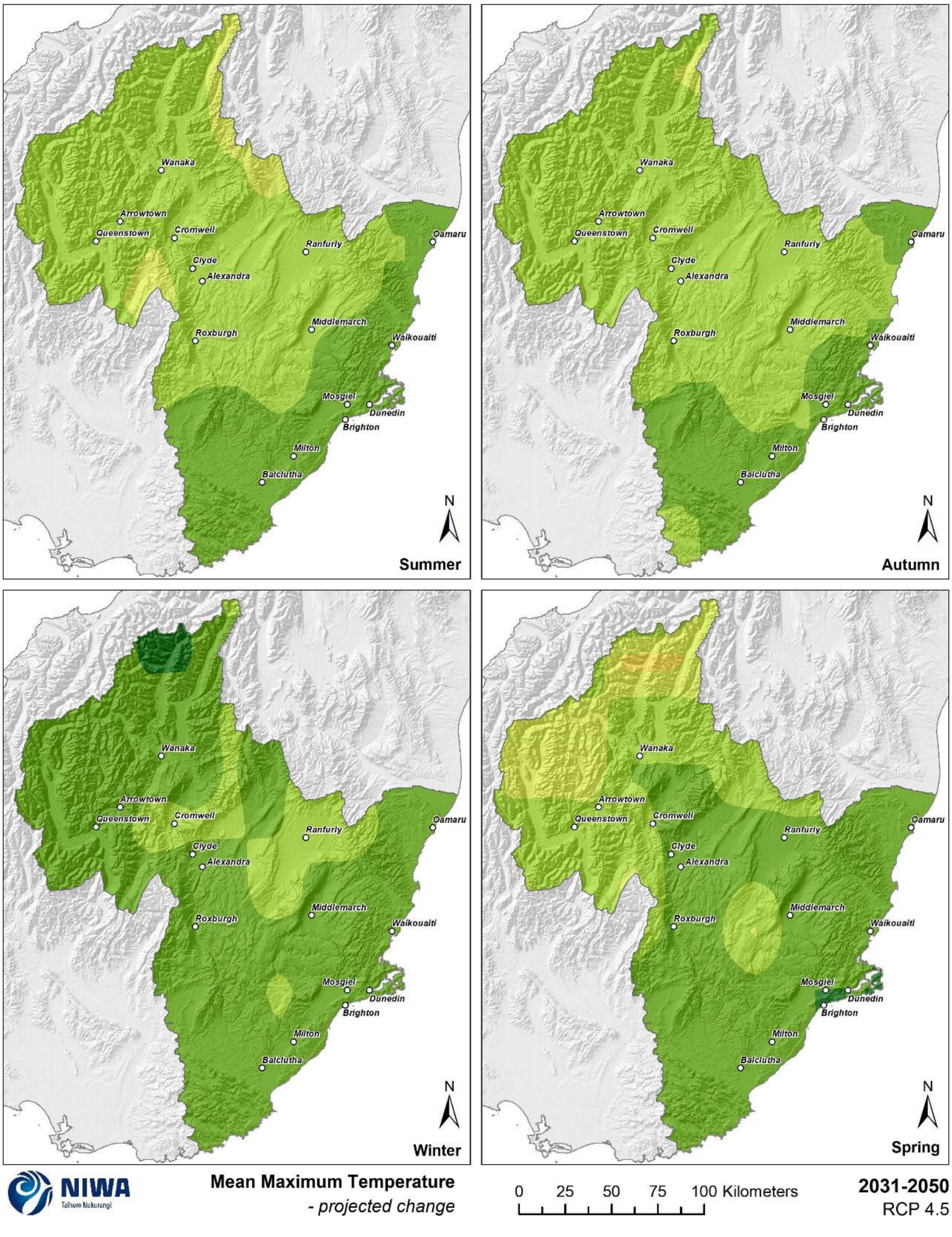


Figure 3-13: Projected seasonal mean maximum temperature changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

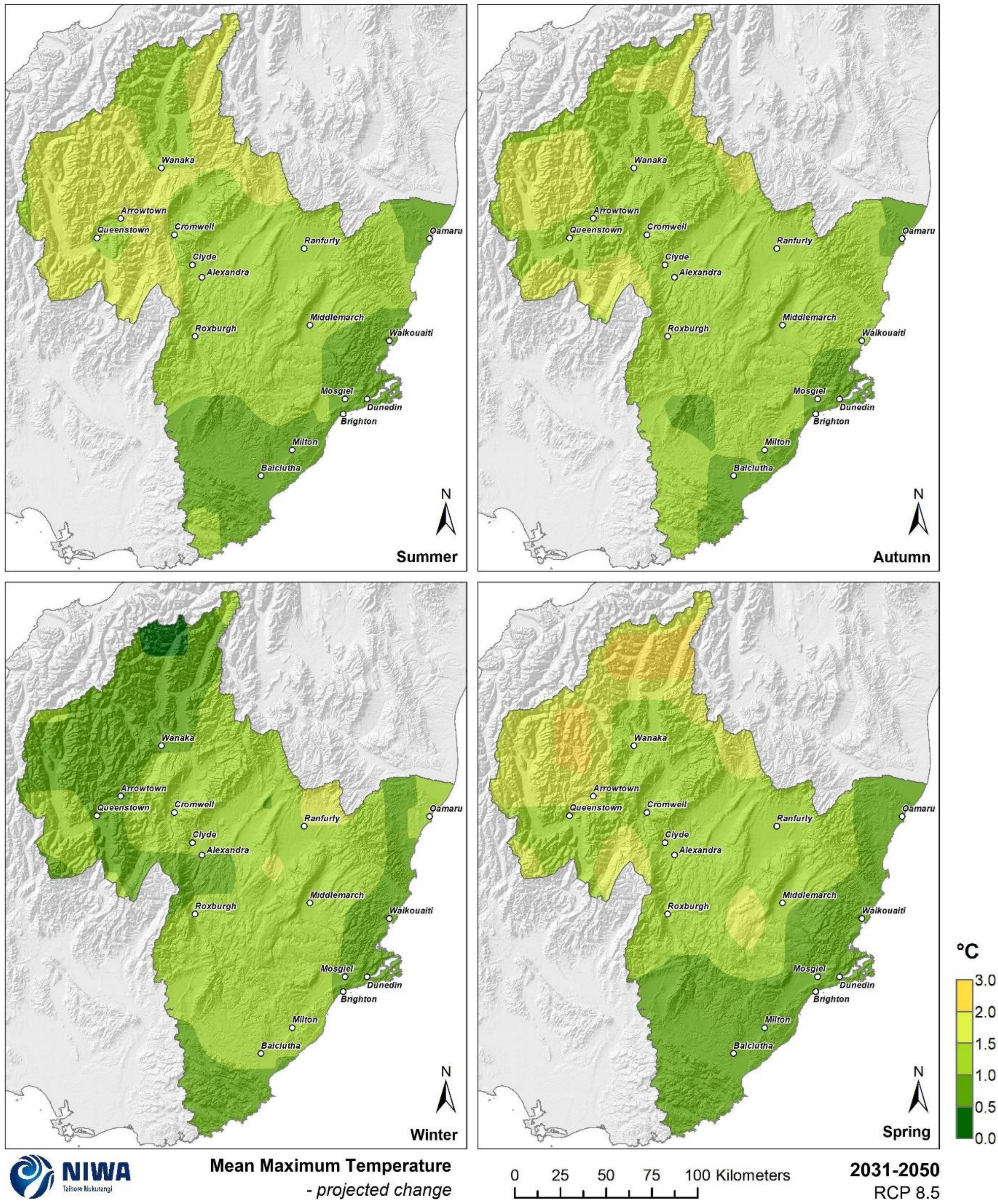


Figure 3-14: Projected seasonal mean maximum temperature changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

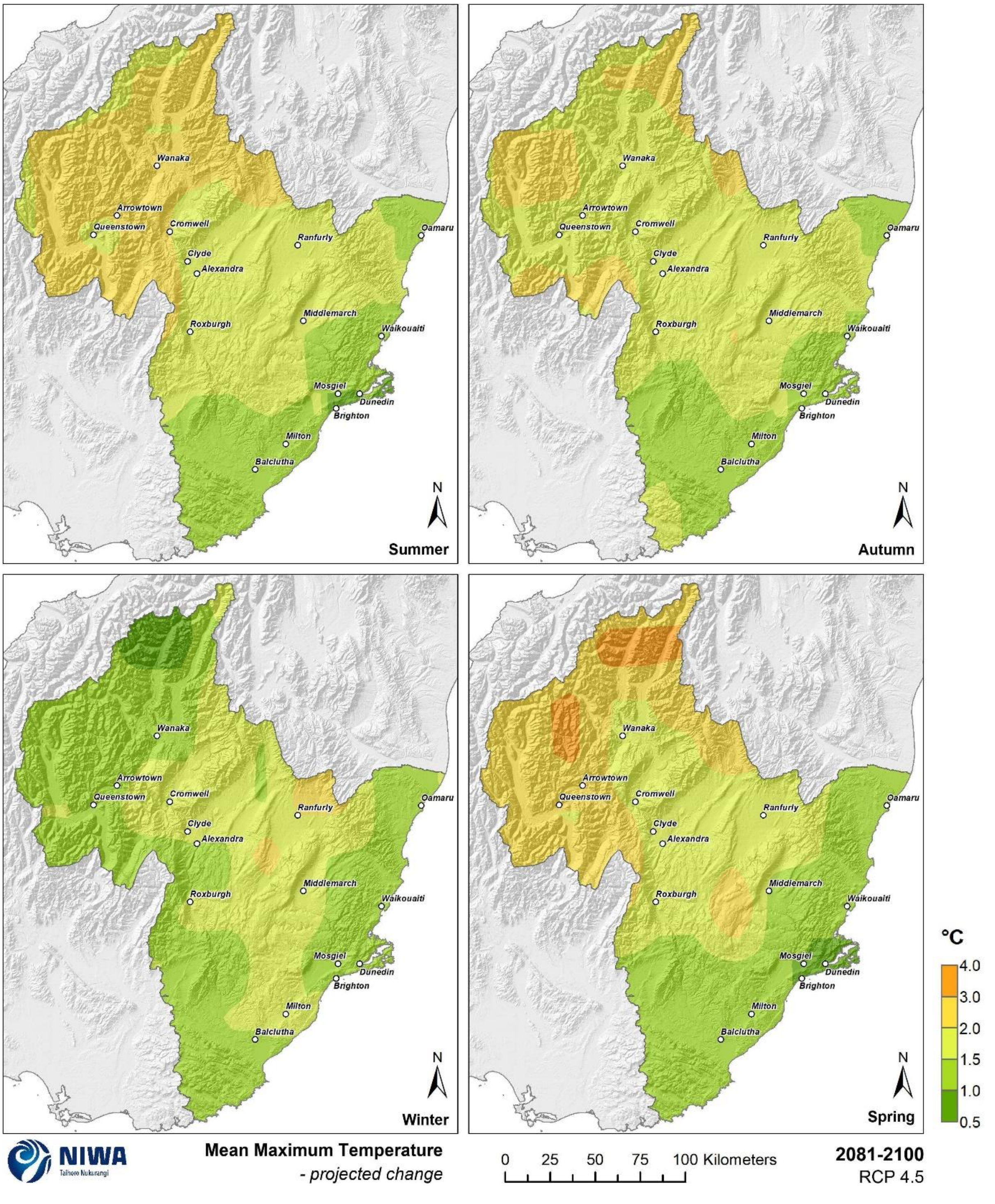


Figure 3-15: Projected seasonal mean maximum temperature changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

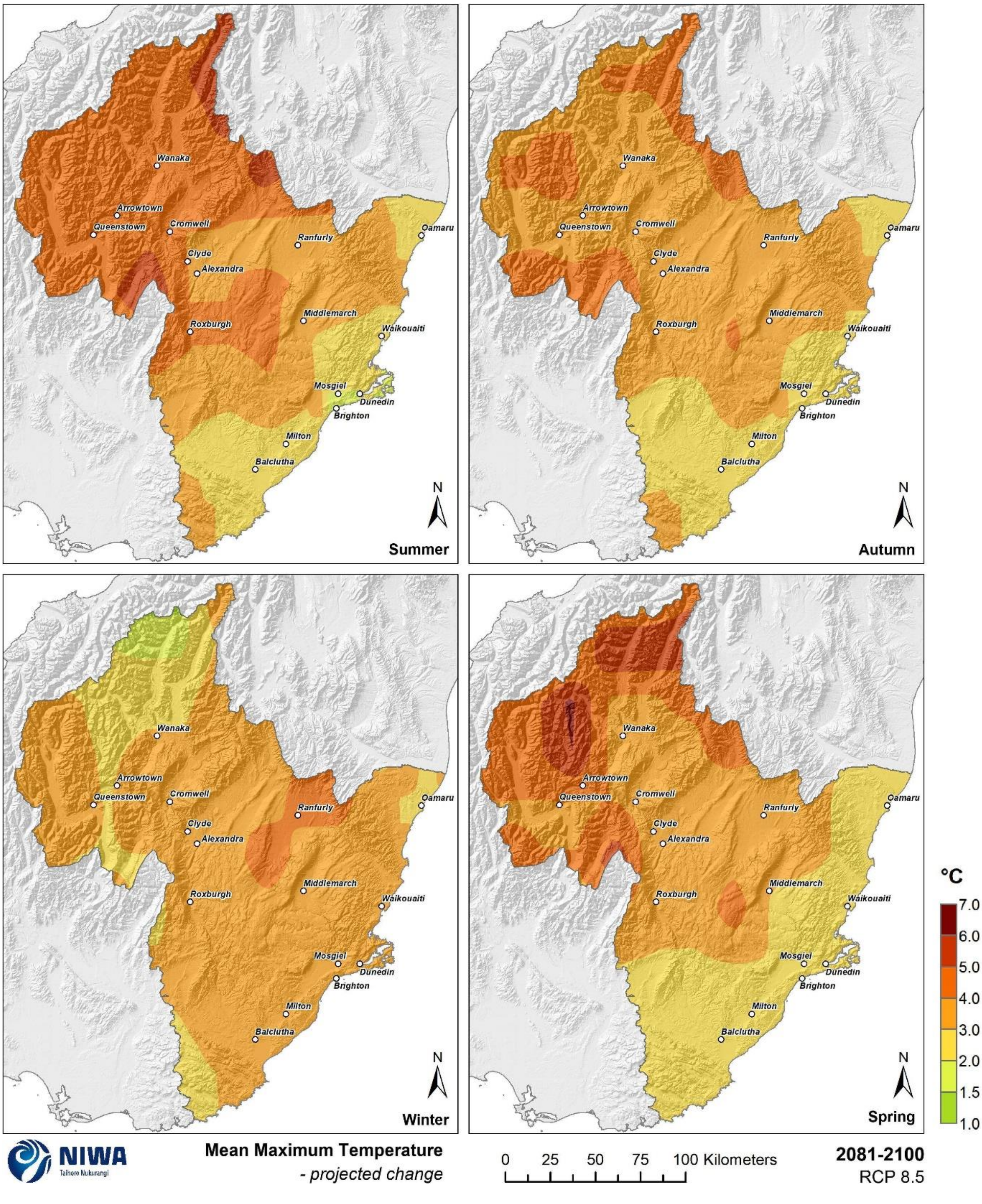


Figure 3-16: Projected seasonal mean maximum temperature changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 3-3: Modelled seasonal and annual mean maximum temperature for present and two climate change scenarios (RCP4.5 and RCP8.5) at two future time periods. Time periods: present (1986-2005), mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models. Annual ("Ann"); Seasons: summer ("Sum"), autumn ("Aut"), winter ("Win") and spring ("Spr").

	PRESENT				
	Sum	Aut	Win	Spr	Ann
Alexandra	23.9	17.2	9.5	17.9	17.1
Arrowtown	21.0	14.5	7.4	14.2	14.2
Balclutha	19.2	15.1	9.9	15.3	14.9
Brighton	17.8	14.8	10.2	14.3	14.3
Clyde	23.6	16.9	9.1	17.5	16.7
Cromwell	24.4	17.6	9.5	18.0	17.3
Dunedin	17.7	14.7	10.2	14.3	14.2
Middlemarch	21.3	15.9	9.9	16.4	15.8
Milton	19.6	15.5	10.3	15.7	15.3
Mosgiel	18.9	16.0	11.4	15.5	15.4
Oamaru	19.7	15.9	11.3	15.9	15.7
Queenstown	20.8	14.6	7.7	14.6	14.4
Ranfurly	21.6	15.5	8.3	16.1	15.3
Roxburgh	22.9	16.9	10.1	17.8	16.9
Waikouaiti	18.7	15.1	10.4	15.1	14.8
Wanaka	23.2	16.4	9.0	16.5	16.3

		2040					2090				
		Sum	Aut	Win	Spr	Ann	Sum	Aut	Win	Spr	Ann
Alexandra	RCP4.5	+1.3	+1.2	+0.9	+0.9	+1.1	+1.9	+1.7	+1.5	+1.6	+1.7
	RCP8.5	+1.3	+1.3	+1.0	+1.1	+1.2	+4.0	+3.5	+3.6	+3.3	+3.6
Arrowtown	RCP4.5	+1.3	+1.3	+0.7	+1.4	+1.2	+2.0	+1.9	+1.3	+2.5	+2.0
	RCP8.5	+1.5	+1.5	+0.8	+1.7	+1.4	+4.6	+3.9	+3.0	+4.7	+4.1
Balclutha	RCP4.5	+0.7	+0.9	+0.9	+0.6	+0.8	+1.2	+1.4	+1.5	+1.2	+1.3
	RCP8.5	+0.8	+1.0	+1.1	+0.8	+0.9	+2.5	+2.7	+3.3	+2.5	+2.8
Brighton	RCP4.5	+0.6	+0.7	+0.9	+0.5	+0.7	+1.0	+1.1	+1.4	+0.9	+1.1
	RCP8.5	+0.7	+0.8	+1.0	+0.7	+0.8	+2.0	+2.2	+3.1	+2.1	+2.4
Clyde	RCP4.5	+1.3	+1.2	+0.9	+0.9	+1.1	+1.8	+1.7	+1.6	+1.7	+1.7
	RCP8.5	+1.3	+1.3	+1.1	+1.1	+1.2	+4.0	+3.5	+3.7	+3.4	+3.7
Cromwell	RCP4.5	+1.4	+1.2	+1.1	+1.0	+1.2	+2.0	+1.8	+1.8	+1.9	+1.9
	RCP8.5	+1.4	+1.4	+1.2	+1.3	+1.4	+4.3	+3.6	+3.9	+3.7	+3.9
Dunedin	RCP4.5	+0.6	+0.7	+0.9	+0.5	+0.7	+1.0	+1.1	+1.4	+0.9	+1.1
	RCP8.5	+0.7	+0.8	+1.0	+0.7	+0.8	+2.0	+2.2	+3.1	+2.1	+2.4
Middlemarch	RCP4.5	+1.1	+1.0	+0.9	+0.8	+1.0	+1.6	+1.6	+1.6	+1.4	+1.6
	RCP8.5	+1.1	+1.2	+1.1	+1.1	+1.1	+3.3	+3.2	+3.5	+3.0	+3.3
Milton	RCP4.5	+0.7	+0.9	+0.9	+0.7	+0.8	+1.2	+1.4	+1.5	+1.2	+1.3
	RCP8.5	+0.8	+1.0	+1.1	+0.9	+1.0	+2.5	+2.8	+3.4	+2.6	+2.9
Mosgiel	RCP4.5	+0.6	+0.7	+0.9	+0.5	+0.7	+1.0	+1.1	+1.4	+0.9	+1.1
	RCP8.5	+0.7	+0.8	+1.0	+0.7	+0.8	+2.0	+2.2	+3.1	+2.1	+2.4
Oamaru	RCP4.5	+0.6	+0.9	+0.9	+0.6	+0.8	+1.1	+1.3	+1.5	+1.0	+1.2
	RCP8.5	+0.7	+1.0	+1.0	+0.8	+0.9	+2.1	+2.6	+3.0	+2.1	+2.5
Queenstown	RCP4.5	+1.3	+1.2	+0.9	+1.2	+1.2	+2.0	+1.9	+1.4	+2.1	+1.9
	RCP8.5	+1.5	+1.5	+0.9	+1.4	+1.3	+4.4	+3.9	+3.1	+4.0	+3.9
Ranfurly	RCP4.5	+1.2	+1.1	+1.2	+0.9	+1.1	+1.8	+1.7	+1.9	+1.7	+1.8
	RCP8.5	+1.3	+1.2	+1.4	+1.2	+1.3	+3.8	+3.5	+4.1	+3.3	+3.7
Roxburgh	RCP4.5	+1.2	+1.1	+0.9	+0.9	+1.1	+1.9	+1.6	+1.5	+1.6	+1.7
	RCP8.5	+1.3	+1.2	+1.1	+1.1	+1.2	+4.1	+3.4	+3.4	+3.3	+3.6
Waikouaiti	RCP4.5	+0.8	+1.0	+0.9	+0.7	+0.8	+1.3	+1.5	+1.4	+1.1	+1.4
	RCP8.5	+0.9	+1.0	+1.0	+0.8	+0.9	+2.7	+3.0	+3.1	+2.5	+2.8
Wanaka	RCP4.5	+1.4	+1.1	+0.8	+1.0	+1.1	+2.0	+1.7	+1.4	+1.9	+1.8
	RCP8.5	+1.5	+1.3	+1.0	+1.3	+1.3	+4.5	+3.5	+3.1	+3.7	+3.7

3.3 Minimum temperature

Key messages

- Annual mean minimum temperature is projected to increase by between 0-1.0°C by 2040 under RCP4.5 and RCP8.5.
- By 2090, annual mean minimum temperature increases of 0.5-1.0°C (RCP4.5) and 1.0-2.0°C (RCP8.5) are projected.
- Seasonal mean minimum temperatures are projected to increase by 0.5-2.5°C for much of Otago (by 2090 under RCP8.5).
- Projected increases in mean minimum temperatures are not as high as increases in mean maximum temperatures, leading to a projected increase in the diurnal temperature range.

Minimum temperatures are generally recorded in the early hours of the morning, and therefore are known as night time temperatures. Present-day (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for mean minimum temperature are shown in this section. The present-day maps show annual and seasonal mean minimum temperature in units of degrees Celsius (°C) and the future projection maps show the change in mean minimum temperature compared with the present day, in units of °C. Note that the present-day maps are on a different colour scale to the future projection maps.

Annual mean minimum temperatures range between 2-6°C for most low-elevation locations of Otago, with lowest annual mean minimum temperatures observed in mountainous terrain (Figure 3-17). For coastal areas of Otago, summer mean minimum temperatures range between 8-10°C, and winter mean minimum temperatures range between 0-4°C (Figure 3-19). For inland low-elevation locations, summer mean minimum temperatures range between 6-10°C, and winter mean minimum temperatures range from just below freezing (-2°C) to just above freezing (2°C).

Annual mean minimum temperature is projected to increase by between 0-1.0°C by 2040 under RCP4.5 and RCP8.5 (Figure 3-18). By 2090, annual mean minimum temperature increases of 0.5-1.0°C (RCP4.5) and 1.0-2.0°C (RCP8.5) are projected. Seasonal projections of mean minimum temperature change are shown for RCP4.5 by 2040 (Figure 3-20) and 2090 (Figure 3-22), and RCP8.5 by 2040 (Figure 3-21) and 2090 (Figure 3-23). By 2040 under RCP4.5 and RCP8.5, seasonal mean minimum temperatures are projected to increase by between 0-1.0°C across Otago, with the larger increases expected inland. By 2090 under RCP4.5, seasonal mean minimum temperatures are projected to increase by 0.5-1.0°C for most of Otago, and up to 1.5°C inland. Under RCP8.5, seasonal mean minimum temperatures are projected to increase by 0.5-2.5°C for much of Otago, with larger increases up to 3°C at high elevations. Notably, increases in mean minimum temperatures are not projected to be as high as increases in mean maximum temperatures, leading to a projected increase in the diurnal temperature range (i.e. the difference in temperature between daytime and night time temperature).

Modelled seasonal and annual mean minimum temperature data have been generated for 16 Otago locations, and these are presented in Table 3-4.

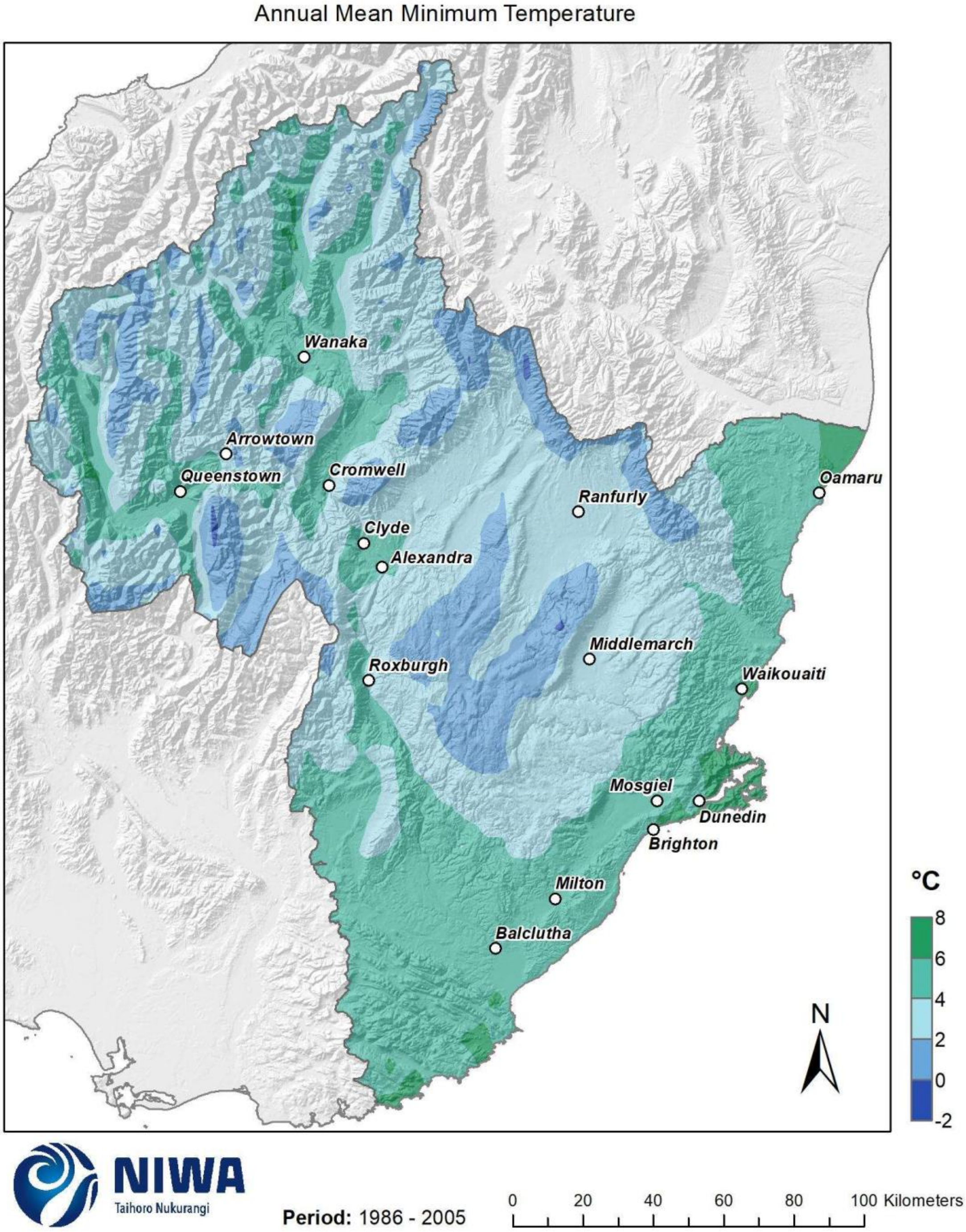


Figure 3-17: Modelled annual mean minimum temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

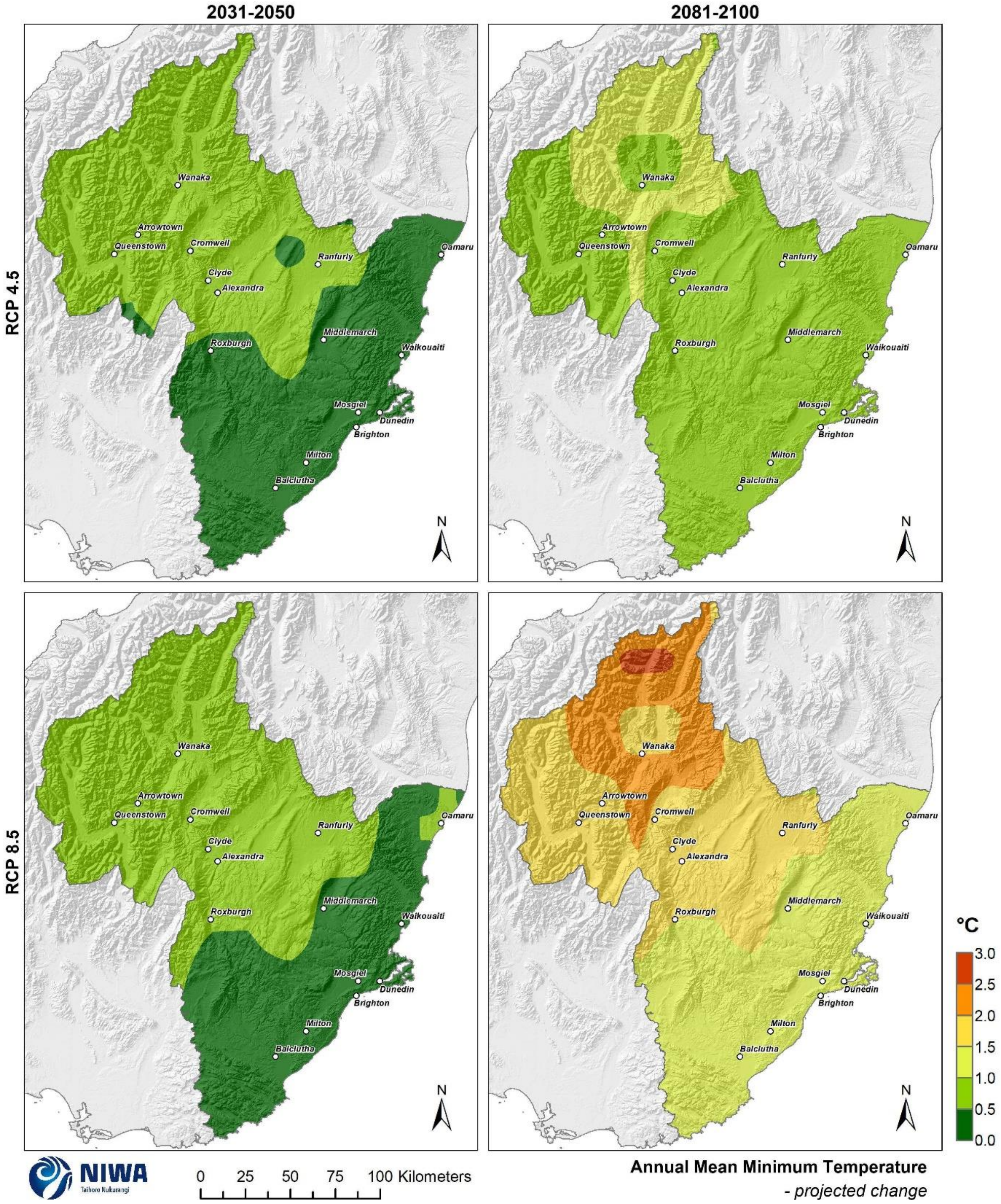


Figure 3-18: Projected annual mean minimum temperature changes by 2040 and 2090, under RCP4.5 and RCP8.5. Climate change scenarios: RCP4.5 (top panels) and RCP8.5 (bottom panels). Time periods: mid-century (2031-2050; "2040" – panels on left) and end-century (2081-2100; "2090" – panels on right). Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

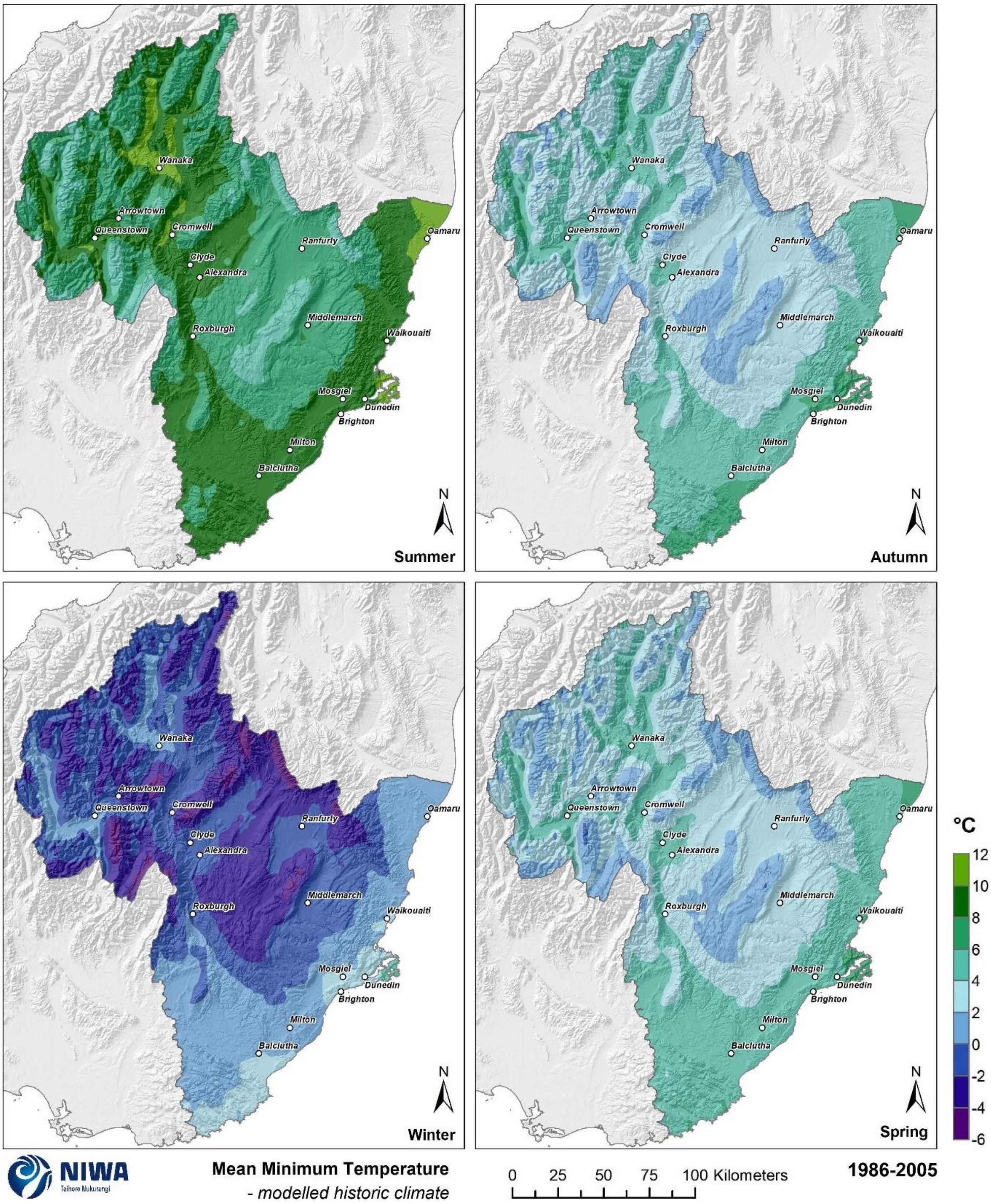


Figure 3-19: Modelled seasonal mean minimum temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

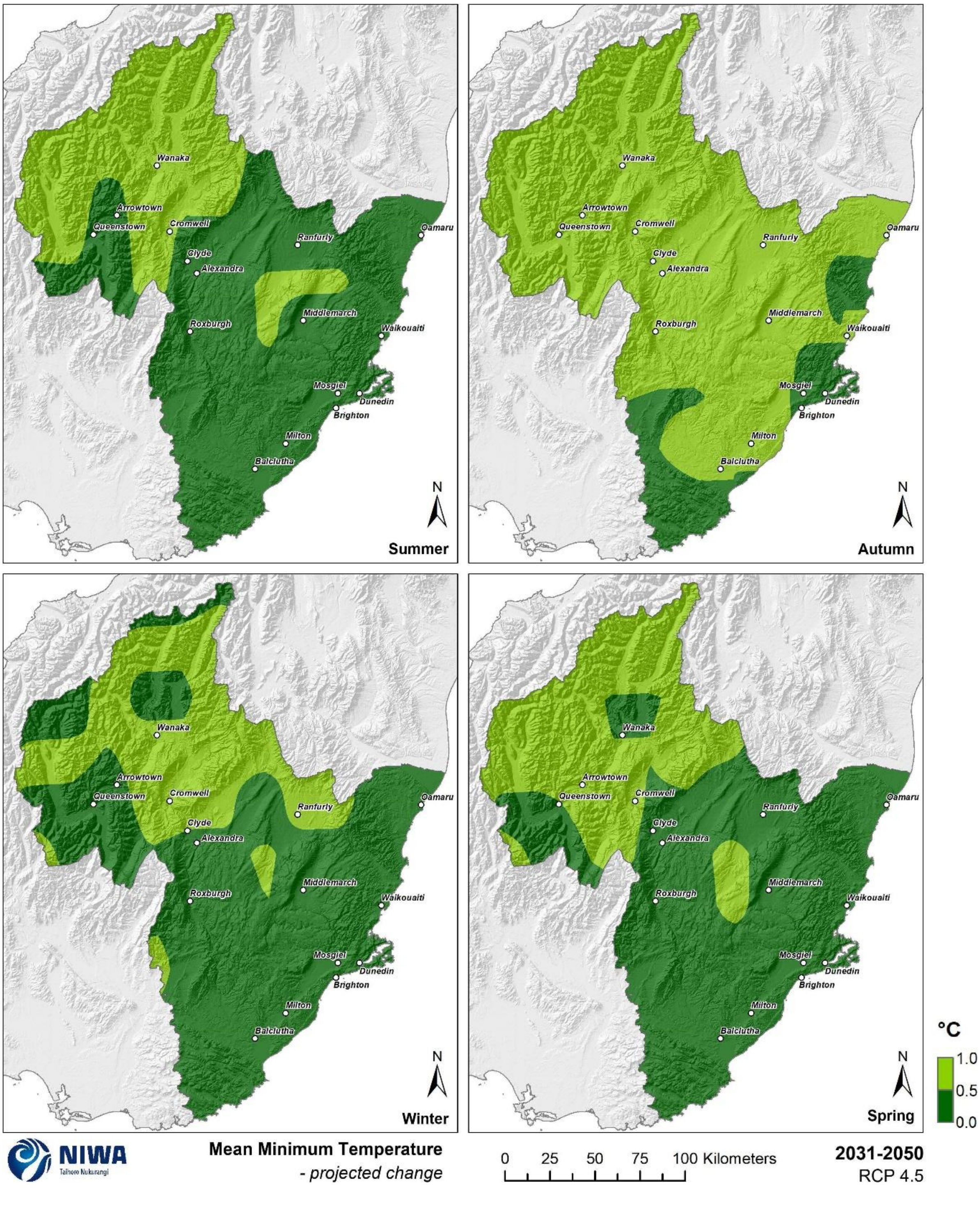


Figure 3-20: Projected seasonal mean minimum temperature changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

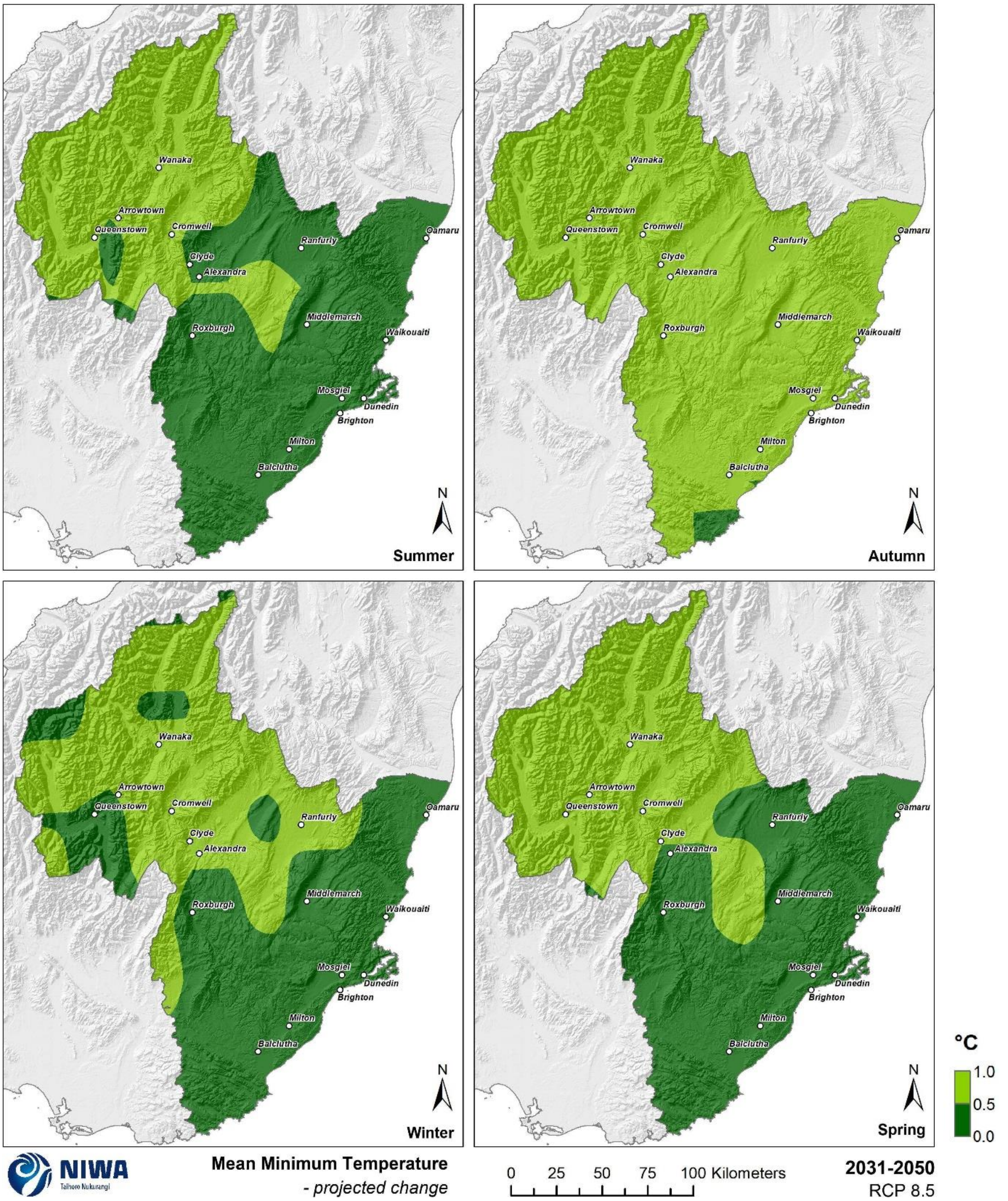


Figure 3-21: Projected seasonal mean minimum temperature changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

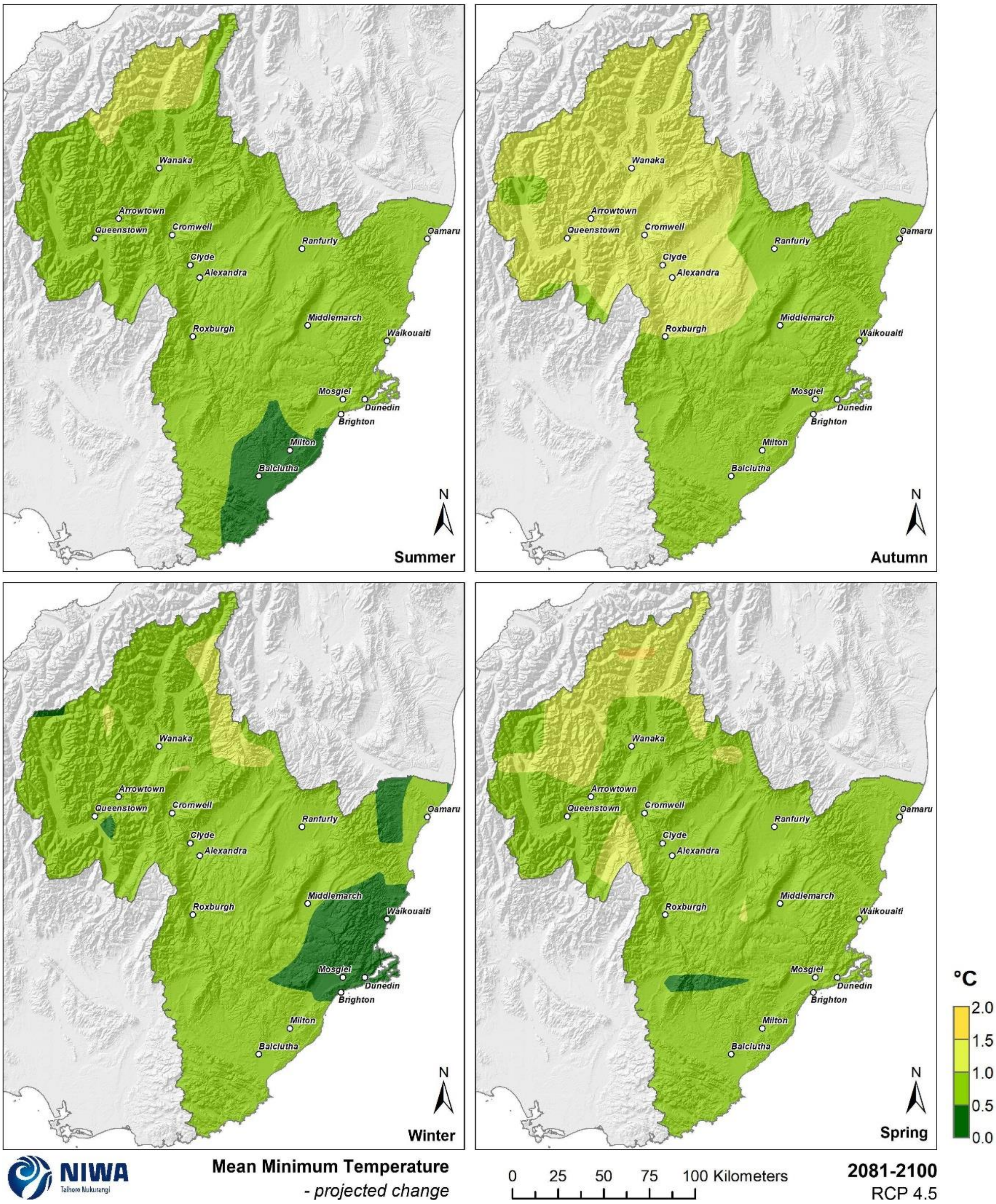


Figure 3-22: Projected seasonal mean minimum temperature changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

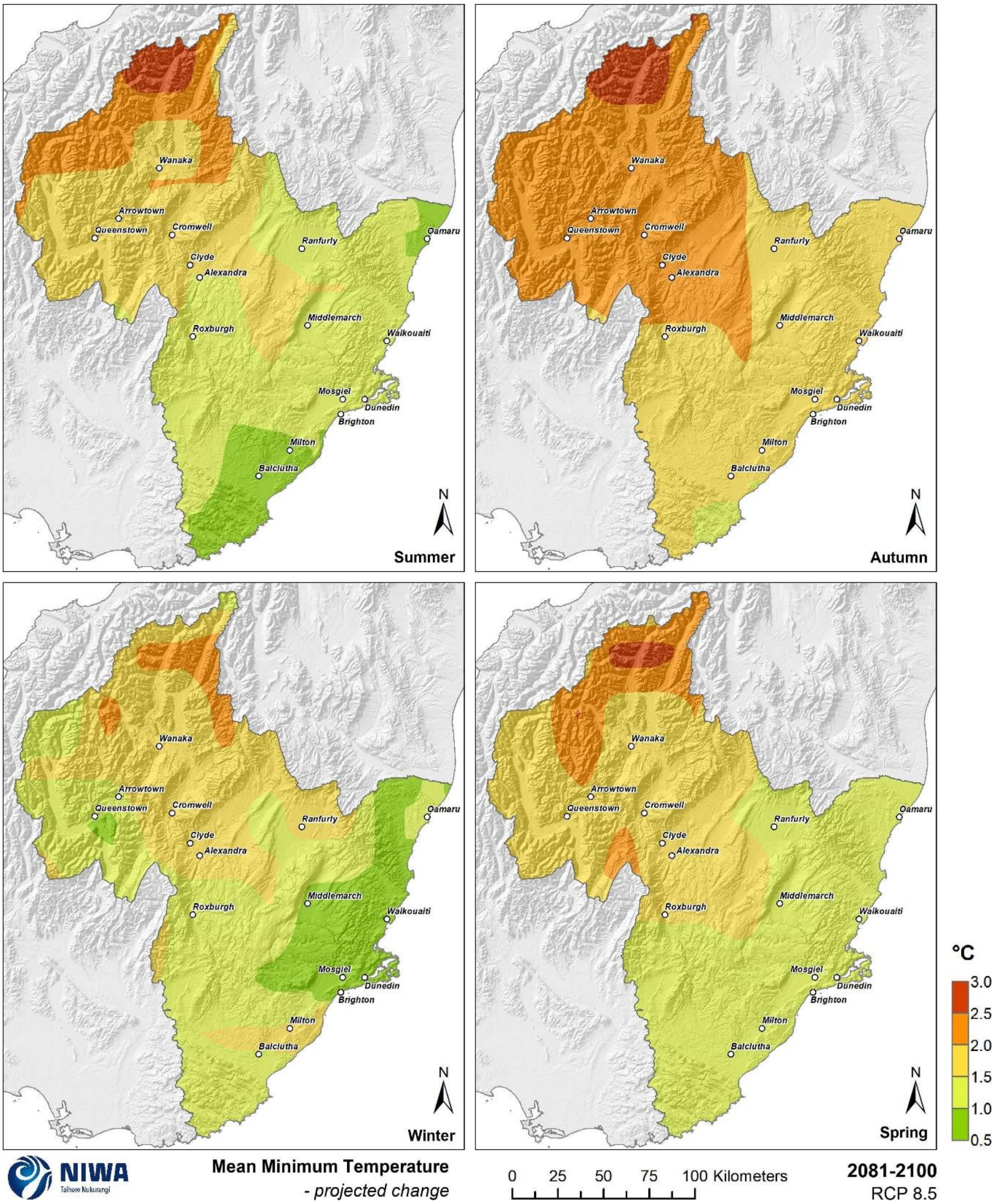


Figure 3-23: Projected seasonal mean minimum temperature changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 3-4: Modelled seasonal and annual mean minimum temperature for present and two climate change scenarios (RCP4.5 and RCP8.5) at two future time periods. Time periods: present (1986-2005), mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models. Annual ("Ann"); Seasons: summer ("Sum"), autumn ("Aut"), winter ("Win") and spring ("Spr").

	PRESENT				
	Sum	Aut	Win	Spr	Ann
Alexandra	9.7	4.4	-0.7	4.8	4.5
Arrowtown	8.8	4.3	-0.9	3.8	4.0
Balclutha	9.1	5.6	1.8	5.4	5.4
Brighton	8.3	5.6	2.0	4.8	5.2
Clyde	9.6	4.3	-0.8	4.7	4.4
Cromwell	10.4	5.2	-0.1	5.3	5.2
Dunedin	9.3	6.6	3.0	5.7	6.1
Middlemarch	8.0	3.7	-0.5	3.8	3.7
Milton	9.2	5.6	1.7	5.4	5.4
Mosgiel	8.9	6.2	2.6	5.3	5.7
Oamaru	10.1	5.9	1.2	5.6	5.7
Queenstown	8.6	4.5	-0.4	3.9	4.2
Ranfurly	7.6	3.3	-1.8	3.2	3.0
Roxburgh	9.4	4.8	0.2	4.7	4.8
Waikouaiti	9.3	5.6	1.6	5.5	5.5
Wanaka	10.4	5.6	0.1	5.1	5.3

		2040					2090				
		Sum	Aut	Win	Spr	Ann	Sum	Aut	Win	Spr	Ann
Alexandra	RCP4.5	+0.5	+0.8	+0.5	+0.4	+0.6	+0.7	+1.2	+0.8	+0.8	+0.9
	RCP8.5	+0.5	+0.9	+0.6	+0.5	+0.6	+1.5	+2.3	+1.6	+1.6	+1.8
Arrowtown	RCP4.5	+0.5	+0.7	+0.4	+0.5	+0.6	+0.8	+1.1	+0.7	+1.0	+0.9
	RCP8.5	+0.5	+0.8	+0.5	+0.6	+0.7	+1.7	+2.2	+1.4	+2.0	+1.8
Balclutha	RCP4.5	+0.3	+0.5	+0.4	+0.4	+0.4	+0.5	+0.9	+0.7	+0.6	+0.7
	RCP8.5	+0.2	+0.6	+0.4	+0.4	+0.4	+0.9	+1.7	+1.5	+1.2	+1.3
Brighton	RCP4.5	+0.3	+0.4	+0.2	+0.3	+0.3	+0.6	+0.8	+0.4	+0.6	+0.6
	RCP8.5	+0.3	+0.5	+0.2	+0.3	+0.3	+1.2	+1.6	+0.8	+1.1	+1.2
Clyde	RCP4.5	+0.5	+0.8	+0.5	+0.5	+0.6	+0.7	+1.1	+0.9	+0.8	+0.9
	RCP8.5	+0.5	+0.9	+0.6	+0.5	+0.6	+1.6	+2.3	+1.7	+1.7	+1.8
Cromwell	RCP4.5	+0.5	+0.8	+0.6	+0.5	+0.6	+0.8	+1.1	+1.0	+0.9	+1.0
	RCP8.5	+0.5	+0.9	+0.7	+0.6	+0.7	+1.8	+2.3	+1.8	+1.9	+2.0
Dunedin	RCP4.5	+0.3	+0.4	+0.2	+0.3	+0.3	+0.6	+0.8	+0.4	+0.6	+0.6
	RCP8.5	+0.3	+0.5	+0.2	+0.3	+0.3	+1.2	+1.6	+0.8	+1.1	+1.2
Middlemarch	RCP4.5	+0.4	+0.5	+0.3	+0.4	+0.4	+0.7	+0.8	+0.5	+0.6	+0.7
	RCP8.5	+0.4	+0.6	+0.4	+0.4	+0.4	+1.3	+1.6	+0.9	+1.2	+1.3
Milton	RCP4.5	+0.3	+0.5	+0.4	+0.4	+0.4	+0.5	+0.9	+0.7	+0.6	+0.7
	RCP8.5	+0.3	+0.6	+0.4	+0.4	+0.4	+0.9	+1.8	+1.6	+1.2	+1.4
Mosgiel	RCP4.5	+0.3	+0.4	+0.2	+0.3	+0.3	+0.6	+0.8	+0.4	+0.6	+0.6
	RCP8.5	+0.3	+0.5	+0.2	+0.3	+0.3	+1.2	+1.6	+0.8	+1.1	+1.2
Oamaru	RCP4.5	+0.3	+0.6	+0.4	+0.3	+0.4	+0.6	+1.0	+0.7	+0.6	+0.7
	RCP8.5	+0.3	+0.7	+0.5	+0.4	+0.5	+1.0	+1.8	+1.1	+1.3	+1.3
Queenstown	RCP4.5	+0.5	+0.7	+0.4	+0.5	+0.5	+0.8	+1.1	+0.6	+0.9	+0.8
	RCP8.5	+0.5	+0.8	+0.4	+0.6	+0.6	+1.7	+2.2	+1.0	+1.8	+1.7
Ranfurly	RCP4.5	+0.4	+0.6	+0.5	+0.4	+0.5	+0.7	+0.9	+0.8	+0.7	+0.8
	RCP8.5	+0.4	+0.7	+0.6	+0.4	+0.6	+1.3	+1.8	+1.6	+1.3	+1.6
Roxburgh	RCP4.5	+0.4	+0.7	+0.4	+0.4	+0.5	+0.6	+1.0	+0.6	+0.8	+0.8
	RCP8.5	+0.4	+0.7	+0.5	+0.4	+0.5	+1.4	+1.9	+1.2	+1.5	+1.5
Waikouaiti	RCP4.5	+0.4	+0.5	+0.2	+0.3	+0.4	+0.6	+0.9	+0.4	+0.6	+0.6
	RCP8.5	+0.4	+0.6	+0.2	+0.3	+0.4	+1.2	+1.8	+0.7	+1.1	+1.2
Wanaka	RCP4.5	+0.6	+0.7	+0.6	+0.5	+0.6	+1.0	+1.1	+0.9	+0.9	+1.0
	RCP8.5	+0.6	+0.9	+0.7	+0.6	+0.7	+2.0	+2.3	+1.9	+1.8	+2.0

3.4 Extreme hot days

Key messages

- Parts of Central Otago are projected to observe a considerable increase in annual extreme hot days of 30-40 days per year (by 2090 under RCP8.5).
- Most remaining inland areas of Otago are projected to observe an increase of 10-30 hot days per year (by 2090 under RCP8.5).
- Extreme hot days are projected to remain a relatively infrequent occurrence for coastal and southernmost parts of Otago, with increases of between 0.1-4 days.

In this report, an extreme hot day is considered to occur when the maximum temperature is above 30°C. Present-day (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for extreme hot days are shown in this section. The present-day maps show annual average numbers of extreme hot days and the future projection maps show the change in the annual number of extreme hot days compared with present. Note that the present-day maps are on a different colour scale to the future projection maps.

At present, extreme hot days occur most regularly in parts of Central Otago about Alexandra, Cromwell and Clyde. Here, the annual number of extreme hot days averages 8-10 days per year (Figure 3-24). For the remainder of Otago, extreme hot days are relatively infrequent, with an average annual occurrence of between 0.1-4 days.

In the future, extreme hot days are projected to remain a relatively infrequent occurrence for coastal and southernmost parts of Otago, with increases of between 0.1-4 days under both time periods and scenarios (Figure 3-25). However, this is in stark contrast to inland parts of Otago, which are projected to observe a considerable increase in the future number of extreme hot days, particularly by 2090. By 2040, 6-10 more extreme hot days are projected for parts of Central Otago under RCP4.5 and RCP8.5. By 2090 under RCP4.5, 10-20 more extreme hot days per year are projected for parts of Central Otago, and 30-40 more extreme hot days per year under RCP8.5. Most remaining inland areas of Otago are projected to observe an increase of 6-10 extreme hot days under RCP4.5 by 2090 and 10-30 extreme hot days per year under RCP8.5 by 2090.

Modelled annual extreme hot days data have been generated for 16 Otago locations, and these are presented in Table 3-5. At present, Dunedin observes an average of 0.2 extreme hot days per year (i.e. on average, one extreme hot day every five years). By 2040 under RCP4.5 Dunedin is projected to observe 0.5 extreme hot days (i.e. on average, one extreme hot day every two years). By 2090 under RCP8.5, the city is projected to observe an average of 1.8 extreme hot days per year. In Cromwell, the town presently observes an average of 9.8 extreme hot days per year. This is projected to increase to between an average of 18.6 extreme hot days per year (by 2040 under RCP4.5) and 47.1 extreme hot days per year (by 2090 under RCP8.5).

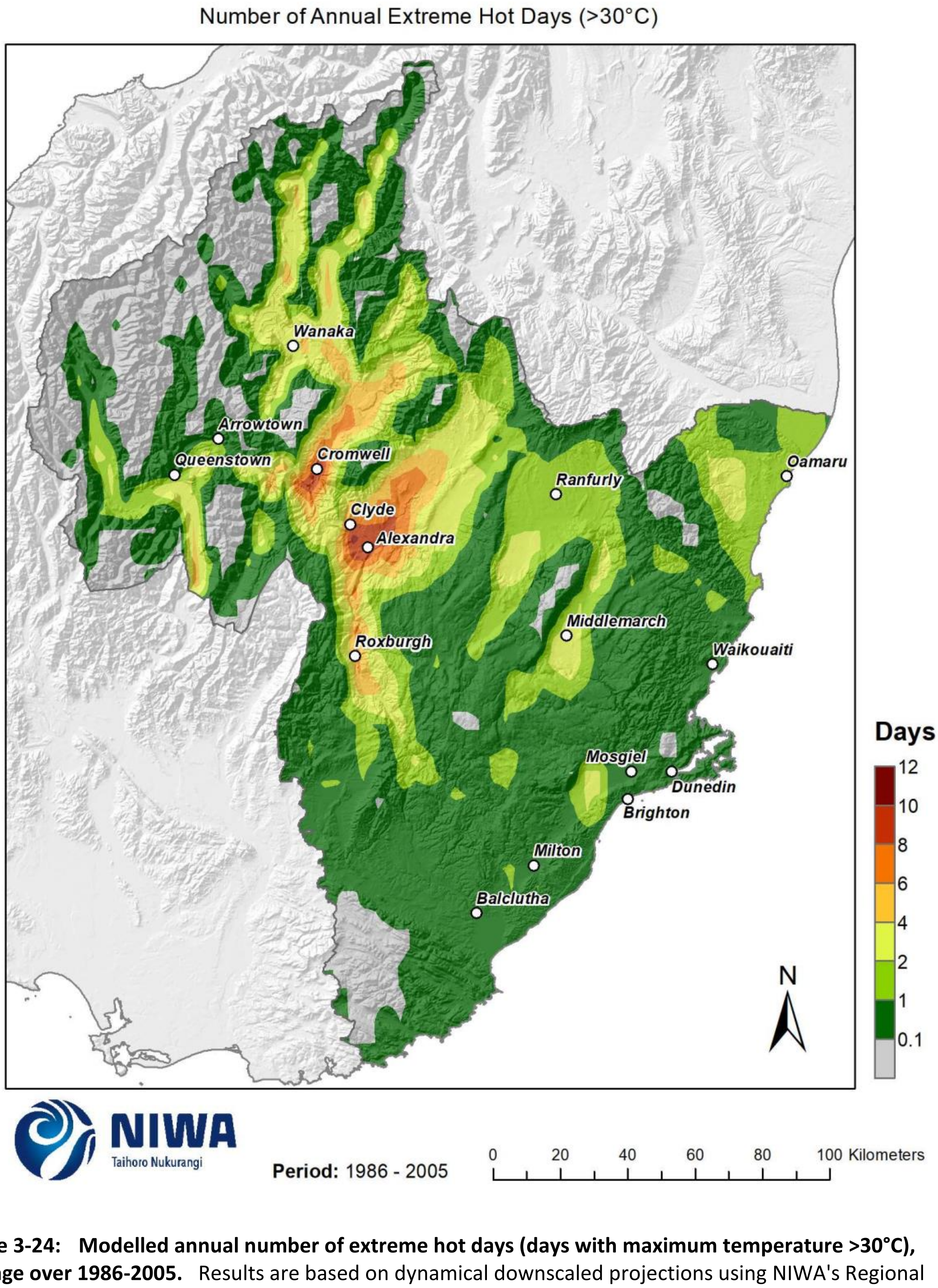


Figure 3-24: Modelled annual number of extreme hot days (days with maximum temperature >30°C), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

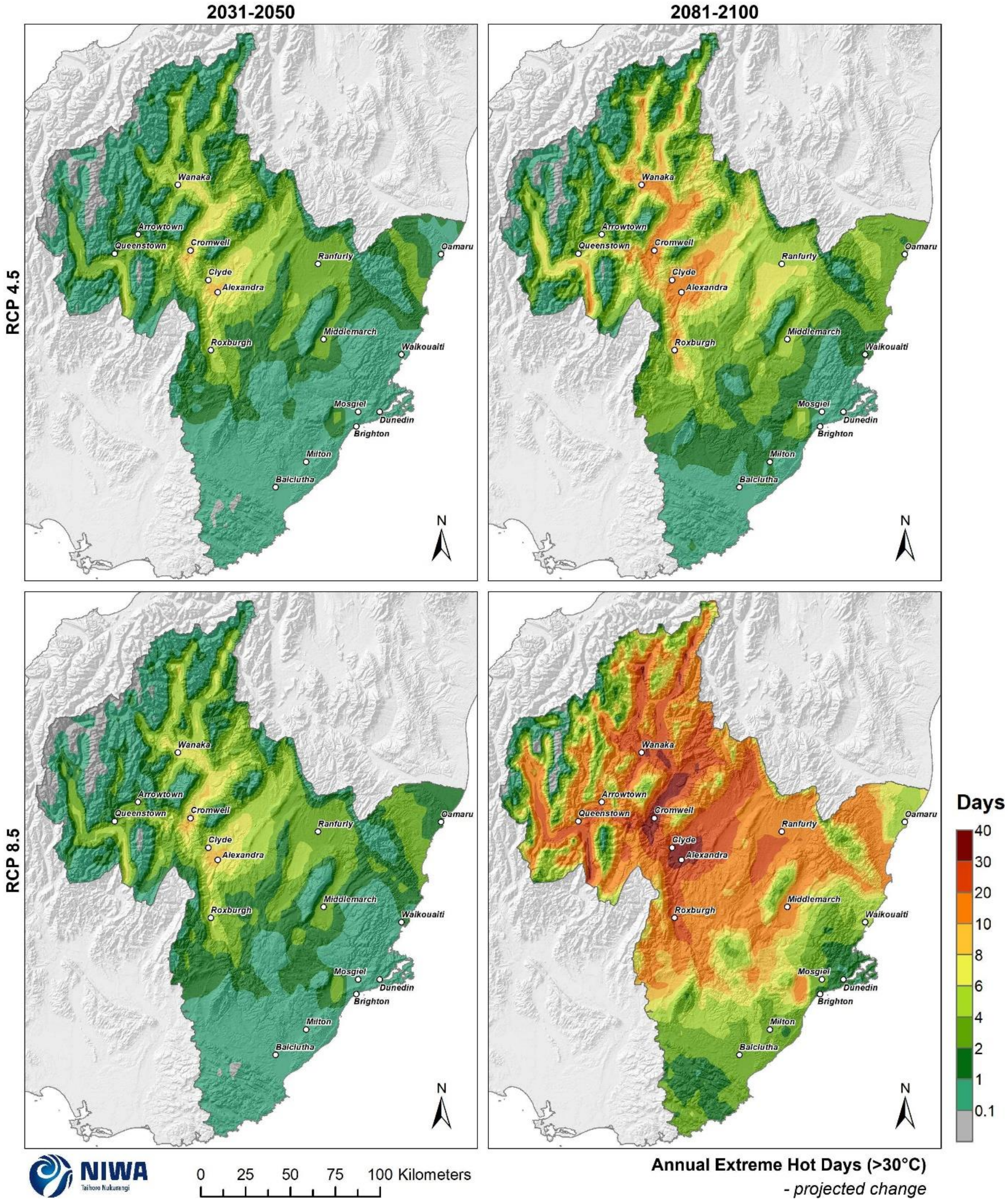


Figure 3-25: Projected annual extreme hot day (maximum temperature >30°C) changes by 2040 and 2090, under RCP4.5 and RCP8.5. Climate change scenarios: RCP4.5 (top panels) and RCP8.5 (bottom panels). Time periods: mid-century (2031-2050; "2040" – panels on left) and end-century (2081-2100; "2090" – panels on right). Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 3-5: Modelled annual average number of extreme hot days (maximum temperature >30°C) for present and two climate change scenarios (RCP4.5 and RCP8.5) at two future time periods. Future projections are shown as the total future projected number of extreme hot days outside the parentheses, and future change inside the parentheses (the top table shows the change in days, and the bottom table shows the change in per cent). Time periods: present (1986-2005), mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models.

		2040 (days change)		2090 (days change)	
	PRESENT	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Alexandra	9.1	17.2 (+8.1)	17.3 (+8.2)	21.7 (+12.6)	42.4 (+33.3)
Arrowtown	0.5	2.3 (+1.8)	2.6 (+2.1)	4.4 (+3.9)	15.7 (+15.2)
Balclutha	0.5	1.0 (+0.5)	1.0 (+0.5)	1.3 (+0.8)	3.4 (+2.9)
Brighton	0.2	0.5 (+0.3)	0.6 (+0.4)	0.8 (+0.6)	1.8 (+1.6)
Clyde	7.4	14.6 (+7.2)	14.8 (+7.4)	18.5 (+11.1)	38.6 (+31.2)
Cromwell	9.8	18.6 (+8.8)	19.1 (+9.3)	23.8 (+14.0)	47.1 (+37.3)
Dunedin	0.2	0.5 (+0.3)	0.6 (+0.4)	0.8 (+0.6)	1.8 (+1.6)
Middlemarch	2.9	5.4 (+2.5)	5.8 (+2.9)	7.6 (+4.7)	16.6 (+13.7)
Milton	0.5	0.9 (+0.4)	1.1 (+0.6)	1.5 (+1.0)	3.7 (+3.2)
Mosgiel	0.5	0.9 (+0.4)	1.1 (+0.6)	1.5 (+1.0)	3.1 (+2.6)
Oamaru	1.3	2.2 (+0.9)	2.9 (+1.6)	3.4 (+2.1)	6.6 (+5.3)
Queenstown	0.3	1.5 (+1.2)	1.9 (+1.6)	3.3 (+3.0)	12.5 (+12.2)
Ranfurly	1.7	4.7 (+3.0)	5.2 (+3.5)	7.5 (+5.8)	20.6 (+18.9)
Roxburgh	6.4	12.5 (+6.1)	12.8 (+6.4)	17.1 (+10.7)	35.0 (+28.6)
Waikouaiti	0.4	1.0 (+0.6)	1.3 (+0.9)	1.9 (+1.5)	4.9 (+4.5)
Wanaka	3.7	9.6 (+5.9)	10.0 (+6.3)	14.0 (+10.3)	33.1 (+29.4)

		2040 (% change)		2090 (% change)	
	PRESENT	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Alexandra	9.1	17.2 (+89)	17.3 (+90)	21.7 (+138)	42.4 (+366)
Arrowtown	0.5	2.3 (+360)	2.6 (+420)	4.4 (+780)	15.7 (+3040)
Balclutha	0.5	1 (+100)	1 (+100)	1.3 (+160)	3.4 (+580)
Brighton	0.2	0.5 (+150)	0.6 (+200)	0.8 (+300)	1.8 (+800)
Clyde	7.4	14.6 (+97)	14.8 (+100)	18.5 (+150)	38.6 (+422)
Cromwell	9.8	18.6 (+90)	19.1 (+95)	23.8 (+143)	47.1 (+381)
Dunedin	0.2	0.5 (+150)	0.6 (+200)	0.8 (+300)	1.8 (+800)
Middlemarch	2.9	5.4 (+86)	5.8 (+100)	7.6 (+162)	16.6 (+472)
Milton	0.5	0.9 (+80)	1.1 (+120)	1.5 (+200)	3.7 (+640)
Mosgiel	0.5	0.9 (+80)	1.1 (+120)	1.5 (+200)	3.1 (+520)
Oamaru	1.3	2.2 (+69)	2.9 (+123)	3.4 (+162)	6.6 (+408)
Queenstown	0.3	1.5 (+400)	1.9 (+533)	3.3 (+1000)	12.5 (+4067)
Ranfurly	1.7	4.7 (+176)	5.2 (+206)	7.5 (+341)	20.6 (+1112)
Roxburgh	6.4	12.5 (+95)	12.8 (+100)	17.1 (+167)	35 (+447)
Waikouaiti	0.4	1 (+150)	1.3 (+225)	1.9 (+375)	4.9 (+1125)
Wanaka	3.7	9.6 (+159)	10 (+170)	14 (+278)	33.1 (+795)

3.5 Frost days

Key messages

- Future number of frost days per year is projected to decline throughout the region; larger reductions in frost days are projected further inland (due to more frosts currently being experienced there).
- By 2040, reductions of 10-15 frost days per year are projected for inland parts of the region
- By 2090, considerable reductions in frost days are projected for inland areas, with around 20-40 fewer frost days for those areas (under RCP8.5).
- It is likely that future frost season length will reduce (i.e. the time between the first and last frost in a given year).

A frost day is defined in this report when the modelled daily minimum temperature falls below 0°C. This is purely a temperature-derived metric for assessing the potential for frosts over the 5 km x 5 km climate model grid. Frost conditions are influenced at the local scale (i.e. finer scale than 5 km x 5 km) by temperature, topography, wind, and humidity, so the results presented in this section can be considered as the large-scale *temperature* conditions conducive to frosts.

Present-day (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for frost days are shown in this section. The present-day maps show annual average numbers of frost days and the future projection maps show the change in the annual number of frost days compared with present. Note that the present-day maps are on a different colour scale to the future projection maps. Table 3-6 shows the present and future projected numbers of frost days for the model grid point closest to specific locations in the Otago region.

At present, the fewest number of frost days per year occurs about the Otago Peninsula, with 1-5 frost days per year (Figure 3-26). The annual number of frost days increases considerably for inland and high-elevation parts of the region. For example, many low-elevation parts of Central Otago typically observe 75-100 days of frost per year. For coastal parts of North Otago, 25-50 frost days per year are experienced.

In the future, the number of frost days per year is projected to decline throughout the region. Larger reductions in frost days are projected further inland, due to more frosts currently being experienced there (Figure 3-27). By 2040, reductions of 10-15 frost days per year are possible for low-elevation inland parts of the region under both RCP4.5 and RCP8.5, with the reductions getting smaller towards the east coast. By 2090, considerable reductions in frost days are projected for inland areas, with around 15-20 fewer frost days for those areas under RCP4.5 and 20-40 fewer frost days under RCP8.5. Larger reductions are projected for high elevations (i.e. decrease of >40 days under RCP8.5 at 2090). In addition, it is likely that future frost season length (i.e. the time between the first and last frost in a given year) will reduce.

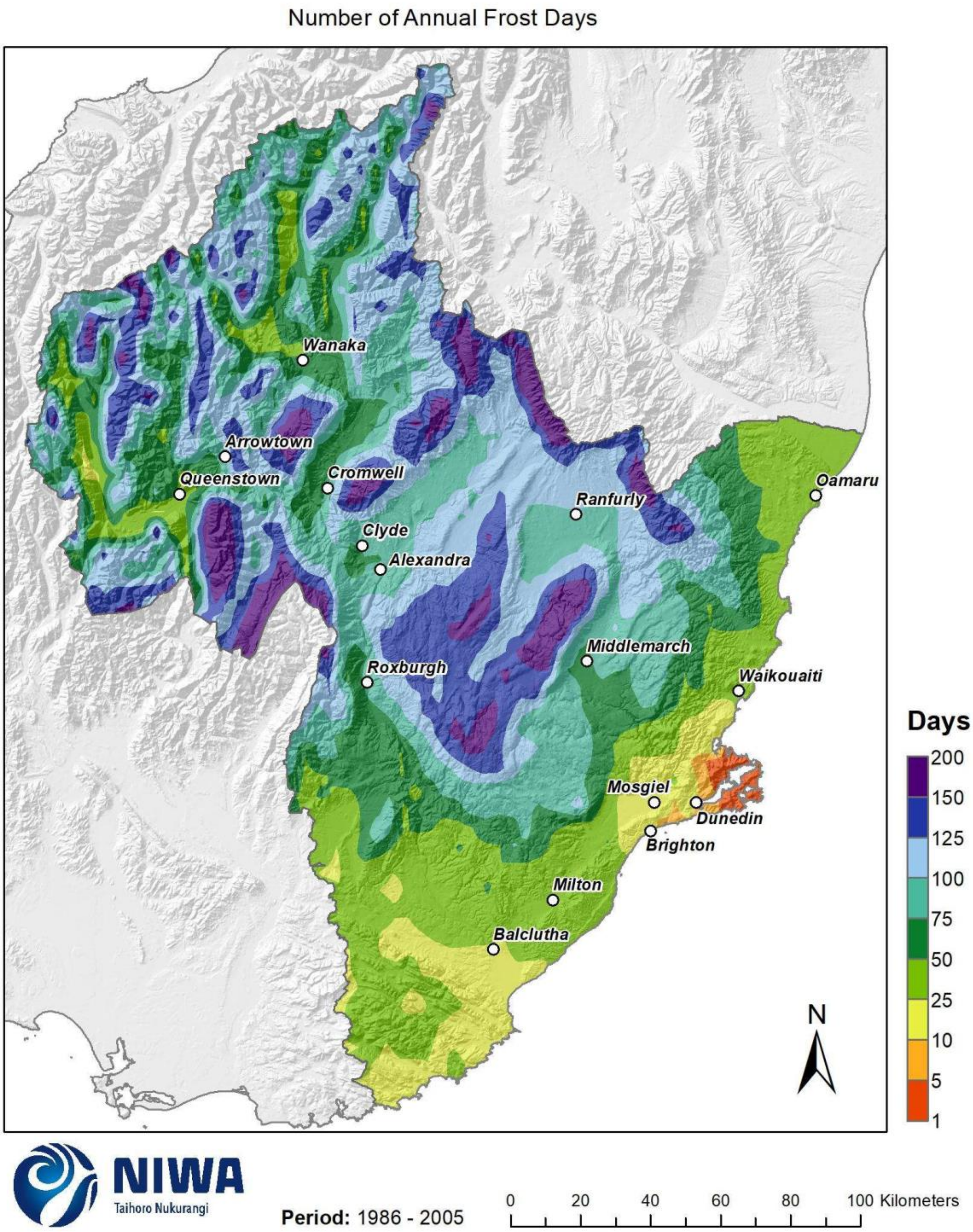


Figure 3-26: Modelled annual number of frost days (daily minimum temperature <0°C), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

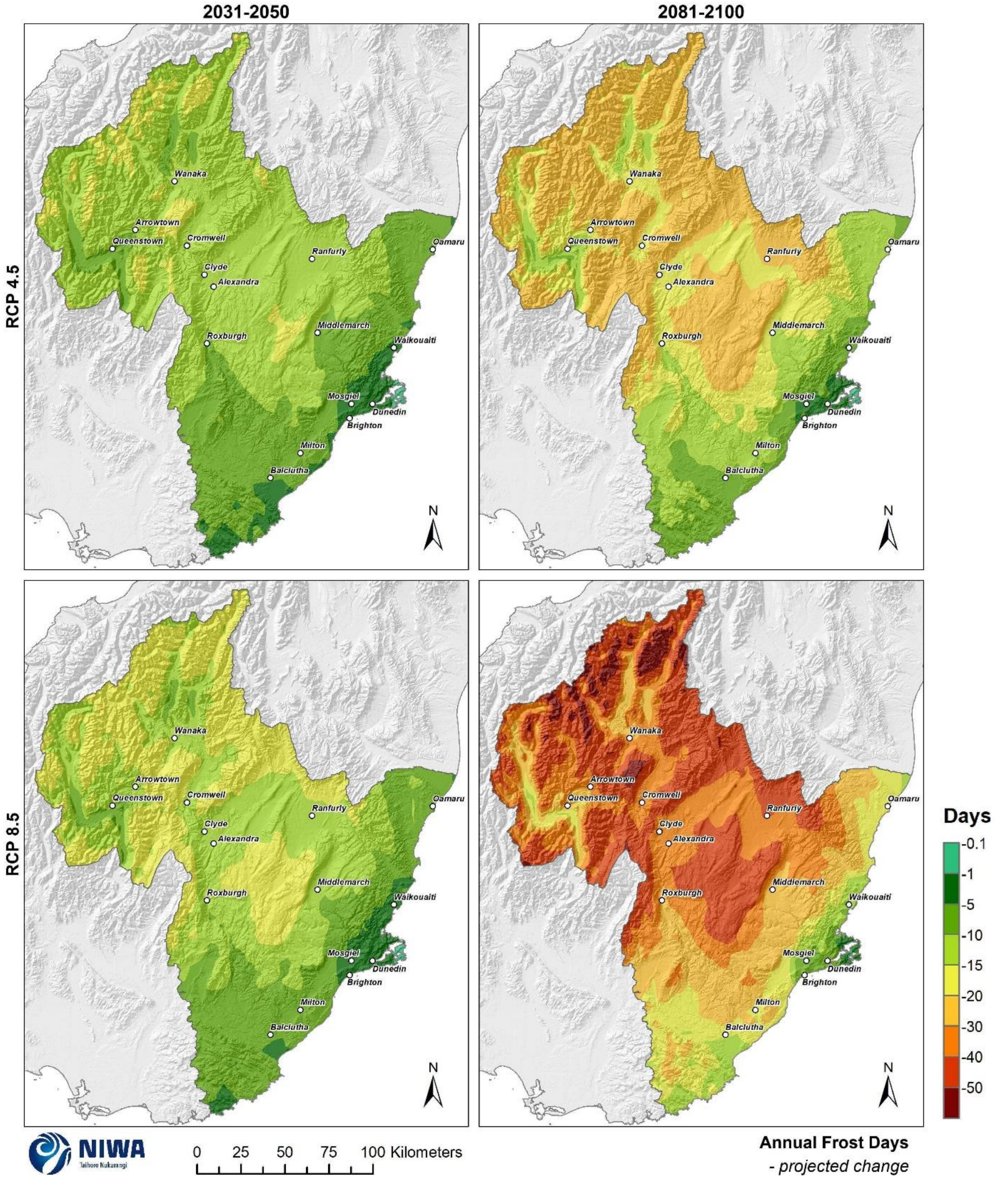


Figure 3-27: Projected annual frost day (minimum temperature <0°C) changes by 2040 and 2090, under RCP4.5 and RCP8.5. Climate change scenarios: RCP4.5 (top panels) and RCP8.5 (bottom panels). Time periods: mid-century (2031-2050; "2040" – panels on left) and end-century (2081-2100; "2090" – panels on right). Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 3-6: Modelled annual average number of frost days (minimum temperature <0°C) for present and two climate change scenarios (RCP4.5 and RCP8.5) at two future time periods. Future projections are shown as the total future projected number of frost days outside the parentheses, and future change inside the parentheses (the top table shows the change in days, and the bottom table shows the change in per cent). Time periods: present (1986-2005), mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models.

		2040 (days change)		2090 (days change)	
	PRESENT	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Alexandra	74.3	62.8 (-11.5)	61.1 (-13.2)	55.5 (-18.8)	39.1 (-35.2)
Arrowtown	74.2	63.7 (-10.5)	62.3 (-11.9)	56.0 (-18.2)	39.3 (-34.9)
Balclutha	25.4	20.0 (-5.4)	19.7 (-5.7)	16.2 (-9.2)	8.5 (-16.9)
Brighton	23.0	20.0 (-3.0)	19.9 (-3.1)	17.7 (-5.3)	12.4 (-10.6)
Clyde	75.7	64.0 (-11.7)	62.9 (-12.8)	56.6 (-19.1)	40.5 (-35.2)
Cromwell	57.8	46.2 (-11.6)	44.5 (-13.3)	39.4 (-18.4)	25.7 (-32.1)
Dunedin	9.3	7.5 (-1.8)	7.4 (-1.9)	6.4 (-2.9)	3.3 (-6.0)
Middlemarch	73.0	64.0 (-9.0)	62.5 (-10.5)	59.1 (-13.9)	49.5 (-23.5)
Milton	26.9	21.0 (-5.9)	20.4 (-6.5)	17.1 (-9.8)	9.1 (-17.8)
Mosgiel	14.2	12.0 (-2.2)	11.8 (-2.4)	10.3 (-3.9)	6.3 (-7.9)
Oamaru	43.1	36.1 (-7.0)	34.0 (-9.1)	31.6 (-11.5)	25.2 (-17.9)
Queenstown	63.5	53.4 (-10.1)	51.8 (-11.7)	48.3 (-15.2)	35.8 (-27.7)
Ranfurly	97.5	85.0 (-12.5)	82.5 (-15.0)	76.9 (-20.6)	56.9 (-40.6)
Roxburgh	57.5	48.9 (-8.6)	47.3 (-10.2)	43.5 (-14.0)	31.4 (-26.1)
Waikouaiti	35.4	30.6 (-4.8)	31.4 (-4.0)	29.1 (-6.3)	23.6 (-11.8)
Wanaka	54.7	44.0 (-10.7)	42.5 (-12.2)	37.9 (-16.8)	24.2 (-30.5)

		2040 (% change)		2090 (% change)	
	PRESENT	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Alexandra	74.3	62.8 (-15)	61.1 (-18)	55.5 (-25)	39.1 (-47)
Arrowtown	74.2	63.7 (-14)	62.3 (-16)	56 (-25)	39.3 (-47)
Balclutha	25.4	20 (-21)	19.7 (-22)	16.2 (-36)	8.5 (-67)
Brighton	23.0	20 (-13)	19.9 (-13)	17.7 (-23)	12.4 (-46)
Clyde	75.7	64 (-15)	62.9 (-17)	56.6 (-25)	40.5 (-46)
Cromwell	57.8	46.2 (-20)	44.5 (-23)	39.4 (-32)	25.7 (-56)
Dunedin	9.3	7.5 (-19)	7.4 (-20)	6.4 (-31)	3.3 (-65)
Middlemarch	73.0	64 (-12)	62.5 (-14)	59.1 (-19)	49.5 (-32)
Milton	26.9	21 (-22)	20.4 (-24)	17.1 (-36)	9.1 (-66)
Mosgiel	14.2	12 (-15)	11.8 (-17)	10.3 (-27)	6.3 (-56)
Oamaru	43.1	36.1 (-16)	34 (-21)	31.6 (-27)	25.2 (-42)
Queenstown	63.5	53.4 (-16)	51.8 (-18)	48.3 (-24)	35.8 (-44)
Ranfurly	97.5	85 (-13)	82.5 (-15)	76.9 (-21)	56.9 (-42)
Roxburgh	57.5	48.9 (-15)	47.3 (-18)	43.5 (-24)	31.4 (-45)
Waikouaiti	35.4	30.6 (-14)	31.4 (-11)	29.1 (-18)	23.6 (-33)
Wanaka	54.7	44 (-20)	42.5 (-22)	37.9 (-31)	24.2 (-56)

4 Precipitation

4.1 Rainfall

Key messages

- Annual rainfall is projected to increase by between 0-10% for most of the region by 2040.
- Increases in winter and spring rainfall of between 5-20% are projected for many western and inland parts of Otago by 2040.
- Annual rainfall increases of 10-20% are projected for the majority of Otago by 2090 (under RCP8.5) with smallest increases expected near Ranfurly (0-5%).
- Winter rainfall is projected to increase considerably by 2090 under RCP8.5, with 20-40% more rainfall projected for many parts of the region.
- Decreases in summer rainfall of 5-10% are projected around Ranfurly and Middlemarch by 2090 under RCP8.5

This section contains maps showing present-day total rainfall and the future projected change in total rainfall. Present-day rainfall maps are in units of mm per year or season (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps show the percentage change in rainfall compared with the present-day total. Note that the present-day maps are on a different colour scale to the future projection maps.

At present, the highest annual rainfall totals are recorded in the high elevations of the western ranges (>2000 mm), with lowest annual rainfall totals about Central Otago (350-400 mm) (Figure 4-1). Alexandra is frequently the driest location in New Zealand, with around 350-400 mm of annual rainfall. Winter is typically the driest season of the year for much of Otago (Figure 4-3), although the inter-seasonal variability of average rainfall totals isn't considerable.

Otago is generally projected to observe an increase in future annual rainfall (Figure 4-2). By 2040 under RCP4.5 and RCP8.5, annual rainfall is projected to increase by between 0-10% for most of the region. The exception is an area about Ranfurly, where annual rainfall is projected to decrease by between 0-5%. By 2090 under RCP4.5, annual rainfall is projected to increase by 5-10% for western areas and 0-5% for eastern and coastal areas. Under RCP8.5, annual rainfall increases of 10-20% are projected for the majority of Otago, with smallest increases expected near Ranfurly (0-5%).

At the seasonal scale, increases in winter and spring rainfall of between 5-20% are projected for many western and inland parts of Otago by 2040 under RCP4.5 (Figure 4-4) and RCP8.5 (Figure 4-5). For summer by 2040 under RCP4.5 and RCP8.5, increases in rainfall (generally 0-10%) are projected for western areas, and decreases in rainfall (generally 0-10%) are projected for central and coastal areas. Autumn rainfall is projected to slightly increase (0-5%) in western parts and decrease (0-5%) in eastern and coastal areas.

By 2090 under RCP4.5 (Figure 4-6), winter rainfall in western and central areas is projected to increase by 5-25% (the larger increases in the western ranges), and increase by 0-10% in most other parts of the region. Summer rainfall is also projected to increase by 0-20% for western and central areas. Most locations expect an increase of 0-10% in autumn rainfall, and spring rainfall projections suggest ±5% change for most of the region (except for 5-10% increase in Central Otago). By 2090 under RCP8.5, seasonal rainfall changes are larger (Figure 4-7). Winter rainfall is projected to increase considerably under RCP8.5, with 20-40% more rainfall projected for many parts of the region and >50% increase for the western ranges. Rainfall increases for the area around Alexandra are projected for summer and spring as well, with 15-25% more rainfall expected there. Decreases in summer rainfall of 5-10% are projected around Ranfurly and Middlemarch by 2090 under RCP8.5. Autumn rainfall is projected to increase by 5-15% across most of the region, with decreases (0-10% near Wanaka).

Table 4-1 shows the present and future projected rainfall for the model grid point closest to specific locations in the Otago region.

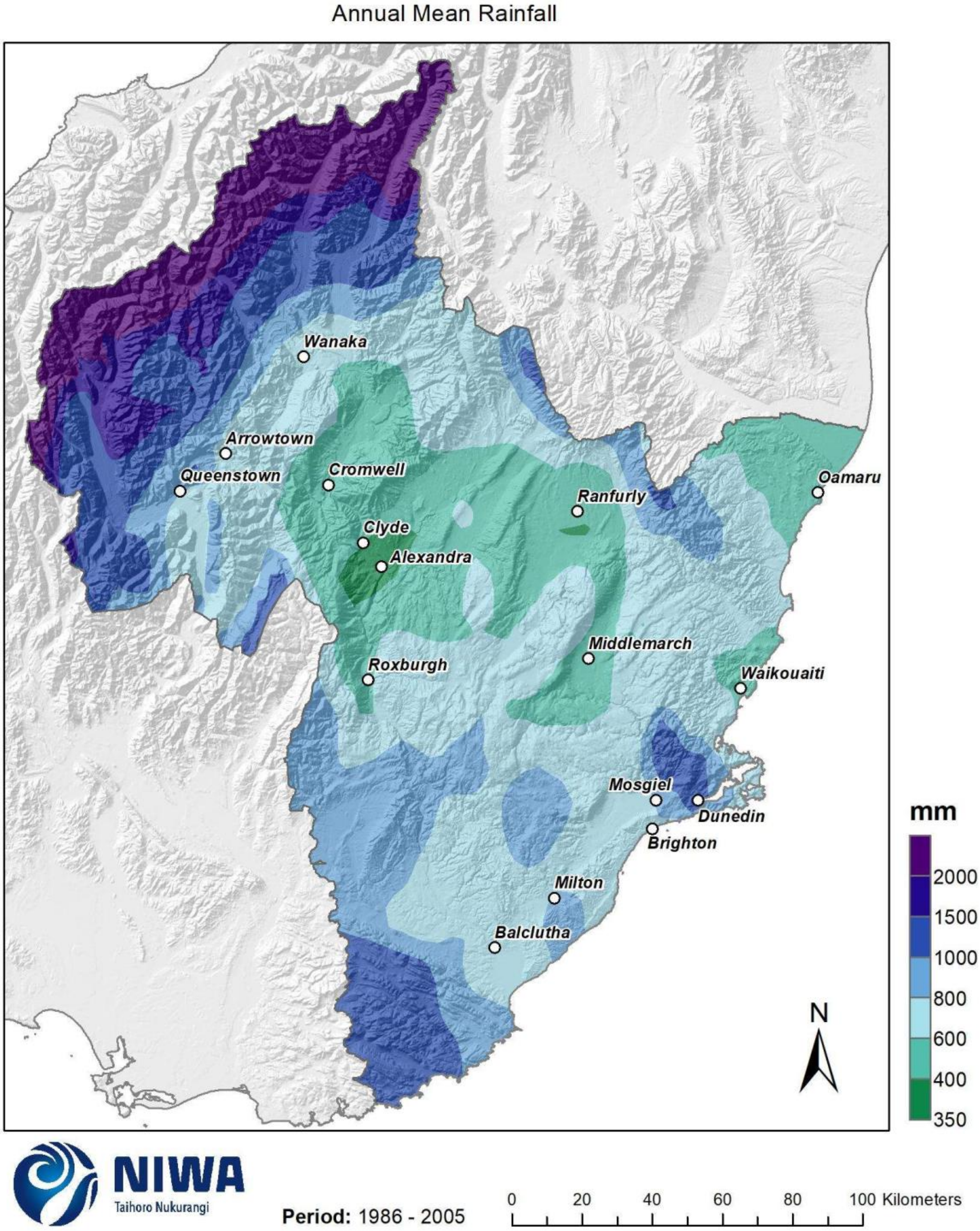


Figure 4-1: Modelled annual mean rainfall (mm), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

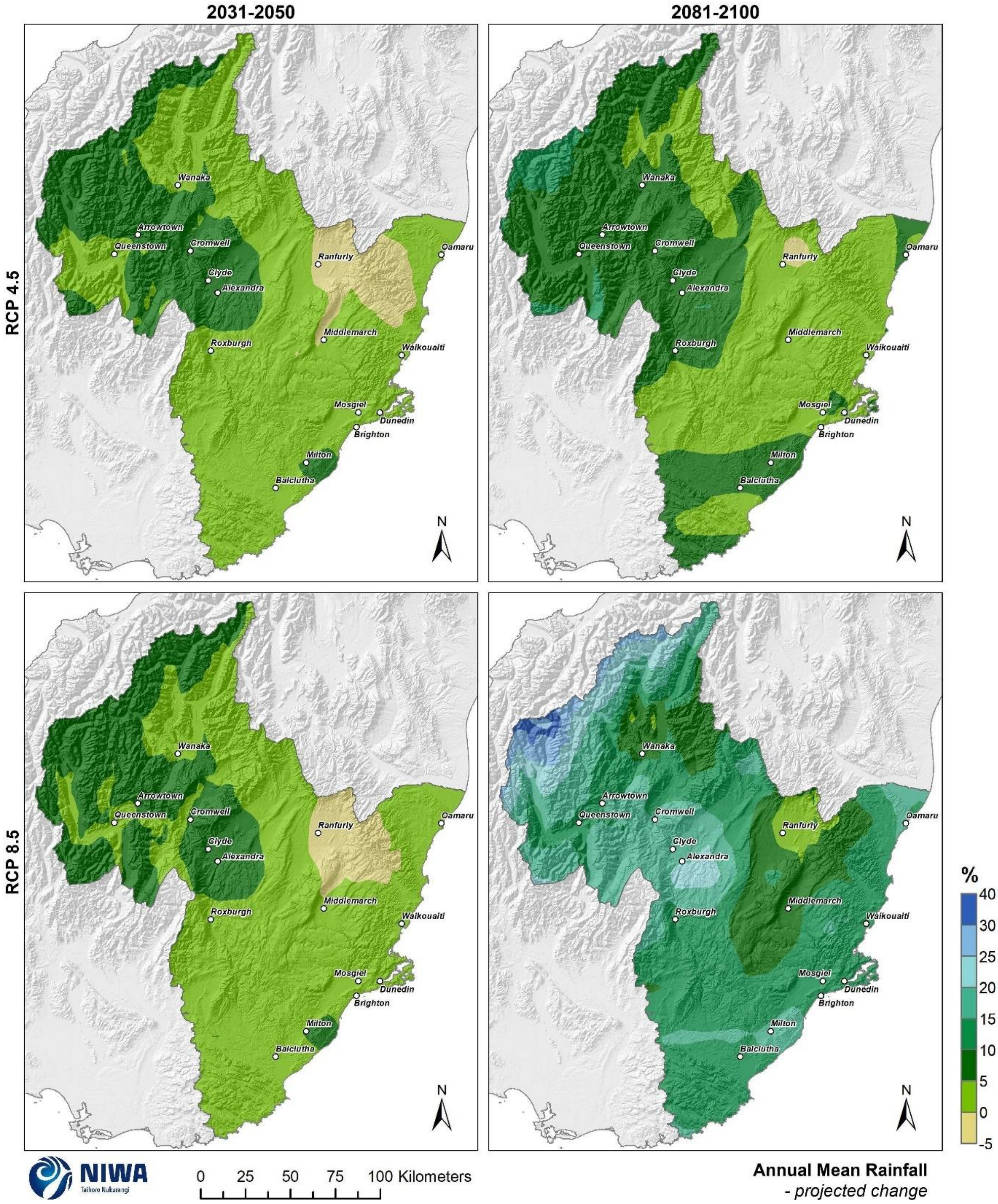


Figure 4-2: Projected annual mean rainfall changes by 2040 and 2090, under RCP4.5 and RCP8.5. Climate change scenarios: RCP4.5 (top panels) and RCP8.5 (bottom panels). Time periods: mid-century (2031-2050; "2040" – panels on left) and end-century (2081-2100; "2090" – panels on right). Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

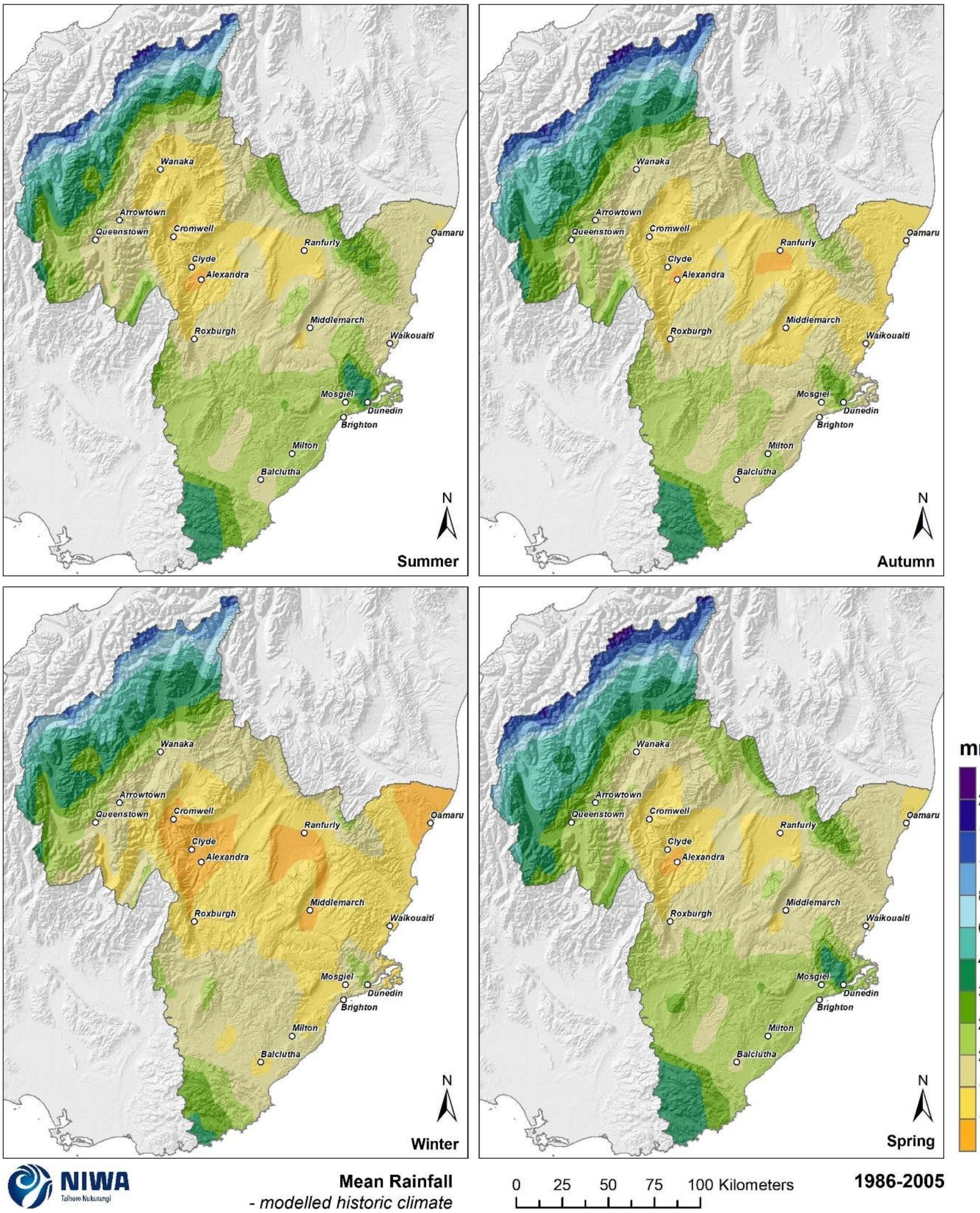


Figure 4-3: Modelled seasonal mean rainfall, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

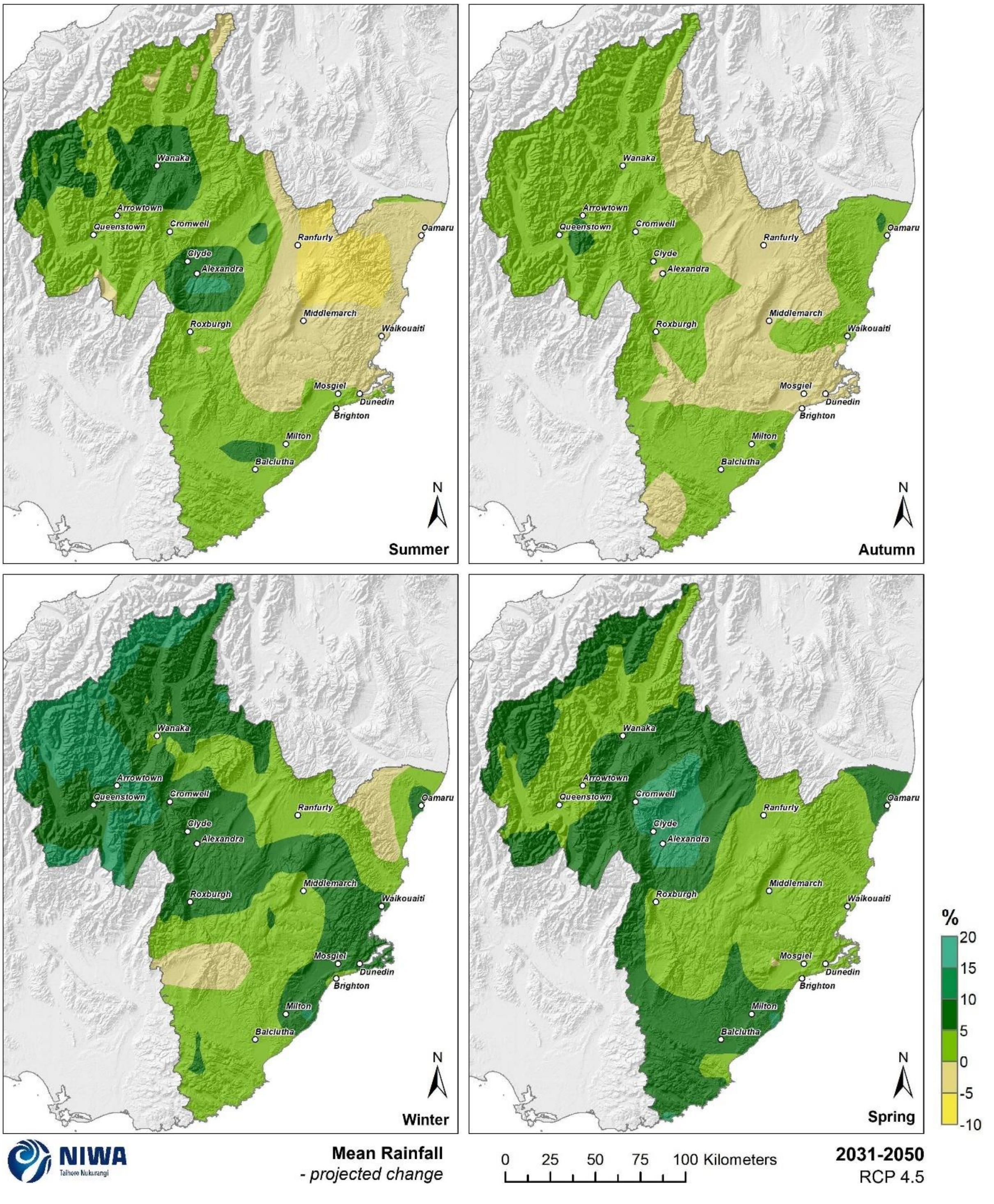


Figure 4-4: Projected seasonal mean rainfall changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

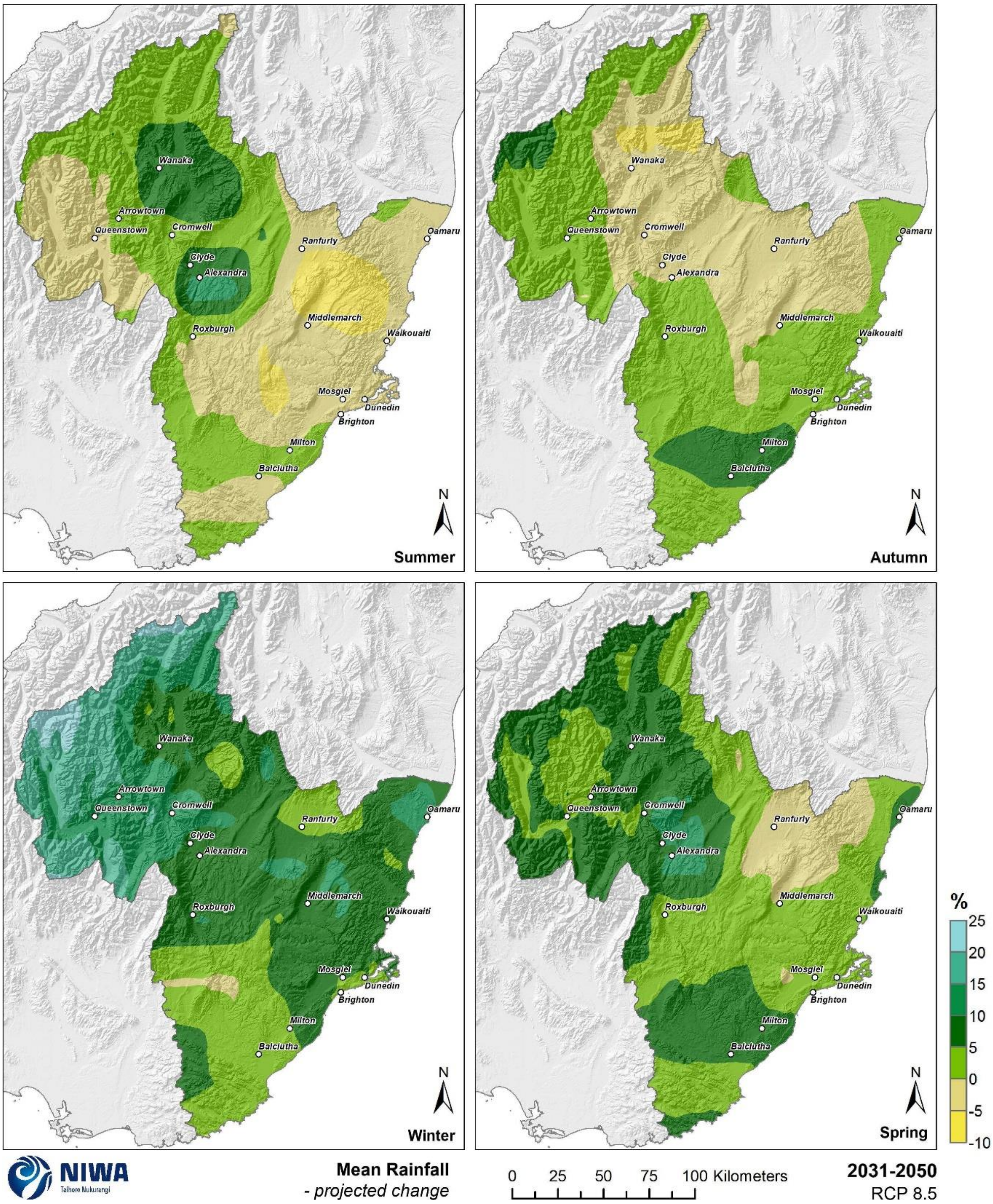


Figure 4-5: Projected seasonal mean rainfall changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

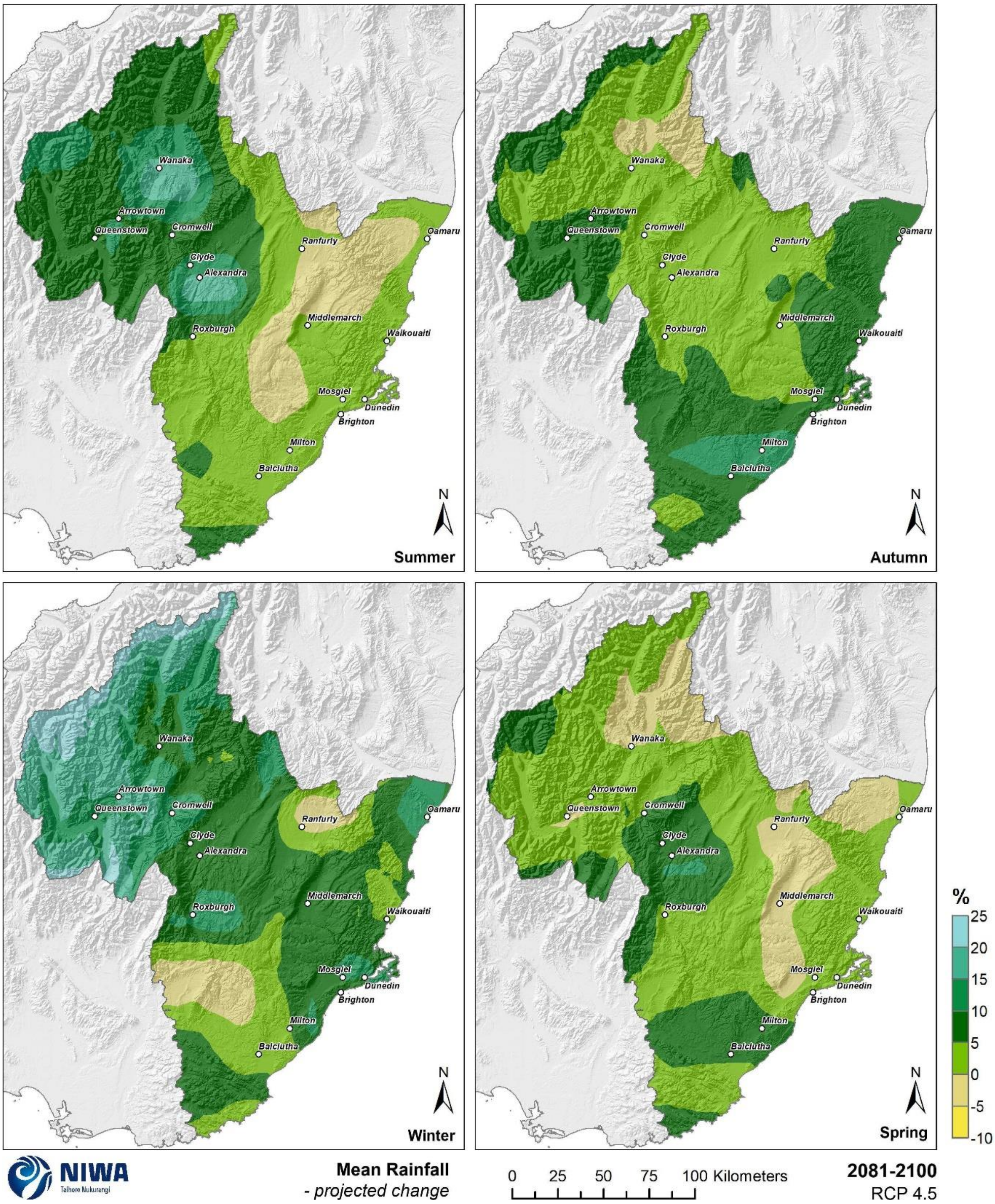


Figure 4-6: Projected seasonal mean rainfall changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

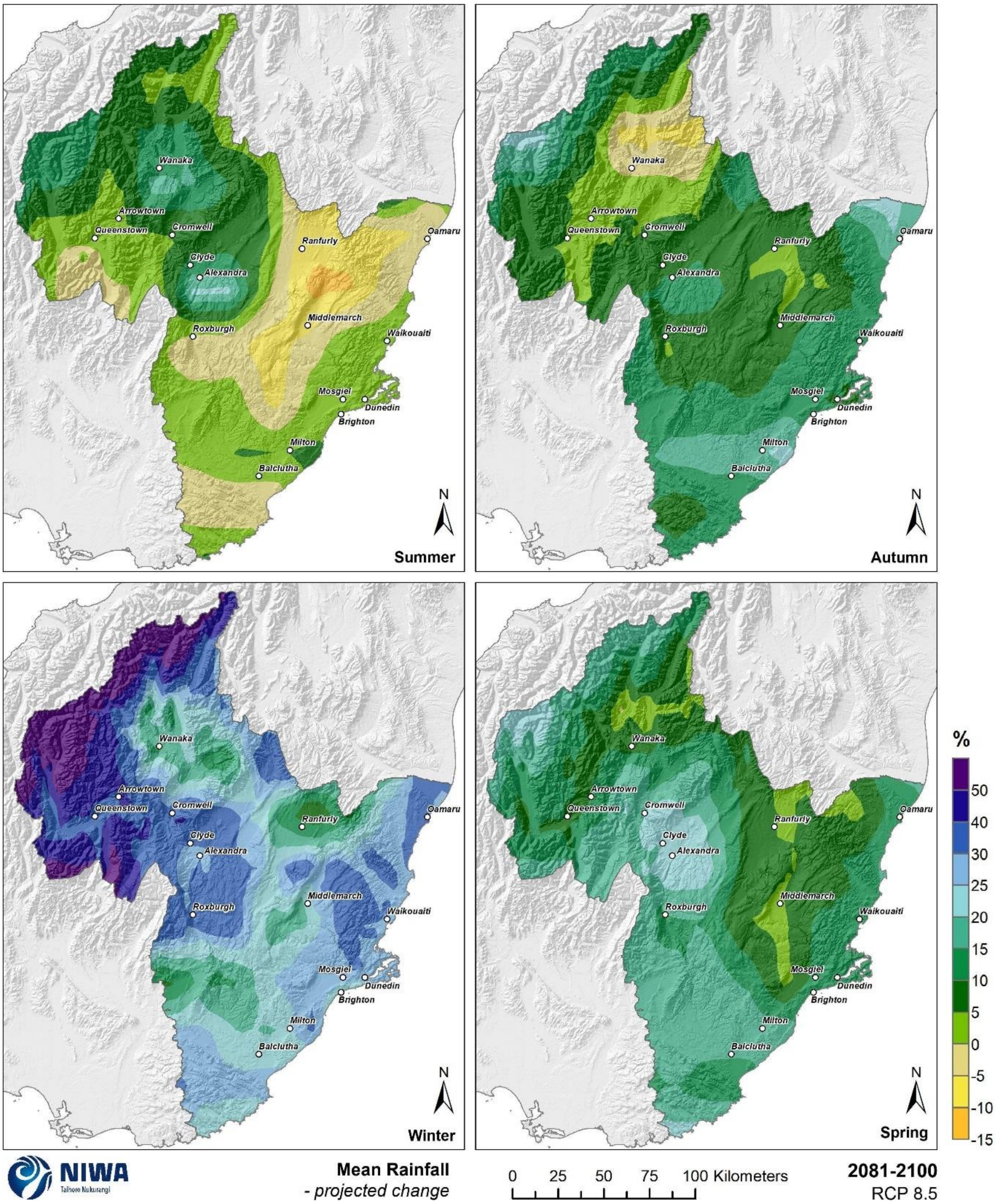


Figure 4-7: Projected seasonal mean rainfall changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 4-1: Modelled seasonal and annual average rainfall for present and two climate change scenarios (RCP4.5 and RCP8.5) at two future time periods. Time periods: present (1986-2005), mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models. Annual ("Ann); Seasons: summer ("Sum"), autumn ("Aut"), winter ("Win") and spring ("Spr"). Note that present rainfall is in millimetres and future rainfall change is in per cent.

	PRESENT (mm)				
	Sum	Aut	Win	Spr	Ann
Alexandra	99	100	78	97	374
Arrowtown	175	216	183	241	815
Balclutha	196	189	150	202	738
Brighton	219	187	151	216	773
Clyde	119	118	90	117	444
Cromwell	105	108	81	113	407
Dunedin	259	216	174	255	904
Middlemarch	146	117	93	144	500
Milton	220	201	154	213	788
Mosgiel	198	166	132	198	694
Oamaru	160	124	88	151	523
Queenstown	191	235	204	263	893
Ranfurly	123	102	92	121	438
Roxburgh	140	133	97	147	516
Waikouaiti	179	134	107	165	585
Wanaka	125	187	203	188	703

		2040 (% change)					2090 (% change)				
		Sum	Aut	Win	Spr	Ann	Sum	Aut	Win	Spr	Ann
Alexandra	RCP4.5	+8	0	+7	+11	+7	+14	+2	+6	+8	+8
	RCP8.5	+9	0	+7	+10	+6	+14	+9	+29	+21	+18
Arrowtown	RCP4.5	+4	+5	+11	+4	+6	+10	+5	+15	+1	+8
	RCP8.5	+1	+2	+14	+4	+5	+4	+3	+39	+9	+14
Balclutha	RCP4.5	+5	+3	+4	+6	+4	+2	+10	+3	+7	+5
	RCP8.5	+0	+7	+2	+6	+4	+2	+15	+23	+16	+14
Brighton	RCP4.5	+1	-1	+5	+4	+2	+1	+6	+8	+2	+5
	RCP8.5	-1	+4	+5	+3	+3	+3	+12	+24	+12	+13
Clyde	RCP4.5	+7	0	+7	+12	+6	+12	+2	+8	+7	+7
	RCP8.5	+7	0	+9	+10	+6	+12	+9	+31	+21	+18
Cromwell	RCP4.5	+3	+2	+9	+11	+6	+7	+4	+13	+6	+8
	RCP8.5	+3	-2	+13	+8	+6	+6	+6	+37	+21	+17
Dunedin	RCP4.5	0	-1	+6	+4	+2	+1	+5	+10	+3	+5
	RCP8.5	-2	+3	+4	+4	+2	+2	+9	+26	+14	+13
Middlemarch	RCP4.5	-3	0	+3	+2	0	+1	+2	+8	-2	+2
	RCP8.5	-4	0	+8	+1	+1	-6	+7	+22	+4	+7
Milton	RCP4.5	+3	+4	+7	+8	+6	+2	+13	+5	+8	+7
	RCP8.5	+1	+8	+5	+8	+5	+5	+19	+25	+18	+17
Mosgiel	RCP4.5	0	-2	+6	+3	+2	0	+5	+10	+1	+4
	RCP8.5	-1	+3	+5	+2	+2	+2	+10	+27	+11	+12
Oamaru	RCP4.5	-3	+5	+7	+7	+4	+1	+5	+14	0	+5
	RCP8.5	-2	+4	+12	+6	+5	-3	+19	+31	+13	+15
Queenstown	RCP4.5	+2	+4	+7	+3	+4	+9	+6	+11	0	+6
	RCP8.5	-2	+2	+12	+5	+4	+1	+4	+35	+9	+12
Ranfurly	RCP4.5	-4	-3	+2	+4	0	0	+2	0	0	+1
	RCP8.5	-3	-2	+4	-2	-1	-6	+5	+12	+6	+4
Roxburgh	RCP4.5	+2	+1	+6	+5	+3	+5	+4	+12	+5	+6
	RCP8.5	0	+2	+10	+3	+4	+1	+7	+35	+16	+14
Waikouaiti	RCP4.5	-3	+1	+7	+3	+2	+1	+7	+4	+3	+4
	RCP8.5	-5	+2	+9	+4	+3	+3	+13	+30	+11	+14
Wanaka	RCP4.5	+7	+1	+4	+6	+4	+17	+2	+6	0	+6
	RCP8.5	+8	-3	+6	+6	+4	+14	-1	+14	+8	+9

4.1.1 Model confidence

Key message

- The complete range of model projections (as shown in this section) demonstrate the difference with season and RCP, allowing interpretation of the range of model uncertainty.
- The direction of change for rainfall is less certain than for temperature, owing to models projecting both increases and decreases of rainfall within the same scenario.
- However, confidence is higher for winter increases in rainfall compared with changes for other seasons.

The climate change projections in other sections this report show the average of six dynamically downscaled climate models. This is useful as the average is the 'best estimate' of future conditions, but these results taken alone do not allow for communication of uncertainty or range in potential future outcomes within the different scenarios and time periods. This section presents the full range of model results for rainfall, to help the reader understand that there is no 'single answer' in terms of future projections.

Projected changes in seasonal and annual rainfall are shown for Dunedin and Queenstown in Table 4-2. Note that data in this table was derived from additional IPCC Fifth Assessment Report models than are presented in the maps in this report (the maps are the average of six dynamically downscaled models, whereas the data here are from ~40 statistically downscaled models), in order to enable an assessment of the range of rainfall change for Dunedin and Queenstown by 2040 and 2090 under RCP4.5 and RCP8.5. The difference between dynamical and statistical downscaling is explained in Appendix A.

Figure 4-8 and Figure 4-9 illustrate the seasonal and annual rainfall projections for each RCP, for the two time periods of 2040 and 2090, respectively. The projections for Dunedin are shown in this example. The coloured vertical bars, and inset stars, show all the individual models, so the complete range is displayed (unlike Table 4-2 where the 5th to 95th percentile range has been calculated). These figures are an excellent way of not only demonstrating the difference between models for each season and RCP, but also the range of model sensitivity (i.e. how the different models predict future conditions under the same scenarios/greenhouse gas concentrations). The closer together the model outcomes are, it can be inferred that these projections have more certainty. The black stars within each vertical bar represent the results of the six RCM simulations selected for presentation in this report.

For 2040 projections (Figure 4-8 and Table 4-2), the average of all the models is similar between the different scenarios, indicated in the table and by the horizontal black line on each bar in the figure (averages between 0 and 5% increase). There is a range of model results, as seen by the size of the coloured bars and the numbers inside the parentheses in the table, and the model results span 0% change under all scenarios. Most models project an increase in rainfall, but overall the direction of change is less certain than, say, for temperature (Section 3.1.1) where all models project warming.

For 2090 projections (Figure 4-9 and Table 4-2), the range of model results is much larger within the scenarios than at 2040. Most models are clustered within -5% to +10% change, but some individual models project up to a 55% increase (winter under RCP8.5) and a 25% decrease (spring under RCP4.5). The model average results show a stronger seasonal signal, with wetter winters and springs expected (not much change is expected for summer and autumn on average). With the average model results for winter and spring showing increases in seasonal and annual rainfall, increases are expected but decreases should not be 'ruled out' as some models project decreases in rainfall.

Table 4-2: Projected changes in seasonal and annual rainfall (%) between 1986-2005 and two climate change scenarios (RCP4.5 and RCP8.5) at two future time periods. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"). The values in each column represent the ensemble average, taken over 41 models (RCP8.5) and 37 models (RCP4.5). Bracketed values represent the range (5th percentile to 95th percentile) over all models within that ensemble.

		Summer	Autumn	Winter	Spring	Annual
2040	Dunedin					
	RCP8.5	2 (-6, 11)	0 (-5, 7)	4 (-4, 13)	3 (-4, 11)	2 (-3, 6)
	RCP4.5	2 (-5, 12)	0 (-7, 6)	4 (-5, 10)	4 (-5, 12)	3 (-2, 7)
	Queenstown					
	RCP8.5	3 (-10, 17)	2 (-10, 11)	16 (-4, 36)	16 (-4, 36)	7 (-1, 19)
	RCP4.5	3 (-10, 15)	1 (-8, 11)	13 (-12, 28)	13 (-12, 28)	6 (0, 14)
2090	Dunedin					
	RCP8.5	3 (-13, 16)	2 (-7, 11)	10 (-5, 22)	9 (-2, 21)	6 (1, 14)
	RCP4.5	4 (-6, 12)	1 (-5, 12)	5 (-7, 16)	5 (-3, 13)	4 (-1, 9)
	Queenstown					
	RCP8.5	4 (-20, 20)	1 (-11, 14)	4 (-3, 14)	17 (-9, 40)	16 (-1, 28)
	RCP4.5	4 (-10, 20)	3 (-8, 12)	19 (-10, 52)	8 (-6, 28)	9 (-4, 21)

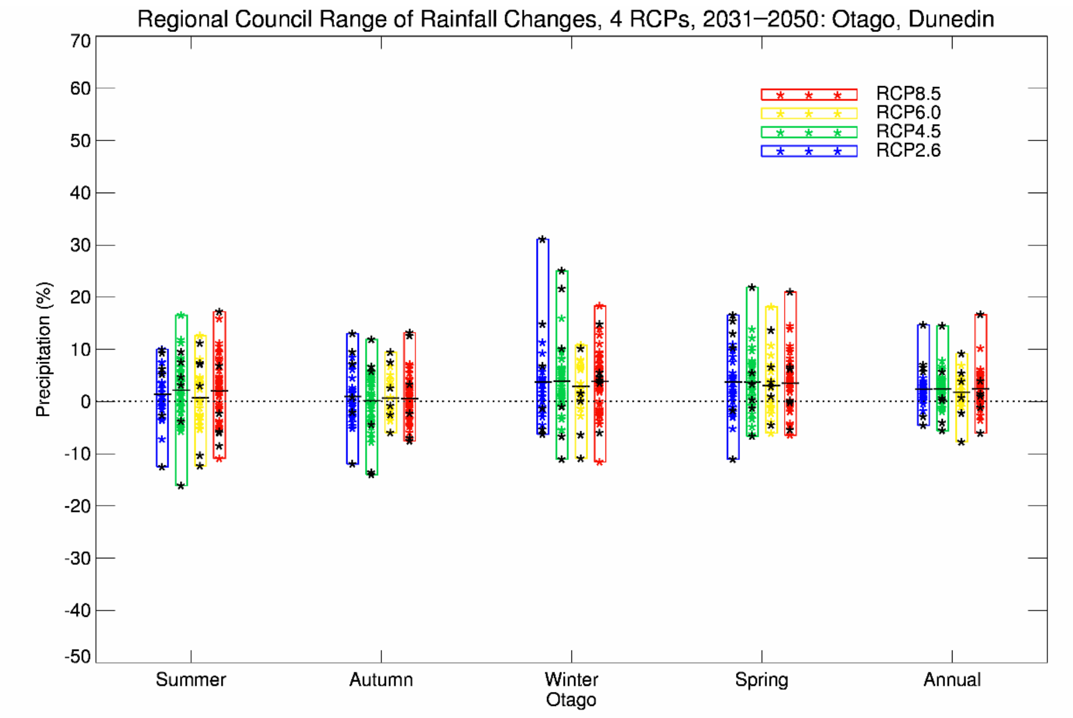


Figure 4-8: Projected seasonal and annual rainfall change for Dunedin by 2040 (2031-2050). Coloured stars represent all models as derived by statistical downscaling. Black stars correspond to the six-model RCM-downscaling, and the horizontal bars are the average over all downscaled results (statistical and RCM).

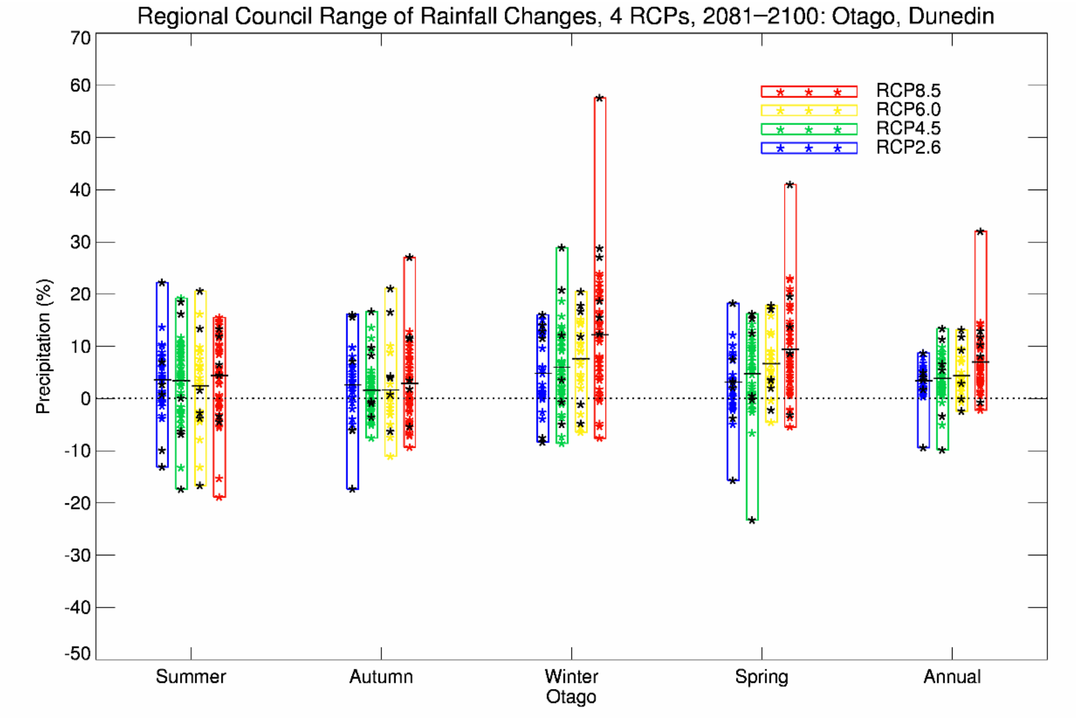


Figure 4-9: Projected seasonal and annual rainfall change for Dunedin by 2090 (2081-2100). Coloured stars represent all models as derived by statistical downscaling. Black stars correspond to the six-model RCM-downscaling, and the horizontal bars are the average over all downscaled results (statistical and RCM).

4.2 Heavy rain days

Key messages

- Relatively small change in future annual number of heavy rain days projected for most of Otago (±0-1 day per year for RCP4.5 and RCP8.5 by 2040 and 2090).
- For far western Otago, the number of heavy rain days is projected to increase by 5-15 days per year (by 2090 under RCP8.5).
- At the seasonal scale, relatively small changes of ±0-1 heavy rain days are projected for most parts of Otago.

A heavy rain day considered here is a daily rainfall total above 25 mm. Present-day (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for heavy rain days are shown in this section. The present-day maps show annual and seasonal average numbers of heavy rain days and the future projection maps show the change in the number of heavy rain days compared with present. Note that the present-day maps are on a different colour scale to the future projection maps.

At present, the area with the highest number of heavy rain days is the highest elevations of the mountain ranges in the west of the Otago region, where there is an average of at least 20 heavy rain days per year (Figure 4-10). Parts of Central Otago have the lowest number of heavy rain days per year (0.1-1 days per year). Heavy rain days are evenly distributed throughout the year, with perhaps a seasonal minimum occurring in winter (Figure 4-12).

In the future, the annual number of heavy rain days are not projected to change much for most of Otago; changes of ±0-1 day per year are projected for RCP4.5 and RCP8.5 by 2040 and 2090 (Figure 4-11). However, western parts of the region may see a considerable increase in heavy rain days. For example, by 2090 under RCP8.5, the number of heavy rain days is projected to increase in the far west of Otago by 5-15 days per year. Seasonal projections of change in heavy rain days are shown for RCP4.5 by 2040 (Figure 4-13) and 2090 (Figure 4-15), and RCP8.5 by 2040 (Figure 4-14) and 2090 (Figure 4-16). At the seasonal scale, for both time periods and scenarios, relatively small changes of ±0-1 heavy rain days are projected for most parts of Otago.

Table 4-3 shows the present and future projected heavy rain days for the model grid point closest to specific locations in the Otago region. Dunedin currently receives 4.9 heavy rain days per year, which is the highest of the 16 Otago locations presented. In future, Dunedin is projected to experience up to one more heavy rain day per year (by 2090 under RCP8.5). Alexandra and Arrowtown are projected to experience two more heavy rain days per year by 2090 under RCP8.5.

Note that although the number of heavy rain days per year/season is not expected to change much, the severity of these heavy rain events (i.e. the amount of rain that falls during these events) is likely to increase (Section 4.3).

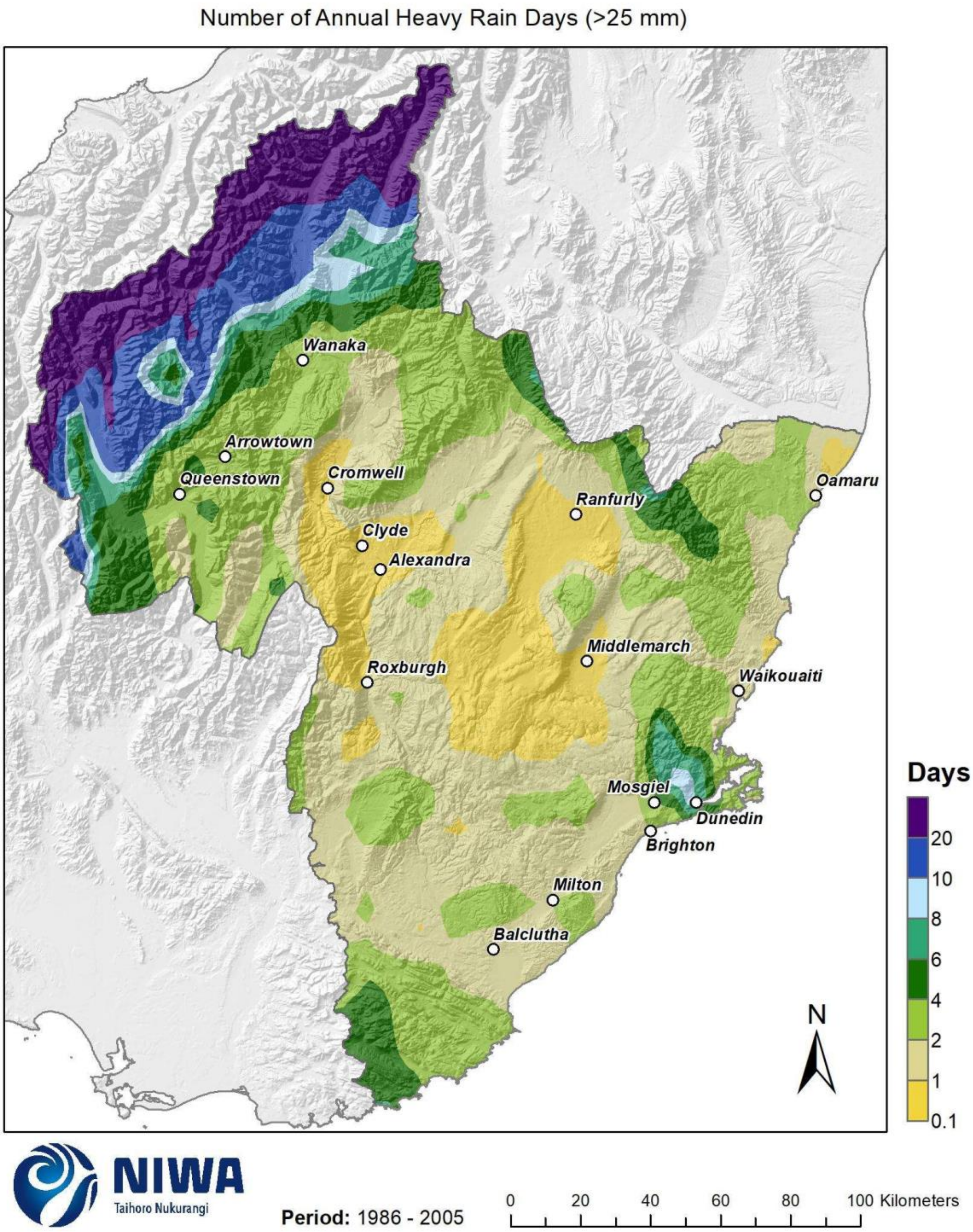


Figure 4-10: Modelled annual number of heavy rain days (daily rainfall >25mm), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

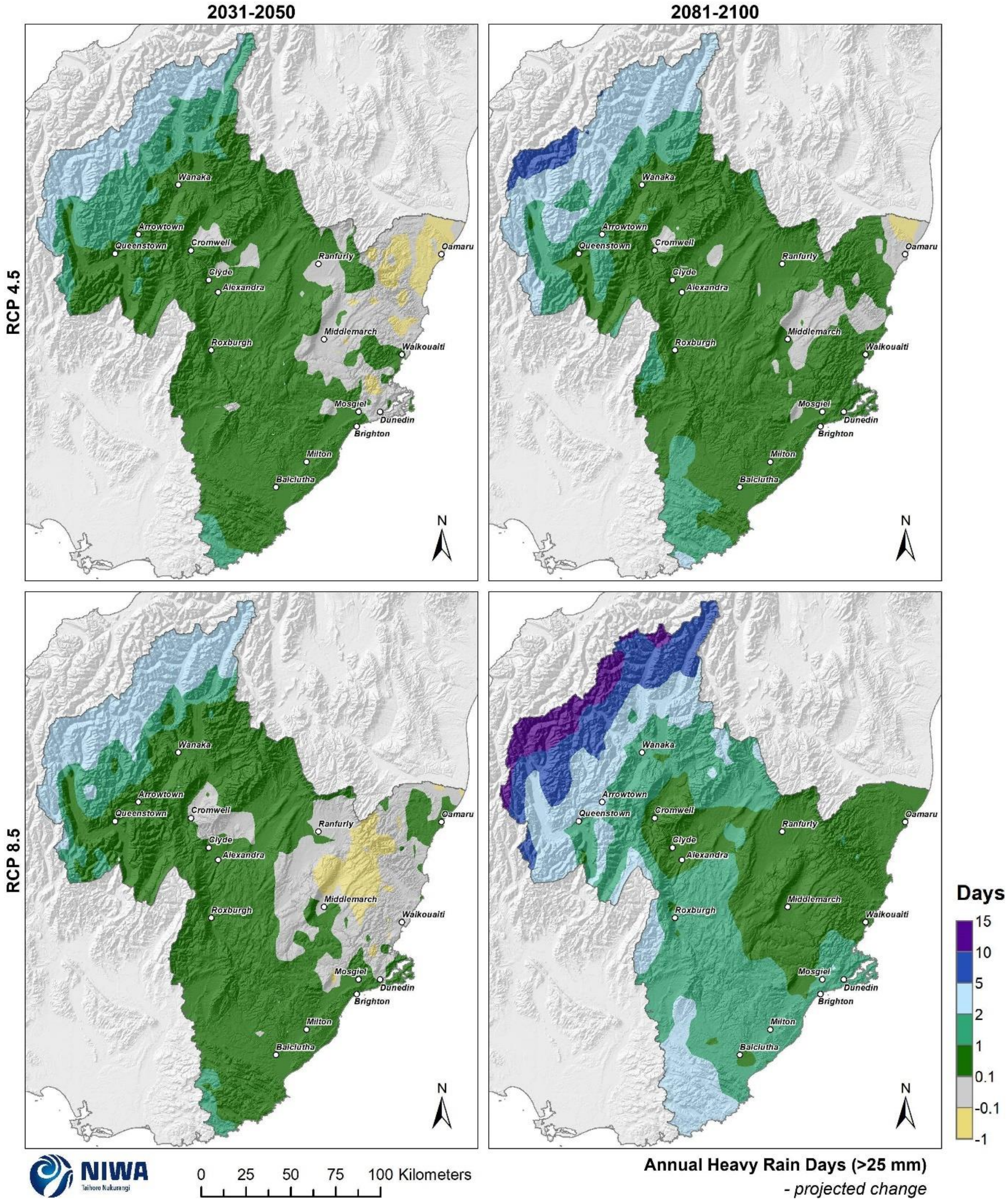


Figure 4-11: Projected annual number of heavy rain day (>25mm) changes by 2040 and 2090, under RCP4.5 and RCP8.5. Climate change scenarios: RCP4.5 (top panels) and RCP8.5 (bottom panels). Time periods: mid-century (2031-2050; "2040" – panels on left) and end-century (2081-2100; "2090" – panels on right). Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

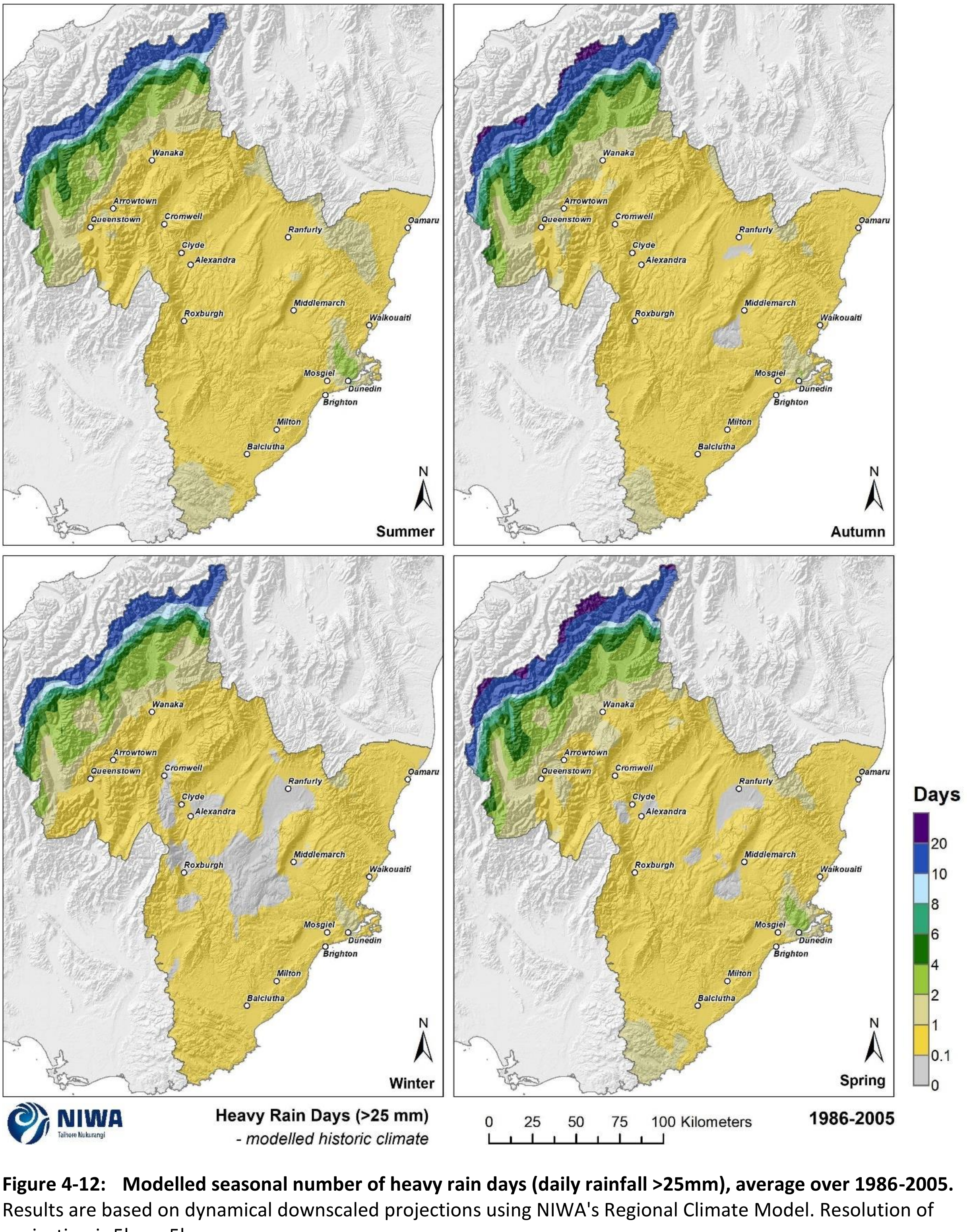


Figure 4-12: Modelled seasonal number of heavy rain days (daily rainfall >25mm), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

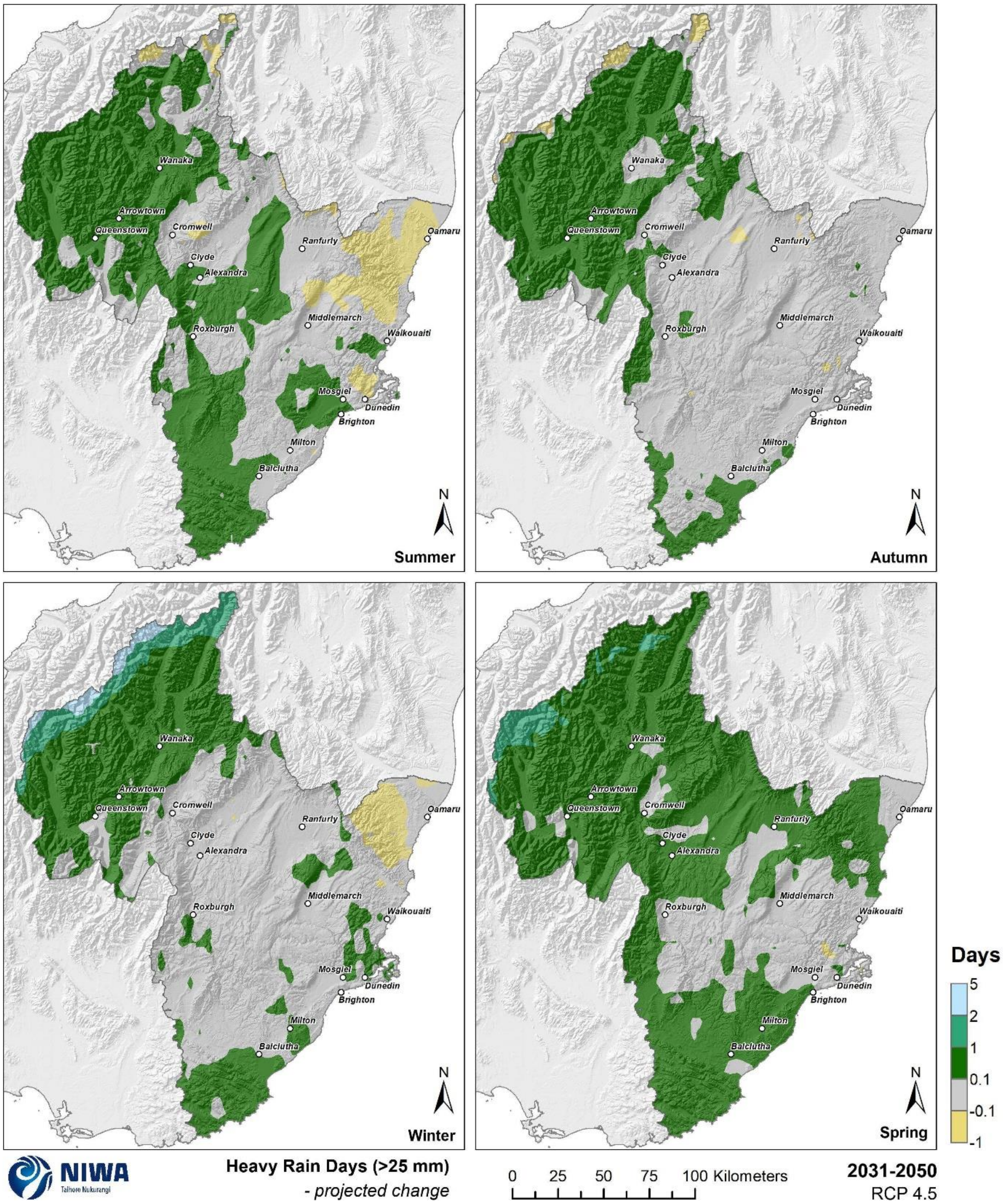


Figure 4-13: Projected seasonal number of heavy rain day (>25mm) changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

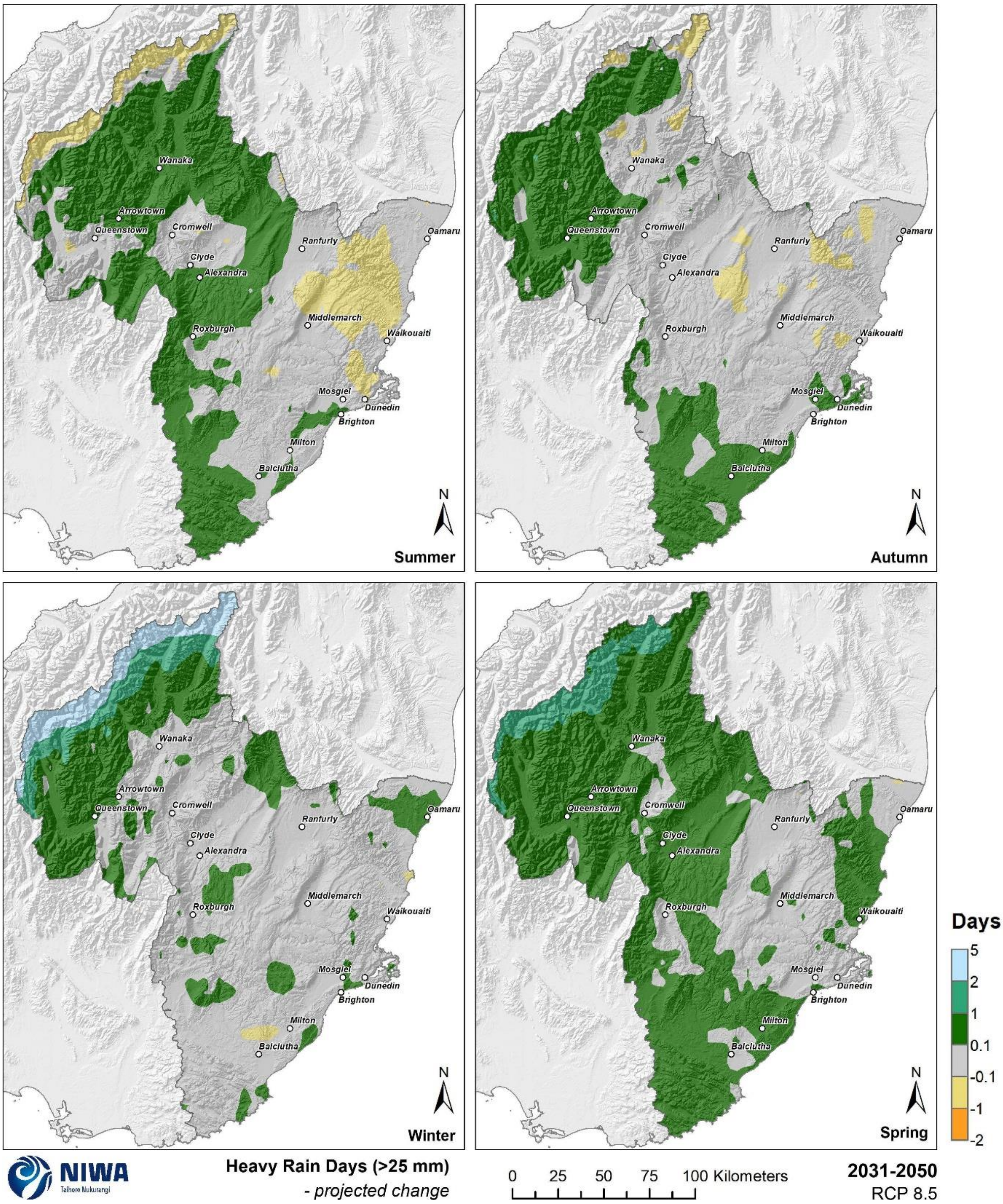


Figure 4-14: Projected seasonal number of heavy rain day (>25mm) changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

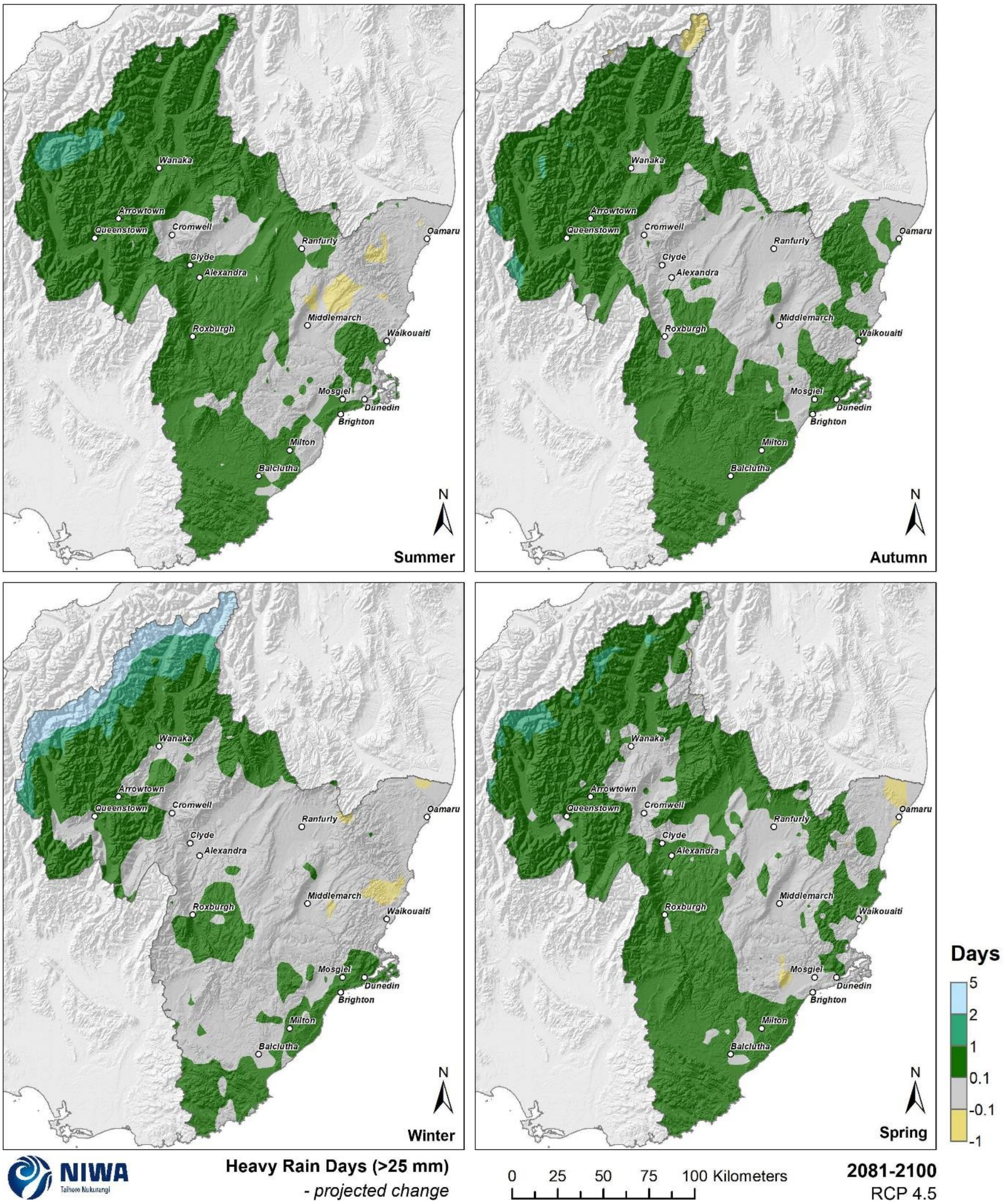


Figure 4-15: Projected seasonal number of heavy rain day (>25mm) changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

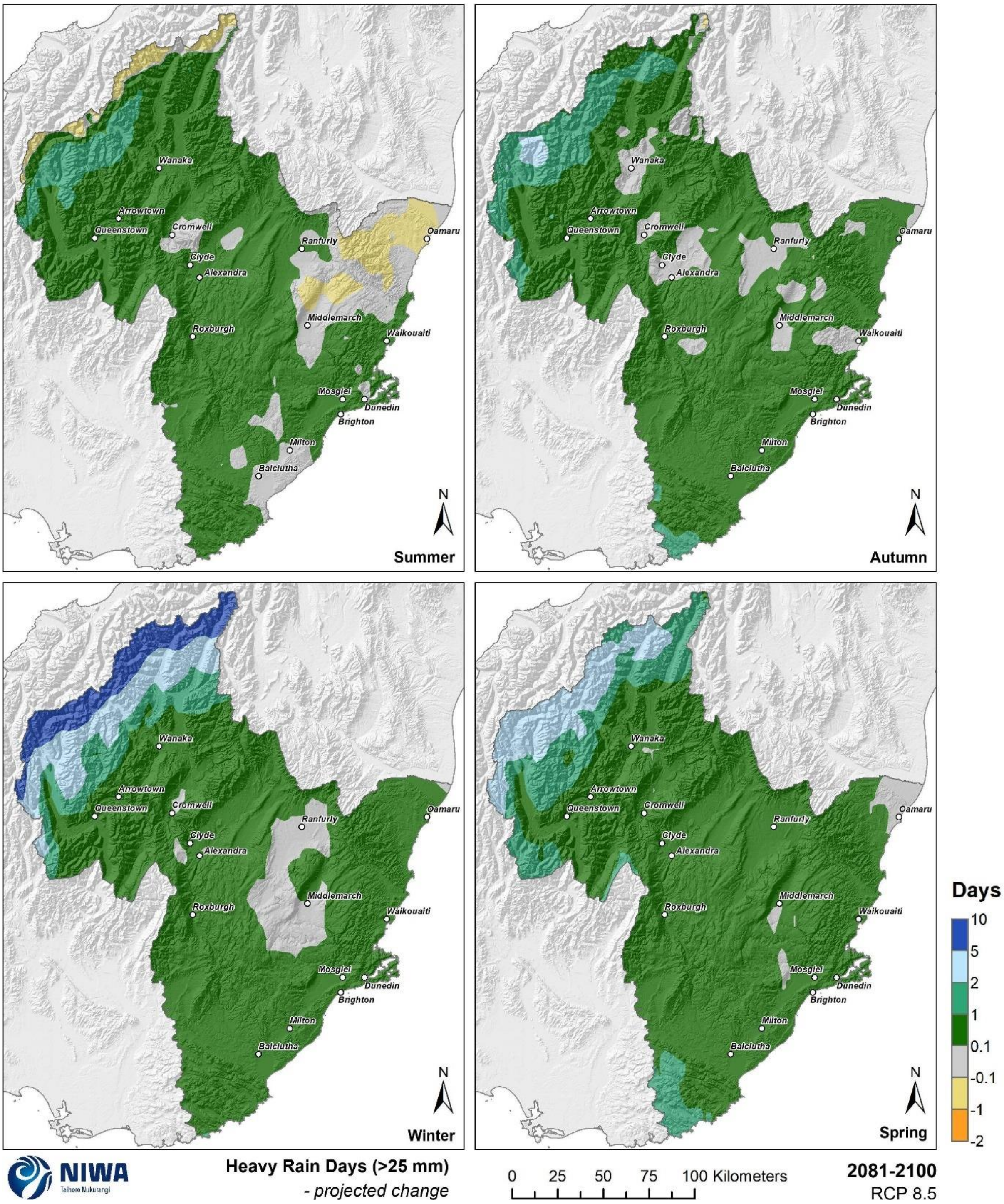


Figure 4-16: Projected seasonal number of heavy rain day (>25mm) changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 4-3: Modelled seasonal and annual average number of heavy rain days (>25 mm) for present and two climate change scenarios (RCP4.5 and RCP8.5) at two future time periods. Time periods: present (1986-2005), mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models. Annual ("Ann"); Seasons: summer ("Sum"), autumn ("Aut"), winter ("Win") and spring ("Spr"). Note that present values are *total* days whereas future values are the *change* in days.

	PRESENT				
	Sum	Aut	Win	Spr	Ann
Alexandra	0.1	0.2	0.1	0.1	0.5
Arrowtown	0.7	0.8	0.5	0.8	2.8
Balclutha	0.5	0.3	0.2	0.4	1.4
Brighton	0.5	0.4	0.2	0.5	1.6
Clyde	0.2	0.3	0.1	0.2	0.8
Cromwell	0.2	0.1	0.1	0.2	0.5
Dunedin	1.5	1.1	0.8	1.5	4.9
Middlemarch	0.2	0.1	0.1	0.1	0.5
Milton	0.7	0.4	0.2	0.5	1.9
Mosgiel	0.5	0.4	0.2	0.5	1.6
Oamaru	0.7	0.5	0.3	0.6	2.1
Queenstown	0.8	0.8	0.6	0.9	3.0
Ranfurly	0.2	0.2	0.1	0.1	0.5
Roxburgh	0.2	0.2	0.0	0.1	0.6
Waikouaiti	0.7	0.5	0.5	0.5	2.1
Wanaka	0.5	0.9	0.7	1.0	3.1

		2040					2090				
		Sum	Aut	Win	Spr	Ann	Sum	Aut	Win	Spr	Ann
Alexandra	RCP4.5	+0.2	+0.4	+0.1	+0.2	+0.9	+0.2	+0.4	+0.1	+0.2	+0.9
	RCP8.5	-0.1	+0.3	+0.2	+0.2	+0.7	+0.3	+0.5	+0.6	+0.6	+2.0
Arrowtown	RCP4.5	+0.2	+0.3	+0.2	+0.2	+0.9	+0.3	+0.4	+0.2	+0.2	+1.0
	RCP8.5	+0.2	+0.2	+0.1	+0.3	+0.7	+0.5	+0.3	+0.6	+0.6	+2.0
Balclutha	RCP4.5	+0.2	-0.1	+0.1	+0.1	+0.4	+0.3	+0.1	0	-0.1	+0.3
	RCP8.5	+0.2	-0.1	0	+0.1	+0.2	+0.4	+0.1	+0.5	+0.2	+1.1
Brighton	RCP4.5	0	+0.1	0	0	+0.1	0	0	0	0	+0.1
	RCP8.5	0	0	0	0	0	+0.1	+0.1	+0.1	+0.2	+0.3
Clyde	RCP4.5	+0.1	+0.1	0	+0.1	+0.3	+0.2	0	0	+0.1	+0.3
	RCP8.5	+0.1	0	+0.1	+0.2	+0.3	+0.3	+0.1	+0.2	+0.3	+0.9
Cromwell	RCP4.5	+0.1	0	0	+0.2	+0.3	+0.2	0	0	+0.1	+0.3
	RCP8.5	+0.1	-0.1	0	+0.1	+0.2	+0.2	+0.1	+0.1	+0.3	+0.7
Dunedin	RCP4.5	+0.1	0	0	+0.1	+0.2	+0.2	+0.1	+0.1	+0.1	+0.5
	RCP8.5	+0.1	0	0	+0.1	+0.2	+0.3	+0.2	+0.2	+0.4	+1.0
Middlemarch	RCP4.5	0	0	0	+0.1	+0.1	+0.1	0	0	+0.1	+0.2
	RCP8.5	0	0	0	+0.1	+0.1	+0.1	+0.1	+0.1	+0.3	+0.6
Milton	RCP4.5	0	0	0	0	0	0	+0.1	0	+0.1	+0.1
	RCP8.5	0	0	+0.1	0	+0.1	+0.1	+0.1	+0.1	+0.1	+0.3
Mosgiel	RCP4.5	-0.2	0	0	0	-0.2	0	+0.1	0	-0.1	0
	RCP8.5	0	0	+0.2	0	+0.2	-0.2	+0.1	+0.1	+0.1	+0.1
Oamaru	RCP4.5	0	0	+0.1	0	+0.1	+0.1	+0.1	0	+0.1	+0.3
	RCP8.5	-0.1	0	0	+0.2	0	+0.2	+0.1	+0.2	+0.3	+0.7
Queenstown	RCP4.5	0	0	+0.1	-0.1	0	+0.1	+0.3	+0.2	0	+0.6
	RCP8.5	0	+0.1	+0.1	-0.1	+0.1	+0.2	+0.4	+0.5	+0.5	+1.6
Ranfurly	RCP4.5	+0.2	0	+0.1	+0.1	+0.3	+0.2	+0.1	+0.1	0	+0.5
	RCP8.5	+0.1	+0.1	+0.1	+0.1	+0.4	+0.2	+0.2	+0.3	+0.3	+1.0
Roxburgh	RCP4.5	+0.2	0	+0.1	+0.1	+0.5	+0.3	+0.1	+0.2	+0.1	+0.7
	RCP8.5	+0.1	+0.1	+0.1	+0.1	+0.4	+0.3	+0.3	+0.4	+0.4	+1.3
Waikouaiti	RCP4.5	-0.1	+0.1	+0.1	+0.3	+0.4	+0.2	+0.2	+0.2	+0.2	+0.7
	RCP8.5	+0.1	+0.1	+0.1	+0.2	+0.5	+0.1	+0.6	+0.3	+0.5	+1.4
Wanaka	RCP4.5	+0.1	0	+0.1	+0.2	+0.4	+0.1	+0.3	+0.1	+0.1	+0.5
	RCP8.5	+0.1	+0.1	0	+0.1	+0.3	+0.1	+0.4	+0.2	+0.4	+1.1

4.3 Extreme, rare rainfall events (HIRDS v4)

Key messages

- Extreme, rare rainfall events are likely to increase in intensity in Otago because a warmer atmosphere can hold more moisture.
- Rainfall depth increases are projected at both future periods (2040 and 2090) under all four climate change scenarios; greatest increases are projected by 2090 under RCP8.5 (up to 35% higher for a 1:100 year 1-hour duration rainfall event).
- Short duration rainfall events have the largest relative increases.
- Extreme rainfall projections for any New Zealand location can be viewed at https://hirds.niwa.co.nz/
- Increases in extreme rainfall events may cause more flooding (see Section 6).

Extreme, rare rainfall events may cause significant damage to land, buildings, and infrastructure. This section analyses how these rainfall events may change in the future for Otago.

Extreme rainfall events (and floods) are often considered in the context of return periods (e.g. 1-in-100-year rainfall events). A return period, also known as an average recurrence interval (ARI), is an estimate of the likelihood of an event. It is a statistical measure typically based on historic data and probability distributions which calculate how often an event of a certain magnitude may occur. Return periods are often used in risk analysis and infrastructure design.

The theoretical return period is the inverse of the probability that the event will be exceeded in any one year. For example, a 1-in-10-year rainfall event has a 1/10 = 0.1 or 10% chance of being exceeded in any one year and a 1-in-100-year rainfall event has a 1/100 = 0.01 or 1% chance of being exceeded in any one year. However, this does not mean that a 1-in-100-year rainfall event will happen regularly every 100 years, or only once in 100 years. The events with larger return periods (i.e. 1-in-100-year events) have larger rainfall amounts for the same duration as events with smaller return periods (i.e. 1-in-2-year events) because larger events occur less frequently (on average).

A warmer atmosphere can hold more moisture, so there is potential for heavier extreme rainfall with global increases in temperatures under climate change (Fischer and Knutti, 2016, Trenberth, 1999). The frequency of heavy rainfall events is 'very likely' to increase over most mid-latitude land areas (this includes New Zealand; IPCC, 2013). Given the mountainous nature of New Zealand, spatial patterns of changes in rainfall extremes are expected to depend on changes in atmospheric circulation and storm tracks.

NIWA's High Intensity Rainfall Design System (HIRDS version 4) allows rainfall event totals (depth; measured in mm) at various recurrence intervals to be calculated for any location in New Zealand (Carey-Smith et al., 2018). The rainfall event durations presented in HIRDS range from 10 minutes to 120 hours. HIRDS calculates historic rainfall event totals for given recurrence intervals as well as future potential rainfall event totals for given recurrence intervals based on climate change scenarios. HIRDS v4 can be freely accessed at https://hirds.niwa.co.nz/, and more background information to the HIRDS methodology can be found at https://www.niwa.co.nz/information-services/hirds/help. HIRDS rainfall projections for locations in Otago are presented in Sections 4.3.1 to 4.3.5. Each section contains two tables; the first table presents data for 1:50 year rainfall events, and the second table presents data for 1:100 year rainfall events.

The depth of historic 1:50 and 1:100-year rainfall events are projected to increase in the future under all four climate change scenarios. The most considerable increases are projected at the end of the century (i.e. 2090) under RCP8.5. Short duration rainfall events have the largest relative increases compared with longer duration rainfall events. For example, the depth of a current 1:100-year 1-hour duration rainfall event is projected to increase by approximately 35% by 2090 under RCP8.5 for locations throughout Otago. In contrast, the depth of a current 1:100-year 48-hour duration rainfall event is projected to increase by approximately 20% by 2090 under RCP8.5 for Otago locations.

4.3.1 1-hour duration rainfall

Table 4-4 (50-year ARI) and Table 4-5 (100-year ARI) show modelled historic and projected rainfall depths for a 1-hour rain event. Rainfall depths are projected to increase across both future periods and for all climate change scenarios. Projected rainfall depth increases range from 8% (by 2040 and 2090 under RCP2.6) to 35% (by 2090 under RCP8.5).

Table 4-4: Modelled historic and projected rainfall depths (mm) for a 1-hour rain event with a 50-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Alexandra	27.1	29.2	29.8	29.5	30.2	29.2	31.5	33.0	36.5
Arrowtown	23.1	24.9	25.4	25.2	25.7	24.9	26.9	28.2	31.1
Balclutha	25.6	27.7	28.2	28.0	28.6	27.7	29.8	31.3	34.6
Brighton	26.3	28.4	28.9	28.7	29.3	28.4	30.6	32.1	35.4
Clyde	23.0	24.9	25.3	25.1	25.7	24.9	26.8	28.1	31.1
Cromwell	22.8	24.6	25.1	24.9	25.4	24.6	26.5	27.8	30.8
Dunedin	27.1	29.2	29.8	29.6	30.2	29.2	31.5	33.0	36.5
Middlemarch	25.8	27.9	28.4	28.2	28.8	27.9	30.0	31.5	34.8
Milton	28.0	30.3	30.8	30.6	31.2	30.3	32.6	34.2	37.8
Mosgiel	27.4	29.6	30.1	29.9	30.5	29.6	31.9	33.4	36.9
Oamaru	26.5	28.6	29.1	28.9	29.5	28.6	30.8	32.3	35.7
Queenstown	22.9	24.8	25.2	25.0	25.6	24.8	26.7	28.0	30.9
Ranfurly	30.8	33.2	33.9	33.6	34.3	33.2	35.8	37.6	41.5
Roxburgh	27.9	30.1	30.7	30.4	31.1	30.1	32.4	34.0	37.6
Waikouaiti	27.6	29.8	30.4	30.2	30.8	29.8	32.2	33.7	37.3
Wanaka	20.2	21.8	22.2	22.0	22.5	21.8	23.5	24.6	27.2

Table 4-5: Modelled historic and projected rainfall depths (mm) for a 1-hour rain event with a 100-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Alexandra	32.3	34.9	35.5	35.3	36.0	34.9	37.6	39.4	43.6
Arrowtown	26.8	28.9	29.5	29.2	29.9	28.9	31.2	32.7	36.2
Balclutha	30.3	32.7	33.3	33.1	33.8	32.7	35.3	37.0	40.9
Brighton	31.0	33.5	34.1	33.9	34.6	33.5	36.1	37.9	41.9
Clyde	27.1	29.3	29.8	29.6	30.2	29.3	31.6	33.1	36.6
Cromwell	26.8	28.9	29.5	29.2	29.9	28.9	31.2	32.7	36.2
Dunedin	32.0	34.5	35.2	34.9	35.7	34.5	37.2	39.0	43.2
Middlemarch	30.6	33.0	33.7	33.4	34.1	33.0	35.6	37.4	41.3
Milton	32.8	35.5	36.1	35.9	36.6	35.5	38.2	40.1	44.4
Mosgiel	32.3	34.9	35.5	35.3	36.0	34.9	37.6	39.5	43.6
Oamaru	30.9	33.4	34.0	33.8	34.5	33.4	36.0	37.8	41.8
Queenstown	26.7	28.8	29.3	29.1	29.7	28.8	31.0	32.6	36.0
Ranfurly	36.3	39.2	40.0	39.7	40.5	39.2	42.3	44.3	49.0
Roxburgh	33.0	35.7	36.4	36.1	36.8	35.7	38.5	40.4	44.6
Waikouaiti	32.5	35.1	35.8	35.5	36.3	35.1	37.9	39.7	43.9
Wanaka	23.1	25.0	25.5	25.3	25.8	25.0	27.0	28.3	31.3

4.3.2 6-hour duration rainfall

Table 4-6 (50-year ARI) and Table 4-7 (100-year ARI) show modelled historic and projected rainfall depths for a 6-hour rain event. Rainfall depths are projected to increase across both future periods and for all climate change scenarios. Projected rainfall depth increases range from 7% (by 2040 and 2090 under RCP2.6) to 30% (by 2090 under RCP8.5).

Table 4-6: Modelled historic and projected rainfall depths (mm) for a 6-hour rain event with a 50-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Alexandra	52.9	56.4	57.3	57.0	58.0	56.4	60.1	62.7	68.3
Arrowtown	57.2	61.0	62.0	61.6	62.7	61.0	65.0	67.8	73.9
Balclutha	53.6	57.2	58.1	57.8	58.8	57.2	61.0	63.5	69.3
Brighton	61.5	65.6	66.6	66.2	67.4	65.6	69.9	72.8	79.4
Clyde	46.7	49.8	50.6	50.3	51.2	49.8	53.1	55.3	60.3
Cromwell	50.9	54.3	55.2	54.8	55.8	54.3	57.9	60.3	65.7
Dunedin	65.1	69.4	70.5	70.1	71.3	69.4	74.0	77.0	84.0
Middlemarch	54.5	58.1	59.1	58.7	59.7	58.1	61.9	64.5	70.4
Milton	62.5	66.7	67.8	67.3	68.5	66.7	71.1	74.1	80.8
Mosgiel	67.3	71.7	72.9	72.4	73.7	71.7	76.5	79.7	86.9
Oamaru	66.2	70.6	71.8	71.3	72.6	70.6	75.3	78.4	85.5
Queenstown	56.4	60.1	61.1	60.7	61.8	60.1	64.1	66.7	72.8
Ranfurly	56.0	59.7	60.7	60.3	61.4	59.7	63.7	66.3	72.3
Roxburgh	52.9	56.4	57.3	56.9	58.0	56.4	60.1	62.6	68.3
Waikouaiti	69.6	74.2	75.4	74.9	76.3	74.2	79.1	82.4	89.9
Wanaka	57.7	61.6	62.6	62.2	63.3	61.6	65.6	68.4	74.6

Table 4-7: Modelled historic and projected rainfall depths (mm) for a 6-hour rain event with a 100-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Alexandra	61.4	65.6	66.6	66.2	67.4	65.6	69.9	72.9	79.6
Arrowtown	65.3	69.8	70.9	70.5	71.7	69.8	74.4	77.6	84.7
Balclutha	62.5	66.7	67.8	67.3	68.6	66.7	71.2	74.2	81.0
Brighton	71.9	76.8	78.1	77.6	79.0	76.8	81.9	85.4	93.3
Clyde	53.8	57.5	58.4	58.0	59.1	57.5	61.3	63.9	69.8
Cromwell	58.5	62.5	63.5	63.1	64.2	62.5	66.7	69.5	75.9
Dunedin	76.2	81.4	82.7	82.1	83.6	81.4	86.8	90.5	98.8
Middlemarch	63.4	67.7	68.8	68.4	69.6	67.7	72.2	75.3	82.2
Milton	72.7	77.6	78.9	78.4	79.8	77.6	82.8	86.3	94.2
Mosgiel	78.6	84.0	85.3	84.8	86.3	84.0	89.6	93.4	102.0
Oamaru	77.0	82.3	83.6	83.1	84.6	82.3	87.8	91.5	99.9
Queenstown	64.4	68.7	69.9	69.4	70.7	68.7	73.3	76.4	83.5
Ranfurly	64.8	69.2	70.3	69.8	71.1	69.2	73.8	76.9	84.0
Roxburgh	61.3	65.5	66.5	66.1	67.3	65.5	69.8	72.8	79.5
Waikouaiti	81.3	86.8	88.2	87.6	89.2	86.8	92.6	96.5	105.0
Wanaka	65.4	69.9	71.0	70.6	71.8	69.9	74.5	77.7	84.8

4.3.3 12-hour duration rainfall

Table 4-8 (50-year ARI) and Table 4-9 (100-year ARI) show modelled historic and projected rainfall depths for a 12-hour rain event. Rainfall depths are projected to increase across both future periods and for all climate change scenarios. Projected rainfall depth increases range from 6% (by 2040 and 2090 under RCP2.6) to 26% (by 2090 under RCP8.5).

Table 4-8: Modelled historic and projected rainfall depths (mm) for a 12-hour rain event with a 50-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Alexandra	65.0	68.7	69.7	69.3	70.4	68.7	72.7	75.4	81.5
Arrowtown	77.5	82.0	83.2	82.7	84.0	82.0	86.8	90.0	97.3
Balclutha	71.2	75.4	76.5	76.0	77.2	75.4	79.8	82.7	89.4
Brighton	85.2	90.2	91.4	90.9	92.4	90.2	95.4	98.9	107.0
Clyde	59.5	62.9	63.8	63.5	64.5	62.9	66.6	69.1	74.7
Cromwell	66.0	69.9	70.8	70.5	71.6	69.9	73.9	76.7	82.9
Dunedin	89.9	95.2	96.5	96.0	97.5	95.2	101.0	104.0	113.0
Middlemarch	71.7	75.9	76.9	76.5	77.7	75.9	80.3	83.2	90.0
Milton	83.3	88.2	89.4	88.9	90.3	88.2	93.3	96.8	105.0
Mosgiel	93.2	98.6	100.0	99.5	101.0	98.6	104.0	108.0	117.0
Oamaru	91.2	96.6	97.9	97.4	98.9	96.6	102.0	106.0	115.0
Queenstown	76.9	81.4	82.6	82.1	83.4	81.4	86.2	89.4	96.6
Ranfurly	67.3	71.3	72.3	71.9	73.0	71.3	75.4	78.2	84.5
Roxburgh	66.1	70.0	71.0	70.6	71.7	70.0	74.1	76.8	83.0
Waikouaiti	94.8	100.0	102.0	101.0	103.0	100.0	106.0	110.0	119.0
Wanaka	81.0	85.7	86.9	86.4	87.8	85.7	90.7	94.1	102.0

Table 4-9: Modelled historic and projected rainfall depths (mm) for a 12-hour rain event with a 100-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Alexandra	74.6	79.0	80.1	79.7	81.0	79.0	83.7	86.8	94.0
Arrowtown	88.0	93.3	94.6	94.1	95.6	93.3	98.8	103.0	111.0
Balclutha	82.5	87.4	88.7	88.2	89.6	87.4	92.6	96.1	104.0
Brighton	99.4	105.0	107.0	106.0	108.0	105.0	112.0	116.0	125.0
Clyde	67.9	72.0	73.0	72.6	73.8	72.0	76.2	79.1	85.6
Cromwell	75.3	79.8	80.9	80.5	81.8	79.8	84.5	87.7	94.9
Dunedin	105.0	111.0	113.0	112.0	114.0	111.0	118.0	122.0	132.0
Middlemarch	82.8	87.7	89.0	88.5	89.9	87.7	92.9	96.4	104.0
Milton	96.6	102.0	104.0	103.0	105.0	102.0	108.0	112.0	122.0
Mosgiel	109.0	115.0	117.0	116.0	118.0	115.0	122.0	126.0	137.0
Oamaru	106.0	112.0	114.0	113.0	115.0	112.0	119.0	123.0	134.0
Queenstown	87.3	92.5	93.8	93.3	94.8	92.5	98.0	102.0	110.0
Ranfurly	77.3	81.9	83.1	82.6	83.9	81.9	86.7	90.0	97.4
Roxburgh	76.0	80.5	81.7	81.2	82.5	80.5	85.3	88.5	95.8
Waikouaiti	110.0	117.0	119.0	118.0	120.0	117.0	124.0	129.0	139.0
Wanaka	91.4	96.8	98.2	97.7	99.2	96.8	103.0	106.0	115.0

4.3.4 24-hour duration rainfall

Table 4-10 (50-year ARI) and Table 4-11 (100-year ARI) show modelled historic and projected rainfall depths for a 24-hour rain event. Rainfall depths are projected to increase across both future periods and for all climate change scenarios. Projected rainfall depth increases range from 5% (by 2040 and 2090 under RCP2.6) to 23% (by 2090 under RCP8.5).

Table 4-10: Modelled historic and projected rainfall depths (mm) for a 24-hour rain event with a 50-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Alexandra	76.6	80.4	81.3	81.0	82.0	80.4	84.4	87.1	93.2
Arrowtown	102.0	107.0	108.0	107.0	109.0	107.0	112.0	115.0	124.0
Balclutha	92.7	97.3	98.5	98.0	99.3	97.3	102.0	105.0	113.0
Brighton	116.0	121.0	123.0	122.0	124.0	121.0	127.0	131.0	141.0
Clyde	72.9	76.5	77.4	77.1	78.1	76.5	80.3	82.9	88.7
Cromwell	81.6	85.7	86.7	86.3	87.5	85.7	89.9	92.8	99.3
Dunedin	121.0	127.0	128.0	128.0	129.0	127.0	133.0	137.0	147.0
Middlemarch	91.7	96.2	97.4	96.9	98.2	96.2	101.0	104.0	112.0
Milton	107.0	113.0	114.0	114.0	115.0	113.0	118.0	122.0	131.0
Mosgiel	125.0	131.0	133.0	132.0	134.0	131.0	138.0	142.0	152.0
Oamaru	121.0	127.0	129.0	128.0	130.0	127.0	134.0	138.0	148.0
Queenstown	101.0	106.0	107.0	107.0	108.0	106.0	111.0	115.0	123.0
Ranfurly	78.8	82.7	83.7	83.3	84.5	82.7	86.8	89.6	95.9
Roxburgh	80.7	84.7	85.7	85.3	86.5	84.7	88.9	91.8	98.2
Waikouaiti	123.0	129.0	131.0	130.0	132.0	129.0	136.0	140.0	150.0
Wanaka	108.0	113.0	114.0	114.0	115.0	113.0	119.0	122.0	131.0

Table 4-11: Modelled historic and projected rainfall depths (mm) for a 24-hour rain event with a 100-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Alexandra	87.0	91.4	92.5	92.1	93.3	91.4	96.0	99.2	106.0
Arrowtown	115.0	121.0	122.0	121.0	123.0	121.0	127.0	131.0	140.0
Balclutha	107.0	112.0	114.0	113.0	115.0	112.0	118.0	122.0	130.0
Brighton	134.0	141.0	143.0	142.0	144.0	141.0	148.0	153.0	164.0
Clyde	82.6	86.8	87.9	87.4	88.6	86.8	91.2	94.2	101.0
Cromwell	92.4	97.1	98.3	97.8	99.1	97.1	102.0	105.0	113.0
Dunedin	141.0	148.0	150.0	149.0	151.0	148.0	155.0	160.0	172.0
Middlemarch	105.0	110.0	112.0	111.0	113.0	110.0	116.0	120.0	128.0
Milton	124.0	130.0	132.0	131.0	133.0	130.0	137.0	142.0	152.0
Mosgiel	145.0	153.0	155.0	154.0	156.0	153.0	160.0	166.0	178.0
Oamaru	141.0	148.0	150.0	149.0	151.0	148.0	155.0	161.0	172.0
Queenstown	114.0	120.0	121.0	120.0	122.0	120.0	126.0	130.0	139.0
Ranfurly	89.8	94.3	95.5	95.0	96.4	94.3	99.1	102.0	110.0
Roxburgh	92.0	96.6	97.8	97.3	98.7	96.6	102.0	105.0	112.0
Waikouaiti	143.0	150.0	152.0	152.0	154.0	150.0	158.0	163.0	175.0
Wanaka	121.0	127.0	129.0	128.0	130.0	127.0	133.0	138.0	148.0

4.3.5 48-hour duration rainfall

Table 4-12 (50-year ARI) and Table 4-13 (100-year ARI) show modelled historic and projected rainfall depths for a 48-hour rain event. Rainfall depths are projected to increase across both future periods and for all climate change scenarios. Projected rainfall depth increases range from 4% (by 2040 and 2090 under RCP2.6) to 20% (by 2090 under RCP8.5).

Table 4-12: Modelled historic and projected rainfall depths (mm) for a 48-hour rain event with a 50-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Alexandra	86.2	89.9	90.0	90.5	91.6	89.9	93.9	96.6	103.0
Arrowtown	128.0	134.0	135.0	135.0	136.0	134.0	140.0	144.0	153.0
Balclutha	117.0	122.0	123.0	122.0	124.0	122.0	127.0	131.0	139.0
Brighton	152.0	158.0	160.0	159.0	161.0	158.0	165.0	170.0	181.0
Clyde	85.0	88.7	89.6	89.3	90.3	88.7	92.6	95.2	101.0
Cromwell	95.1	99.2	100.0	99.9	101.0	99.2	104.0	107.0	113.0
Dunedin	156.0	162.0	164.0	163.0	165.0	162.0	170.0	174.0	185.0
Middlemarch	112.0	117.0	119.0	118.0	120.0	117.0	123.0	126.0	134.0
Milton	132.0	138.0	140.0	139.0	141.0	138.0	144.0	148.0	158.0
Mosgiel	160.0	167.0	169.0	169.0	171.0	167.0	175.0	180.0	191.0
Oamaru	154.0	161.0	162.0	162.0	164.0	161.0	168.0	173.0	183.0
Queenstown	126.0	131.0	133.0	132.0	134.0	131.0	137.0	141.0	150.0
Ranfurly	89.8	93.7	94.7	94.3	95.5	93.7	97.9	101.0	107.0
Roxburgh	95.4	99.6	101.0	100.0	101.0	99.6	104.0	107.0	114.0
Waikouaiti	151.0	158.0	159.0	159.0	161.0	158.0	165.0	169.0	180.0
Wanaka	134.0	140.0	141.0	141.0	142.0	140.0	146.0	150.0	160.0

Table 4-13: Modelled historic and projected rainfall depths (mm) for a 48-hour rain event with a 100-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Alexandra	96.8	101.0	102.0	102.0	103.0	101.0	106.0	109.0	116.0
Arrowtown	144.0	150.0	152.0	151.0	153.0	150.0	157.0	162.0	172.0
Balclutha	134.0	139.0	141.0	140.0	142.0	139.0	146.0	150.0	159.0
Brighton	176.0	184.0	186.0	185.0	187.0	184.0	192.0	197.0	210.0
Clyde	95.5	99.7	101.0	100.0	102.0	99.7	104.0	107.0	114.0
Cromwell	107.0	111.0	113.0	112.0	114.0	111.0	116.0	120.0	127.0
Dunedin	181.0	189.0	191.0	190.0	192.0	189.0	197.0	203.0	216.0
Middlemarch	128.0	134.0	135.0	135.0	136.0	134.0	140.0	144.0	153.0
Milton	152.0	159.0	161.0	160.0	162.0	159.0	166.0	171.0	182.0
Mosgiel	186.0	194.0	196.0	195.0	198.0	194.0	203.0	209.0	222.0
Oamaru	179.0	186.0	188.0	188.0	190.0	186.0	195.0	200.0	213.0
Queenstown	141.0	147.0	149.0	148.0	150.0	147.0	154.0	158.0	168.0
Ranfurly	102.0	106.0	107.0	107.0	108.0	106.0	111.0	114.0	121.0
Roxburgh	108.0	113.0	114.0	113.0	115.0	113.0	118.0	121.0	129.0
Waikouaiti	175.0	183.0	185.0	184.0	186.0	183.0	191.0	196.0	209.0
Wanaka	150.0	156.0	158.0	158.0	159.0	156.0	163.0	168.0	179.0

4.4 Dry days

Key messages

- By 2040 under RCP4.5 the number of dry days per year decreases near the coast and parts of Central Otago (1-4 fewer dry days per year), with increases of 1-6 more annual dry days for many remaining parts of Otago.
- By 2090 under RCP8.5, decreases in annual dry days of 2-6 days are projected for coastal and some central parts of Otago, with increases of 2-10 more dry days per year for many remaining parts of Otago.
- Seasonally, the largest changes are projected for winter and summer by 2090 under RCP8.5: e.g. 4-10 fewer *winter* dry days projected for many western parts of Otago, with 2-8 more *summer* dry days projected for western and inland parts of Otago.

A dry day considered here is when < 1 mm of rainfall is recorded. Present-day (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for dry days are shown in this section. The present-day maps show annual and seasonal average numbers of dry days and the future projection maps show the change in the number of dry days compared with present. Note that the present-day maps are on a different colour scale to the future projection maps.

At present, the largest annual number of dry days is experienced in parts of Central Otago and about Oamaru (275-300 days per year; Figure 4-17). Areas around Dunedin, the Taieri Plains, Balclutha and Queenstown average around 225-250 dry days per year. Southern-most and northwestern areas of Otago experience the fewest annual dry days for the region, averaging 150-175 dry days per year. Winter is typically the season with the largest number of dry days, with 60-80 dry days for much of the region Figure 4-19. Spring typically has the fewest dry days (50-70 dry days for much of the region).

By 2040 under RCP4.5 (Figure 4-18), the number of dry days per year decreases near the coast and parts of Central Otago (1-4 fewer dry days per year), with increases of 1-6 more annual dry days for many remaining parts of Otago. This pattern is amplified under RCP8.5 at 2040 and RCP4.5 and RCP8.5 at 2090 (decreasing dry days for central and coastal areas and increasing dry days for many other areas). By 2090 under RCP8.5, decreases in annual dry days are projected for coastal and some central parts of Otago (2-6 fewer dry days per year), with increases of 2-10 more dry days per year for many remaining parts of Otago.

Seasonal projections of change in dry days are shown for RCP4.5 by 2040 (Figure 4-20) and 2090 (Figure 4-22), and RCP8.5 by 2040 (Figure 4-21) and 2090 (Figure 4-23). Generally, decreases in dry days are projected for winter (whole region) and spring and autumn (eastern areas), and increases are projected for summer (whole region) and for spring and autumn (western/inland areas). The changes generally get larger with time and emission scenario. The largest changes are projected for winter and summer by 2090 under RCP8.5. For example, 4-10 fewer winter dry days are projected for many western parts of Otago by 2090 under RCP8.5. During summer, 2-8 more dry days are projected for western and inland parts of Otago by 2090 under RCP8.5.

Table 4-14 shows the present and future projected dry days for the model grid point closest to specific locations in the Otago region. Alexandra currently experiences 286 dry days per year, which is the highest of the 16 Otago locations presented. In future, Alexandra is projected to experience five fewer dry days per year (by 2090 under RCP8.5). Wanaka and Arrowtown are projected to experience seven and five more dry days per year by 2090 under RCP8.5, respectively.

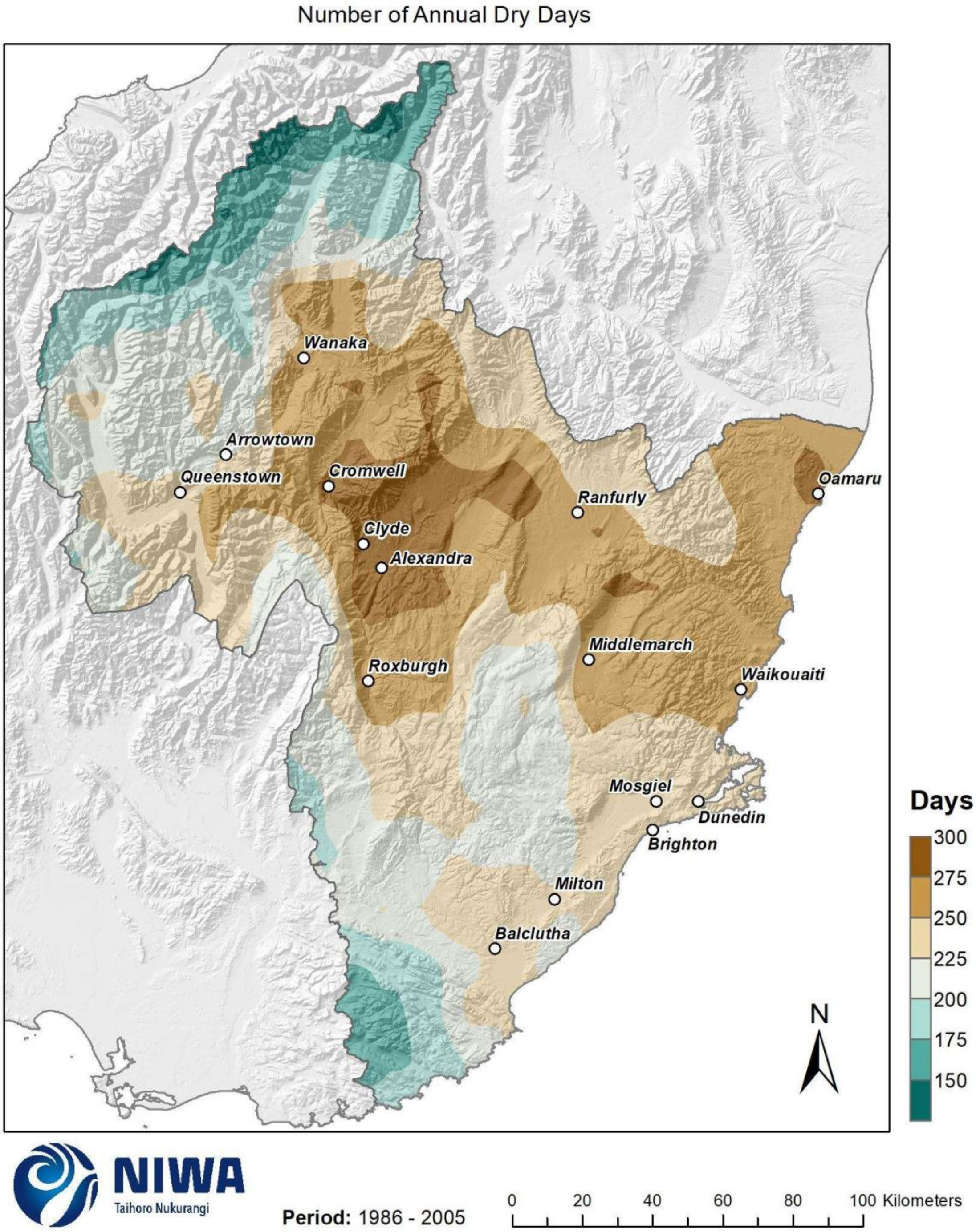


Figure 4-17: Modelled annual number of dry days (daily rainfall <1mm), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

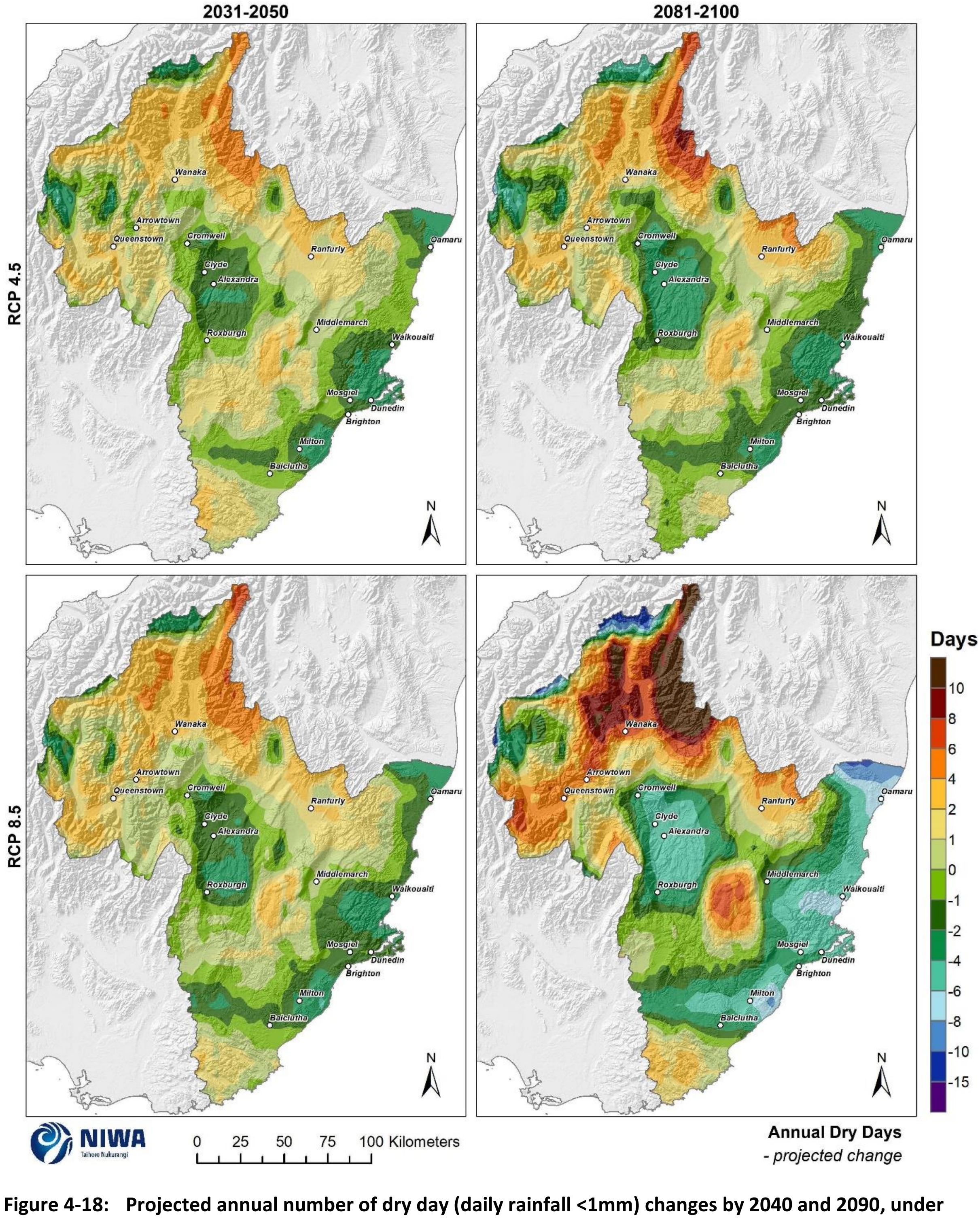


Figure 4-18: Projected annual number of dry day (daily rainfall <1mm) changes by 2040 and 2090, under RCP4.5 and RCP8.5. Climate change scenarios: RCP4.5 (top panels) and RCP8.5 (bottom panels). Time periods: mid-century (2031-2050; "2040" – panels on left) and end-century (2081-2100; "2090" – panels on right). Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

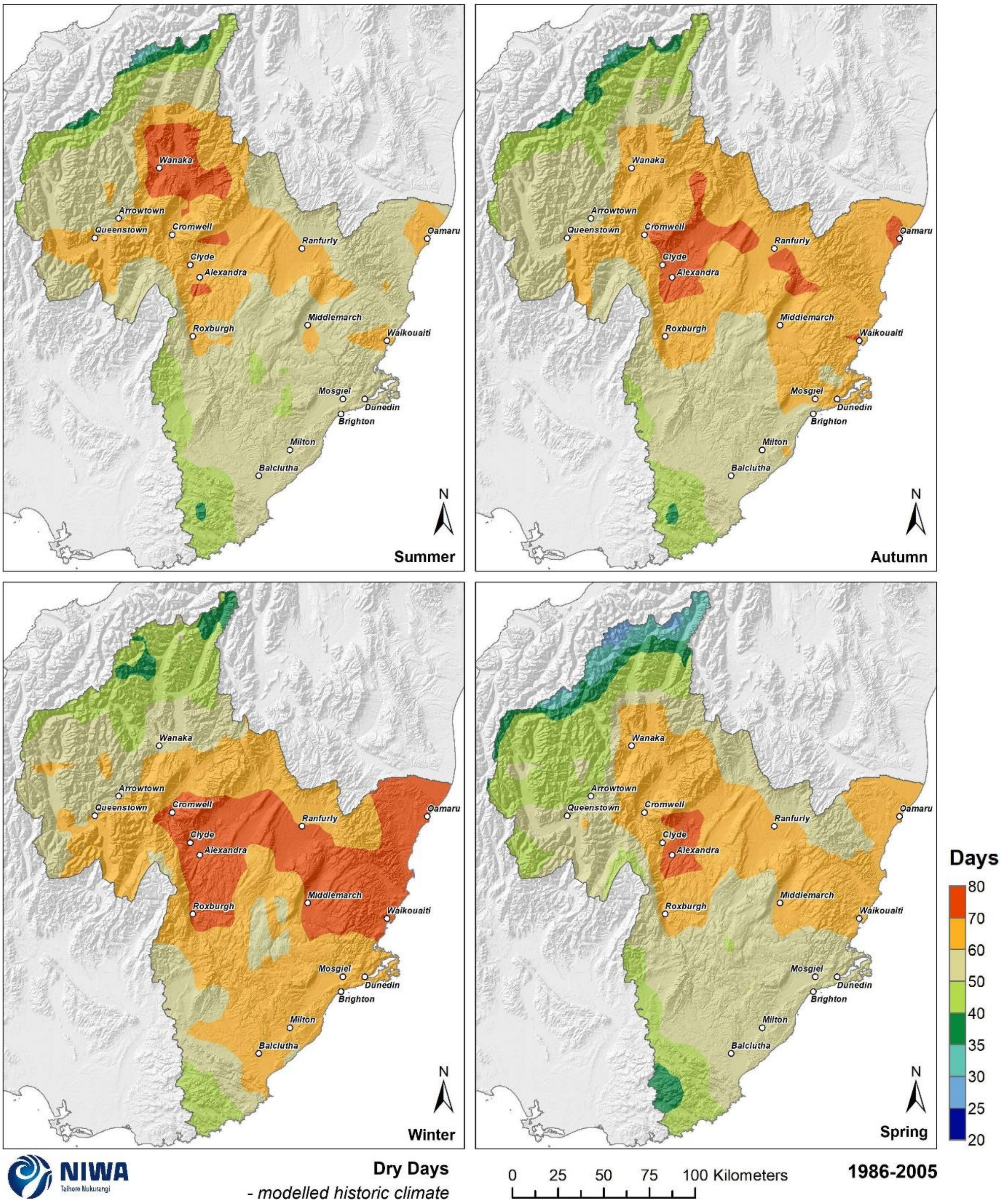


Figure 4-19: Modelled seasonal number of dry days (daily rainfall <1mm), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

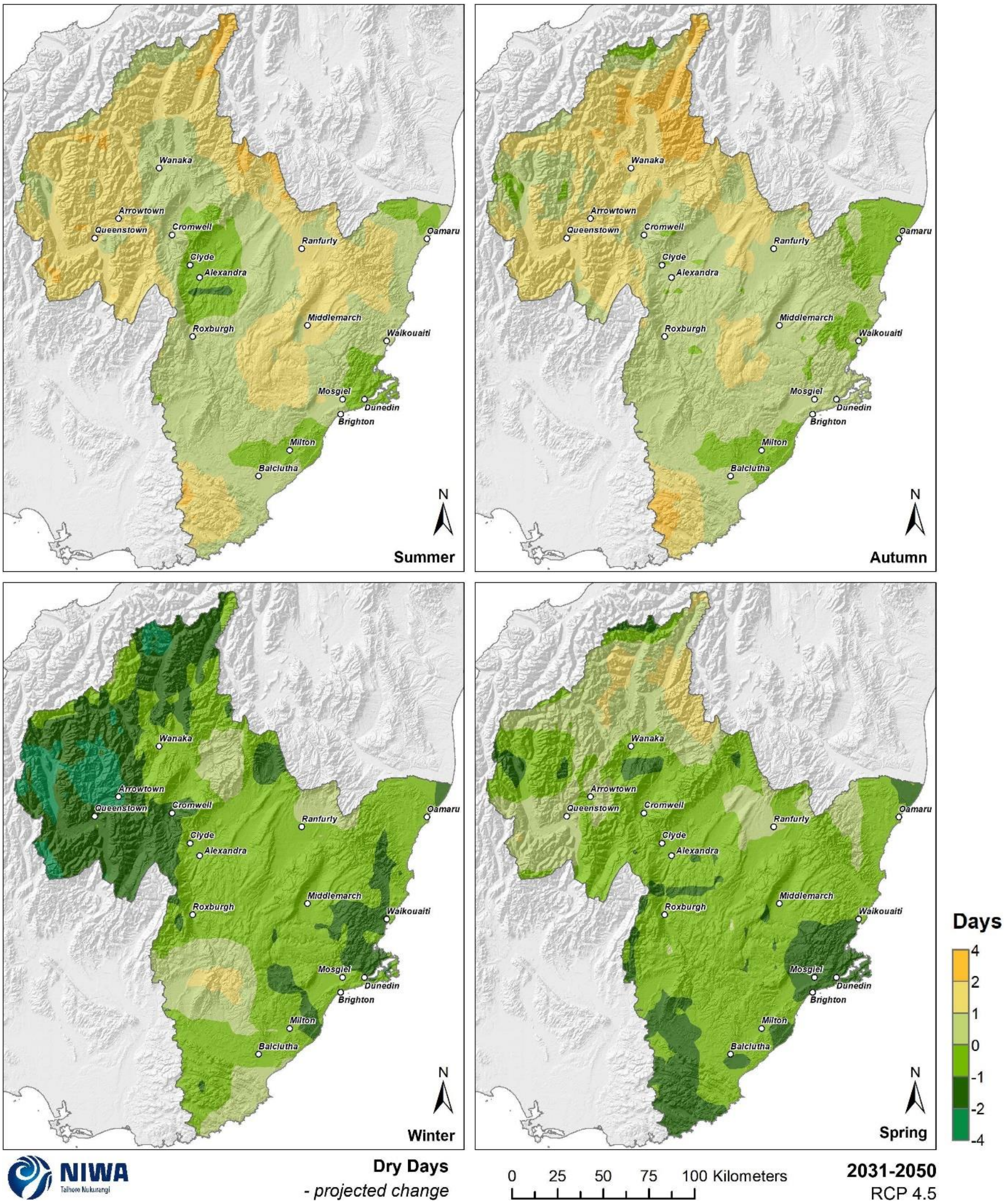


Figure 4-20: Projected seasonal number of dry day (daily rainfall <1mm) changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

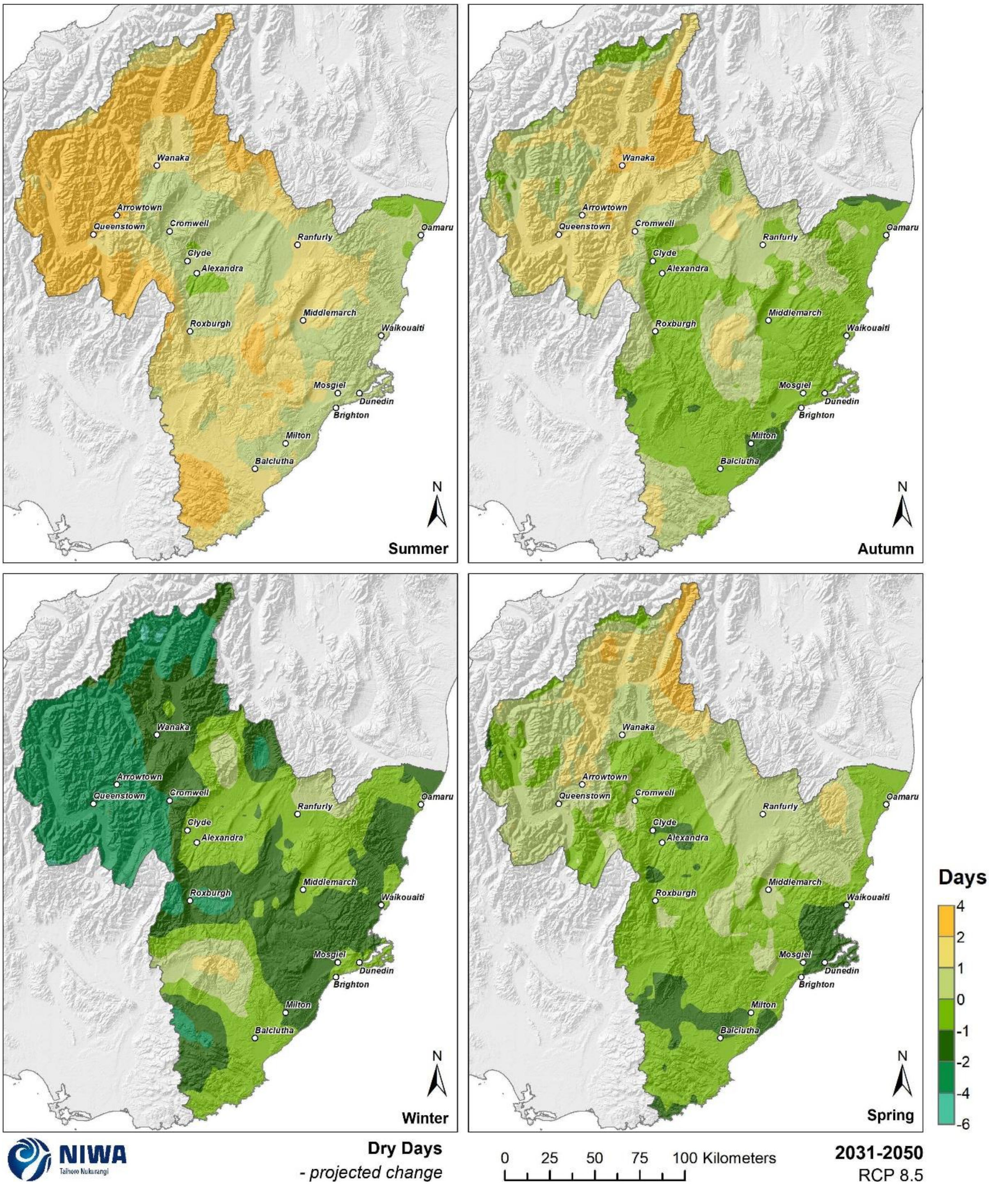


Figure 4-21: Projected seasonal number of dry day (daily rainfall <1mm) changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

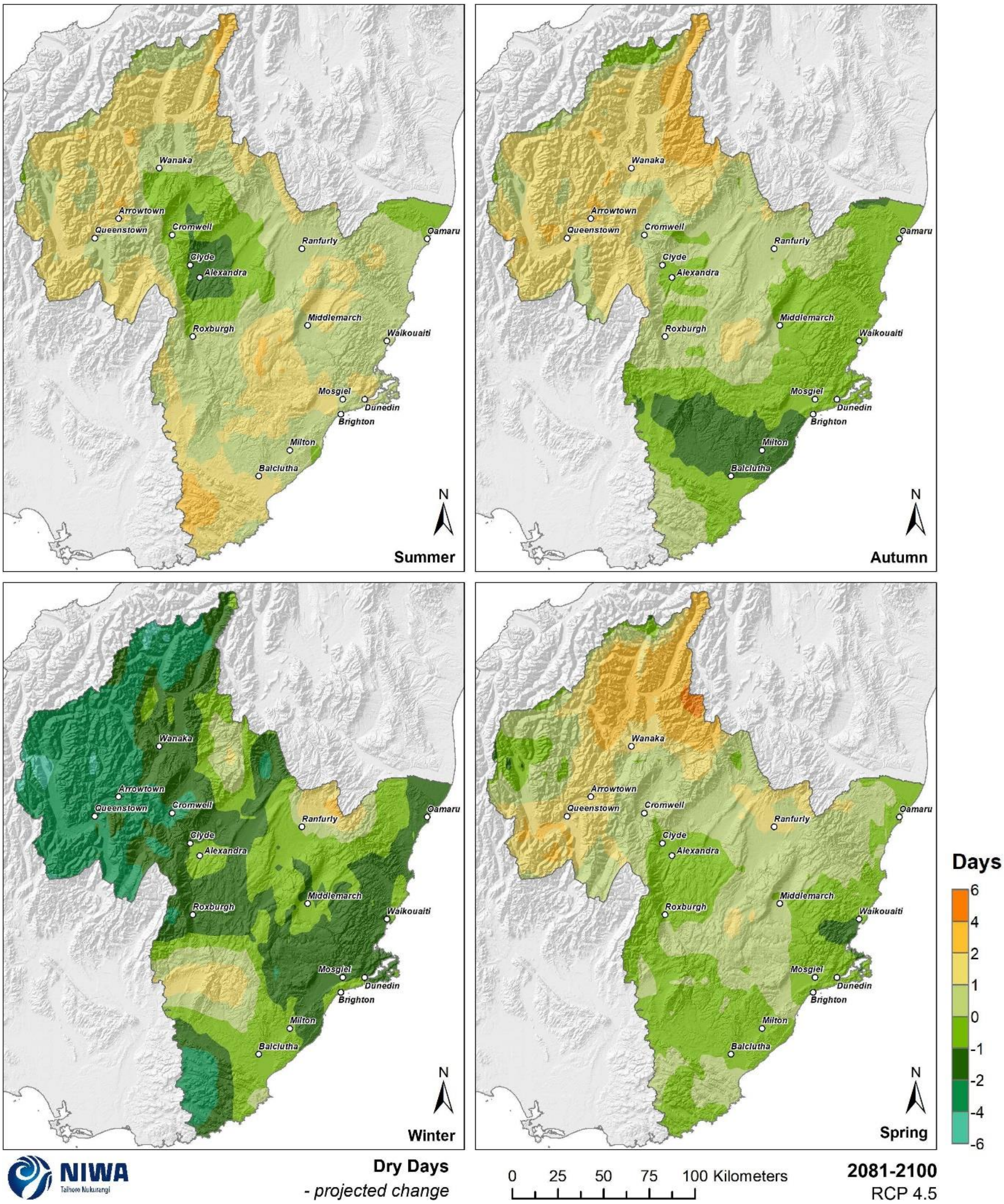


Figure 4-22: Projected seasonal number of dry day (daily rainfall <1mm) changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

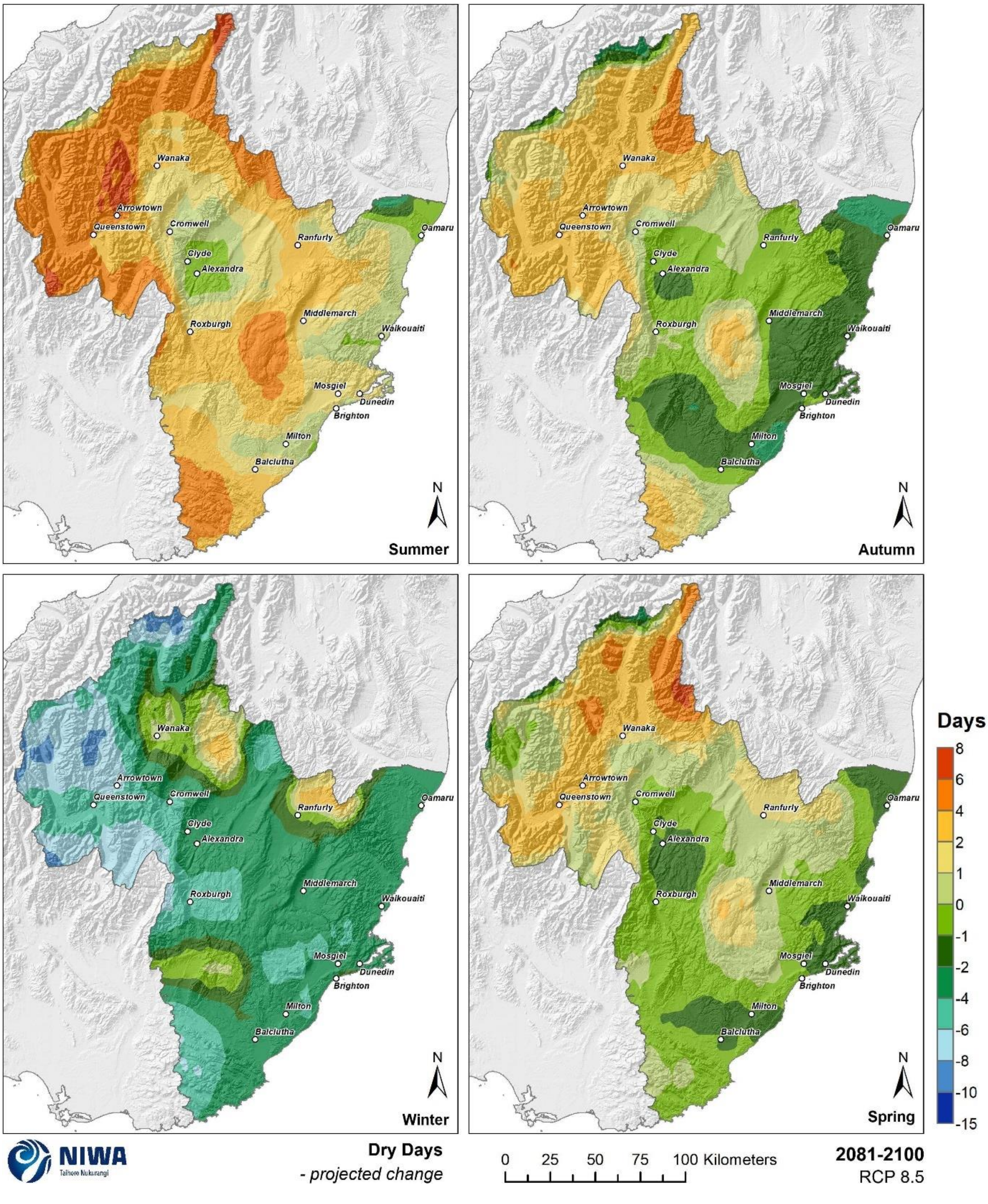


Figure 4-23: Projected seasonal number of dry day (daily rainfall <1mm) changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 4-14: Modelled seasonal and annual average number of dry days (<1 mm) for present and two climate change scenarios (RCP4.5 and RCP8.5) at two future time periods . Time periods: present (1986-2005), mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models. Annual ("Ann"); Seasons: summer ("Sum"), autumn ("Aut"), winter ("Win") and spring ("Spr").

	PRESENT				
	Sum	Aut	Win	Spr	Ann
Alexandra	69	72	75	71	286
Arrowtown	59	56	58	49	222
Balclutha	55	57	63	55	230
Brighton	53	59	62	55	229
Clyde	67	71	74	69	282
Cromwell	69	70	74	68	281
Dunedin	56	62	67	58	244
Middlemarch	62	69	74	64	267
Milton	53	57	64	55	229
Mosgiel	55	62	67	57	241
Oamaru	65	71	77	67	280
Queenstown	62	59	60	53	233
Ranfurly	62	69	71	64	266
Roxburgh	62	66	72	63	264
Waikouaiti	63	71	76	66	275
Wanaka	72	64	57	64	257

		2040					2090				
		Sum	Aut	Win	Spr	Ann	Sum	Aut	Win	Spr	Ann
Alexandra	RCP4.5	0	0	0	-1	-1	-1	0	-1	0	-2
	RCP8.5	0	0	0	-1	-1	0	-1	-3	-1	-5
Arrowtown	RCP4.5	+1	+1	-3	0	-1	+2	+2	-3	+2	+1
	RCP8.5	+3	+1	-4	+1	+1	+6	+3	-7	+3	+5
Balclutha	RCP4.5	0	0	0	-1	-1	+1	-1	0	0	-1
	RCP8.5	+1	-1	0	-1	-1	+1	-1	-2	-1	-3
Brighton	RCP4.5	0	0	0	-1	-1	+1	-1	-1	-1	-1
	RCP8.5	+1	-1	-1	-1	-1	+1	-1	-2	-1	-3
Clyde	RCP4.5	-1	0	0	-1	-2	-1	0	-1	0	-3
	RCP8.5	0	0	0	-1	-2	0	-1	-3	-1	-5
Cromwell	RCP4.5	0	+1	-1	-1	-1	-1	+1	-2	0	-2
	RCP8.5	0	+1	-2	0	-1	+1	+1	-4	-1	-3
Dunedin	RCP4.5	0	0	-1	-1	-2	+1	0	-1	-1	-1
	RCP8.5	+1	0	0	-1	-1	+1	-1	-3	-1	-4
Middlemarch	RCP4.5	+1	0	0	0	+1	+1	0	-1	0	0
	RCP8.5	+1	0	-1	0	0	+1	-1	-3	0	-2
Milton	RCP4.5	0	0	-1	-1	-2	+1	-2	-1	0	-2
	RCP8.5	+1	-1	-1	-1	-2	+1	-2	-3	-1	-6
Mosgiel	RCP4.5	0	0	-1	-1	-1	+1	-1	-1	-1	-1
	RCP8.5	+1	0	-1	-1	-2	+1	-1	-3	-1	-4
Oamaru	RCP4.5	0	-1	0	-1	-2	0	-1	-1	-1	-2
	RCP8.5	0	-1	-1	-1	-2	0	-2	-3	-2	-7
Queenstown	RCP4.5	+1	+2	-2	+1	+2	+1	+2	-2	+2	+3
	RCP8.5	+2	+1	-3	+1	+1	+4	+3	-5	+3	+4
Ranfurly	RCP4.5	+1	+1	0	0	+2	+1	0	0	+1	+2
	RCP8.5	+1	0	0	+1	+2	+2	0	-1	+1	+2
Roxburgh	RCP4.5	0	+1	-1	-1	-1	0	0	-2	0	-2
	RCP8.5	+1	0	-2	0	-2	+2	0	-5	-1	-4
Waikouaiti	RCP4.5	+1	0	-1	-1	-1	+1	-1	-1	-1	-2
	RCP8.5	+1	-1	-1	-1	-2	0	-2	-3	-1	-6
Wanaka	RCP4.5	0	+2	0	0	+1	0	+1	-1	+1	+1
	RCP8.5	+1	+2	-1	0	+2	+2	+3	0	+2	+7

4.5 Snow days

Key message
• The number of snow days reduces everywhere, with the largest reduction in the coldest mountainous areas where there are a relatively large number of snow days in the present climate.

Snow days were estimated by counting precipitation days where the mean temperature was below freezing point. As such, it is a fairly crude measure of snow days. It is likely the modelled number of present (1986-2005) snow days (Figure 4-24 and Table 4-15) is underestimated, particularly for low elevation locations where snowfall often occurs when the ambient air temperature is at or above 0°C. Nevertheless, this measure provides a reference to which future changes can be compared. The modelled present-day conditions suggest that 0-1 snow days per year occur for low elevation areas, and 1-5 days per year for the Maniototo. 10-30 snow days per year occur in higher elevation parts of the region. In the future, the number of snow days reduces everywhere, with the largest reduction (>15 days) in the coldest mountainous areas where there are a relatively large number of snow days in the present climate (Figure 4-25).

A factor needing further analysis is the potential change in snow amounts. In general, climate simulations show a reduction in snow days. It is possible snow amount could increase with rising temperatures in certain circumstances; a warmer atmosphere can hold more moisture, and on a day where temperatures are higher but still cool enough to snow, there is potential for increased heavy snowfalls. No analysis of snow extremes has been carried out at this point, however.

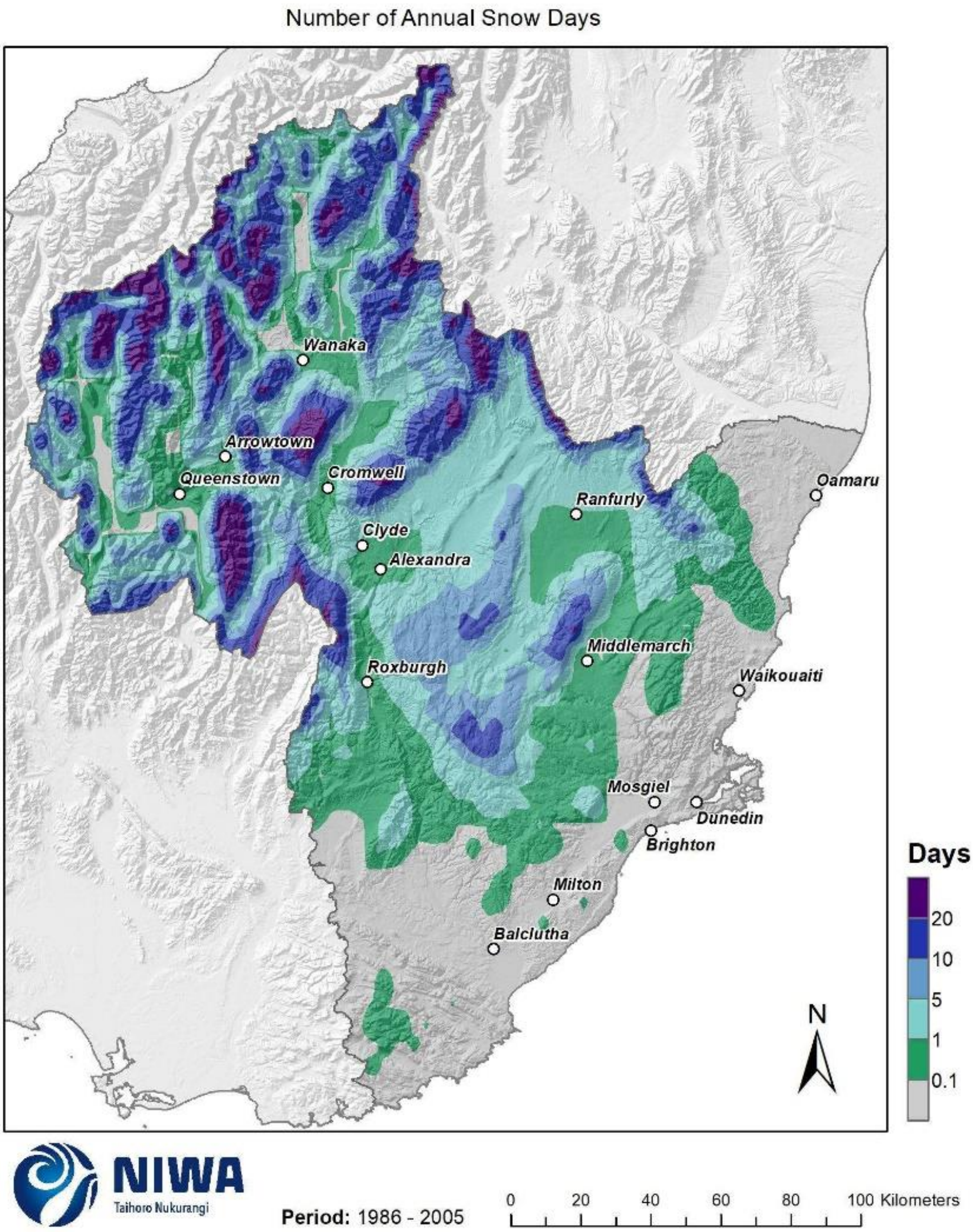


Figure 4-24: Modelled annual number of snow days, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

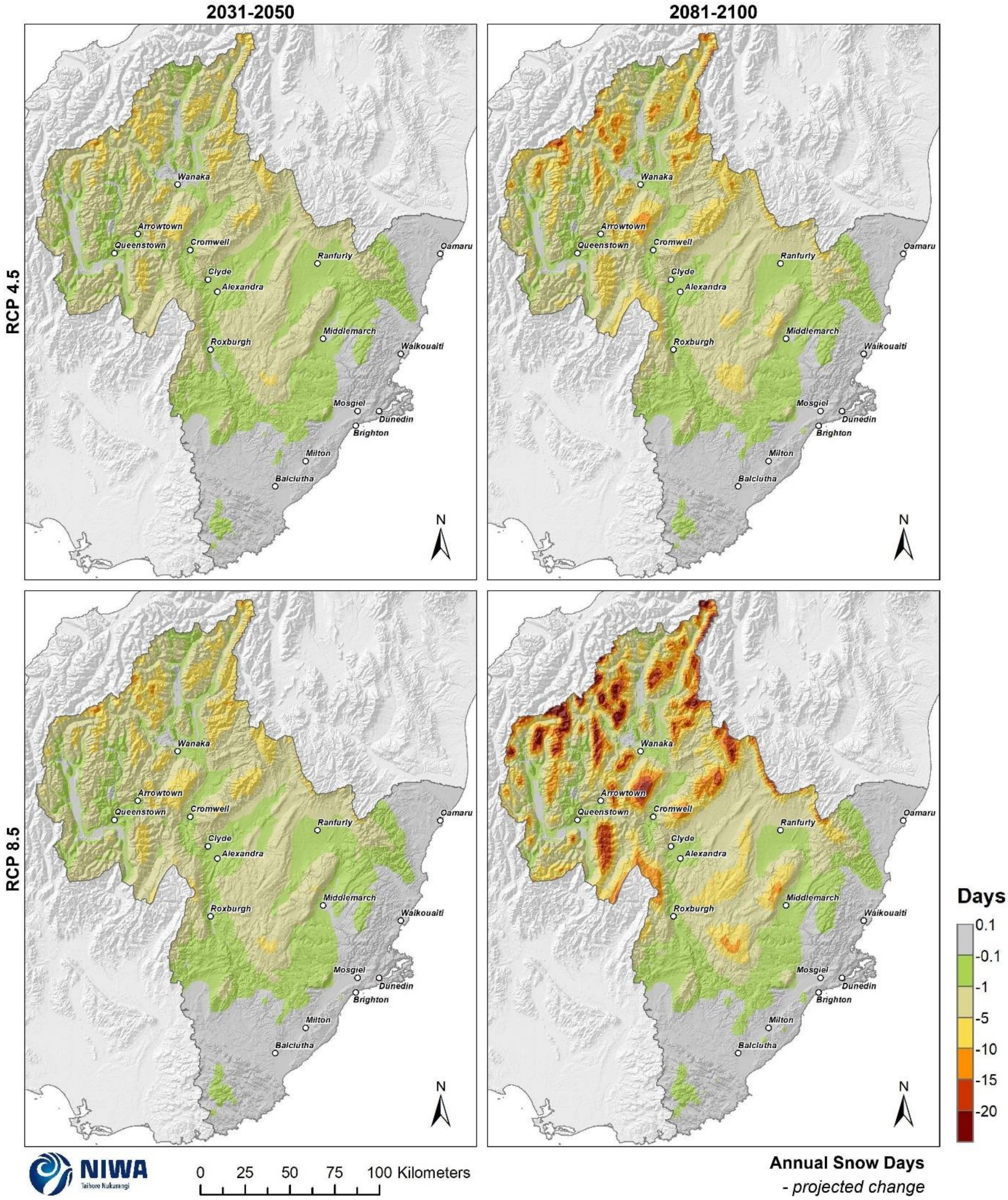


Figure 4-25: Projected change in the number of annual snow days by 2040 and 2090, under RCP4.5 and RCP8.5. Climate change scenarios: RCP4.5 (top panels) and RCP8.5 (bottom panels). Time periods: mid-century (2031-2050; "2040" – panels on left) and end-century (2081-2100; "2090" – panels on right). Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 4-15: Modelled annual average number of snow days for present and two climate change scenarios (RCP4.5 and RCP8.5) at two future time periods. Future projections are shown as the total future projected number of snow days outside the parentheses, and future change inside the parentheses. Time periods: present (1986-2005), mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models.

		2040		2090	
	PRESENT	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Alexandra	0.3	0.1 (-0.2)	0.1 (-0.2)	0.1 (-0.2)	0.0 (-0.3)
Arrowtown	0.8	0.2 (-0.6)	0.2 (-0.6)	0.1 (-0.7)	0.0 (-0.8)
Balclutha	0.0	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Brighton	0.0	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Clyde	0.6	0.2 (-0.4)	0.2 (-0.4)	0.2 (-0.4)	0.0 (-0.6)
Cromwell	0.3	0.1 (-0.2)	0.1 (-0.2)	0.0 (-0.3)	0.0 (-0.3)
Dunedin	0.0	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Middlemarch	0.2	0.0 (-0.2)	0.1 (-0.1)	0.0 (-0.2)	0.0 (-0.2)
Milton	0.0	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Mosgiel	0.0	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Oamaru	0.0	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Queenstown	0.5	0.1 (-0.4)	0.2 (-0.3)	0.1 (-0.4)	0.0 (-0.5)
Ranfurly	0.8	0.4 (-0.4)	0.3 (-0.5)	0.2 (-0.6)	0.0 (-0.8)
Roxburgh	0.1	0.0 (-0.1)	0.0 (-0.1)	0.0 (-0.1)	0.0 (-0.1)
Waikouaiti	0.0	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Wanaka	0.3	0.2 (-0.1)	0.0 (-0.3)	0.0 (-0.3)	0.0 (-0.3)

5 Wind

Modelled wind data have not had bias correction processes applied as has been carried out for temperature and rainfall data. The bias correction process corrects the historic modelled data to observed values (the Virtual Climate Station Network, which is interpolated climate station data across New Zealand), and there is not enough historic VCSN data coverage for wind to undertake this procedure. This means that current modelled wind conditions are different to actual observed conditions, and therefore not useful for understanding current wind conditions in Otago. For this reason, only the future *relative changes* in this variable has been mapped here using the modelled climate data. By doing this, the effect of biases in absolute values of these variables are minimised.

5.1 Extreme wind

Key messages

- The future magnitude of the 99th percentile daily mean wind speed is projected to decrease about the eastern coast of Otago, and increase for inland areas about Central Otago and the Southern Lakes.
- Inland areas about Clyde, Cromwell and Queenstown are projected to observe an increase in extreme wind of 6-12% by 2090 under RCP8.5.

Extreme wind is considered here as the 99th percentile of daily mean wind speeds. This equates to the top 1% of daily mean winds recorded, i.e. about the top three windiest days each year. The annual extreme wind from 2000 to 2018 is shown for several Otago locations in Figure 5-1. During this period, the average annual extreme wind speed for Dunedin was 29.7 km/h, whilst in Ranfurly the average was 23.2 km/h.

In the future (Figure 5-2), the magnitude of 99th percentile daily mean wind speed is typically projected to decrease about the eastern coast of Otago, and increase for inland areas about Central Otago and the Southern Lakes. Decreases of 2-6% are projected for eastern areas about Dunedin and Oamaru by 2040 under RCP4.5. By 2090 under RCP8.5, inland areas about Clyde, Cromwell and Queenstown are projected to observe an increase in extreme wind of 6-12%.

Table 5-1 shows the projected change in extreme winds by 2040 and 2090 for the model grid point closest to specific locations in the Otago region.

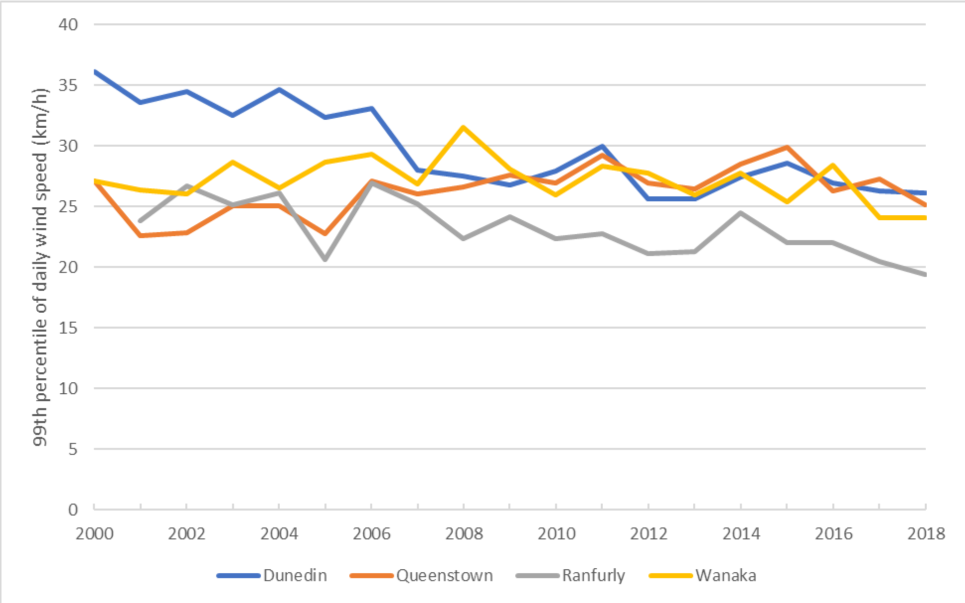


Figure 5-1: 99th percentile of daily wind speed (km/h), 2000-2018. Stations used: Dunedin Musselburgh EWS, Queenstown Aero AWS, Wanaka Aero AWS and Ranfurly EWS.

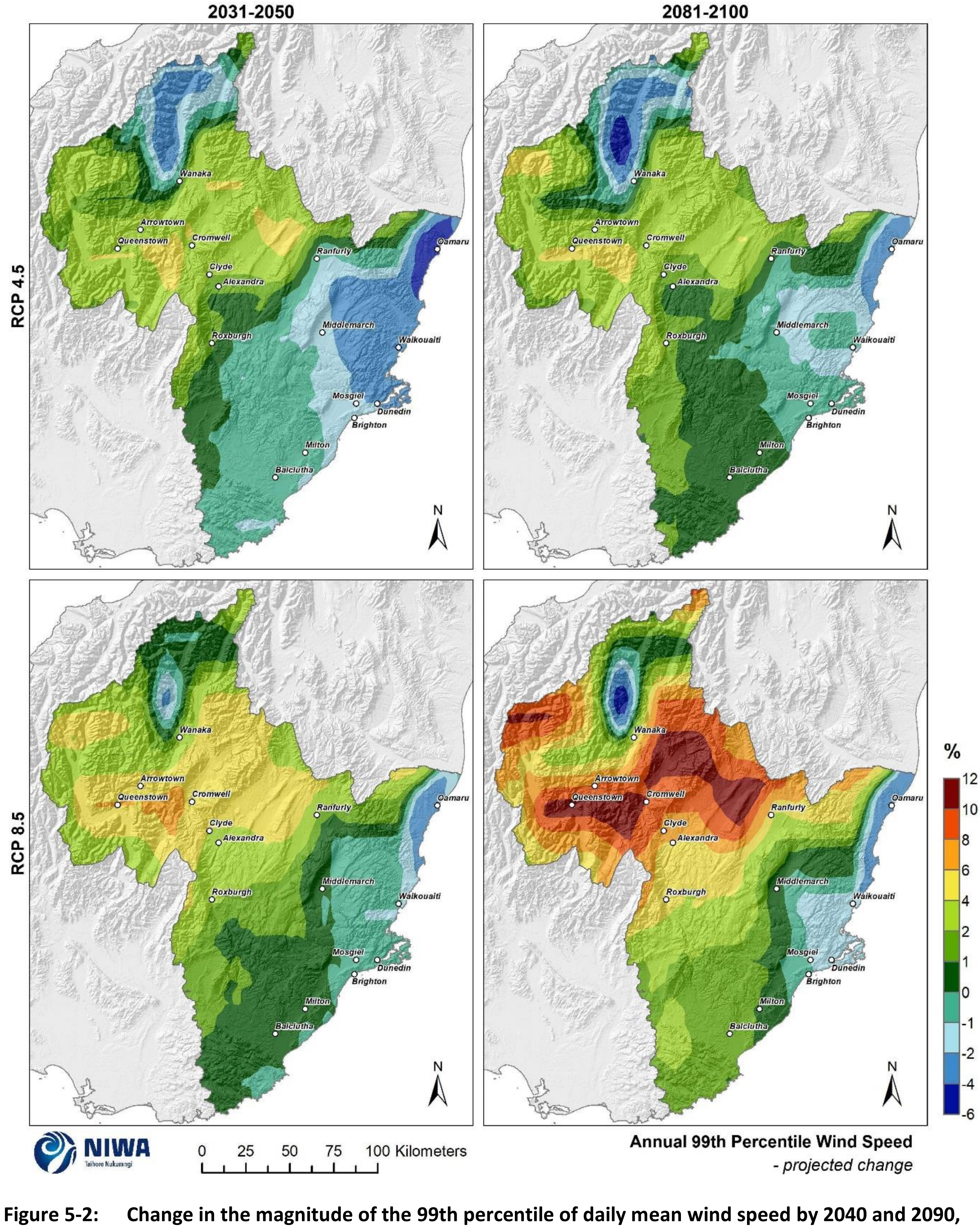


Figure 5-2: Change in the magnitude of the 99th percentile of daily mean wind speed by 2040 and 2090, for RCP4.5 and RCP8.5. Climate change scenarios: RCP4.5 (top panels) and RCP8.5 (bottom panels). Time periods: mid-century (2031-2050; "2040" – panels on left) and end-century (2081-2100; "2090" – panels on right). Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 5-1: Modelled change in the magnitude (%) of the 99th percentile of daily mean wind speed by 2040 and 2090, for RCP4.5 and RCP8.5. Note, values shown are the percentage change compared to present (1986-2005). Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models.

	2040		**2090**	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Alexandra	+1.5	+3.4	+1.1	+6.4
Arrowtown	+2.9	+4.7	+2.6	+7.6
Balclutha	-0.8	+0.3	+0.5	+1.5
Brighton	-1.5	-0.1	-0.6	-0.6
Clyde	+2.3	+4.0	+1.7	+7.4
Cromwell	+3.8	+5.5	+3.2	+9.8
Dunedin	-2.0	-0.3	-0.6	-1.3
Middlemarch	-1.5	+0.1	-1.0	+0.3
Milton	-0.7	+0.2	+0.4	+0.8
Mosgiel	-1.6	-0.1	-0.6	-0.8
Oamaru	-5.3	-2.3	-2.9	-3.3
Queenstown	+3.9	+6.1	+4.0	+10.8
Ranfurly	-0.3	+2.8	+0.9	+6.0
Roxburgh	+1.1	+2.3	+2.0	+4.5
Waikouaiti	-2.8	-0.9	-0.7	-1.3
Wanaka	+0.5	+2.2	-0.5	+3.8

6 Hydrological impacts of climate change

Key messages

- By the end of the century and with increased emissions, average annual flows are expected to increase across the region (above 50% across all FMUs[2] except headwaters of Taieri and North Otago).
- Large decrease in low flow expected with time and increased radiative forcing for North Otago and Taieri FMUs.
- Mean annual flood is expected to become larger everywhere, with increases up to 100% in some locations by the end of the century.

This section covers the projected differences in several hydrological statistics between the baseline period (1986-2005) and two future periods. These are mid-century (2036-2056) and late-century (2086-2099), and are slightly different from the corresponding time slices of the atmospheric modelling because the modelling was done before this project was initiated. We do not expect that the conclusions drawn would be substantively different if the periods were aligned. The statistics include:

- The Q95% flow[3];
- Mean annual and seasonal discharges;
- The mean annual flood (MAF); and
- Surface water supply reliability

6.1 Low flow

The projected future differences in the Q95% flows for all four RCPs and two time periods are presented in Figure 6-1 and Figure 6-2. There are both increases and decreases projected for the management units of interest, with the more pronounced differences generally manifesting themselves during the late-century period and under higher RCPs. Increases in Q95% are more tangible and consistent in FMU headwaters such as Clutha/Mata Au FMU, mountain ranges between Taieri and North Otago FMUs (increasing by up to 50%) and the Dunedin Coast FMU. Decreases are modelled in all units but consistently in the headwaters of the Taieri FMU and Manuherikia Rohe, dropping below -20%.

[2] FMU: Freshwater Management Unit
[3] Q95: Flow that is exceeded 95 percent of the time

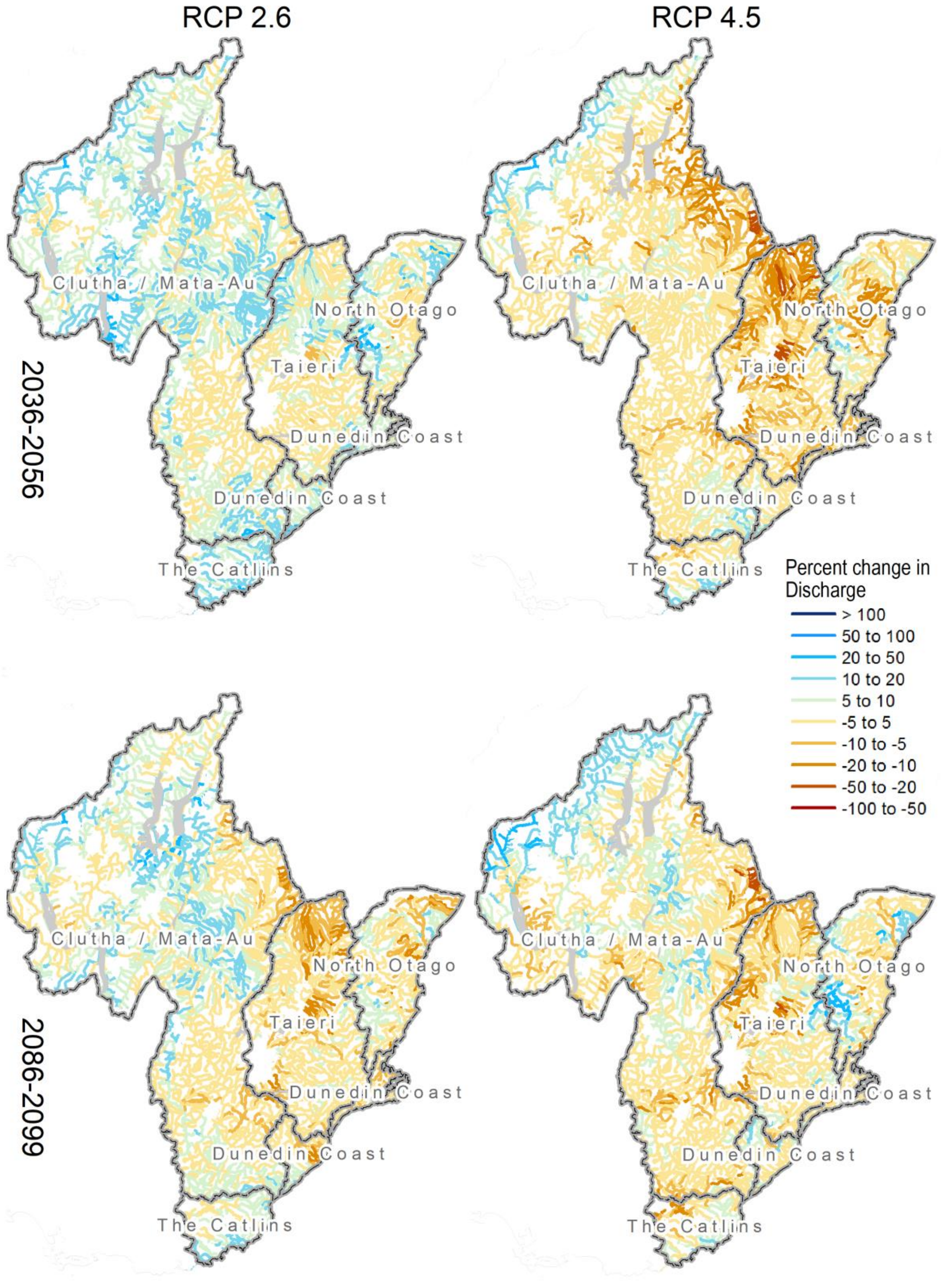


Figure 6-1: Percent changes in multi-model median Q95% across Otago for mid (top) and end of century (bottom). Climate change scenarios: RCP2.6 (left panels) and RCP4.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

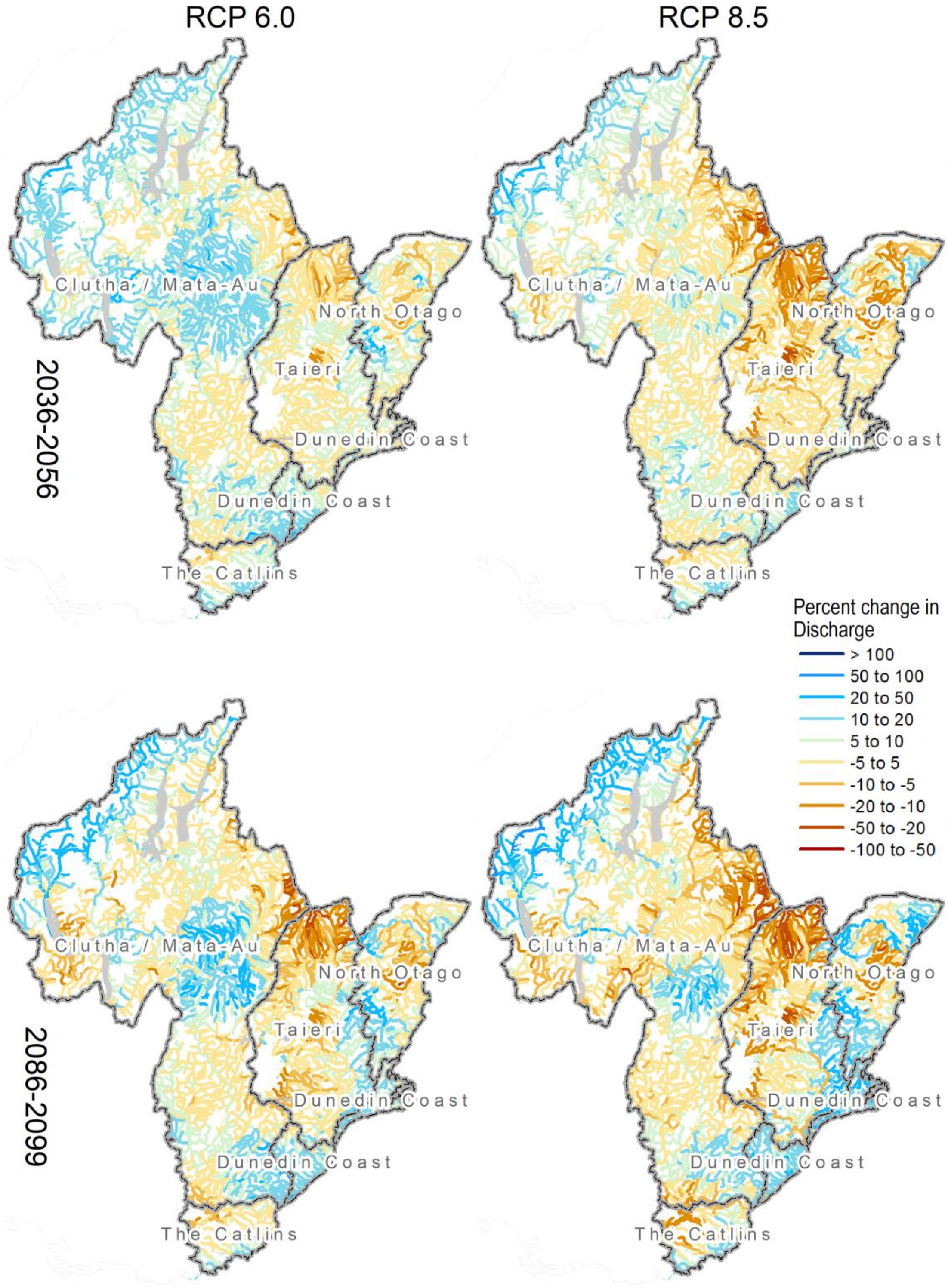


Figure 6-2: Percent changes in multi-model median Q95% across Otago for mid (top) and end of century (bottom). Climate change scenarios: RCP6.0 (left panels) and RCP8.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

6.2 Mean annual discharge

The projected future differences in the annual discharges for all four RCPs and two time periods are presented in Figure 6-3 and Figure 6-4. At the annual scale, mean discharges consistently decrease by mid-century across the FMUs. By late century, mean discharge increase with radiative forcing (up to 50%) except for the headwaters of the Taieri and North Otago FMUs.

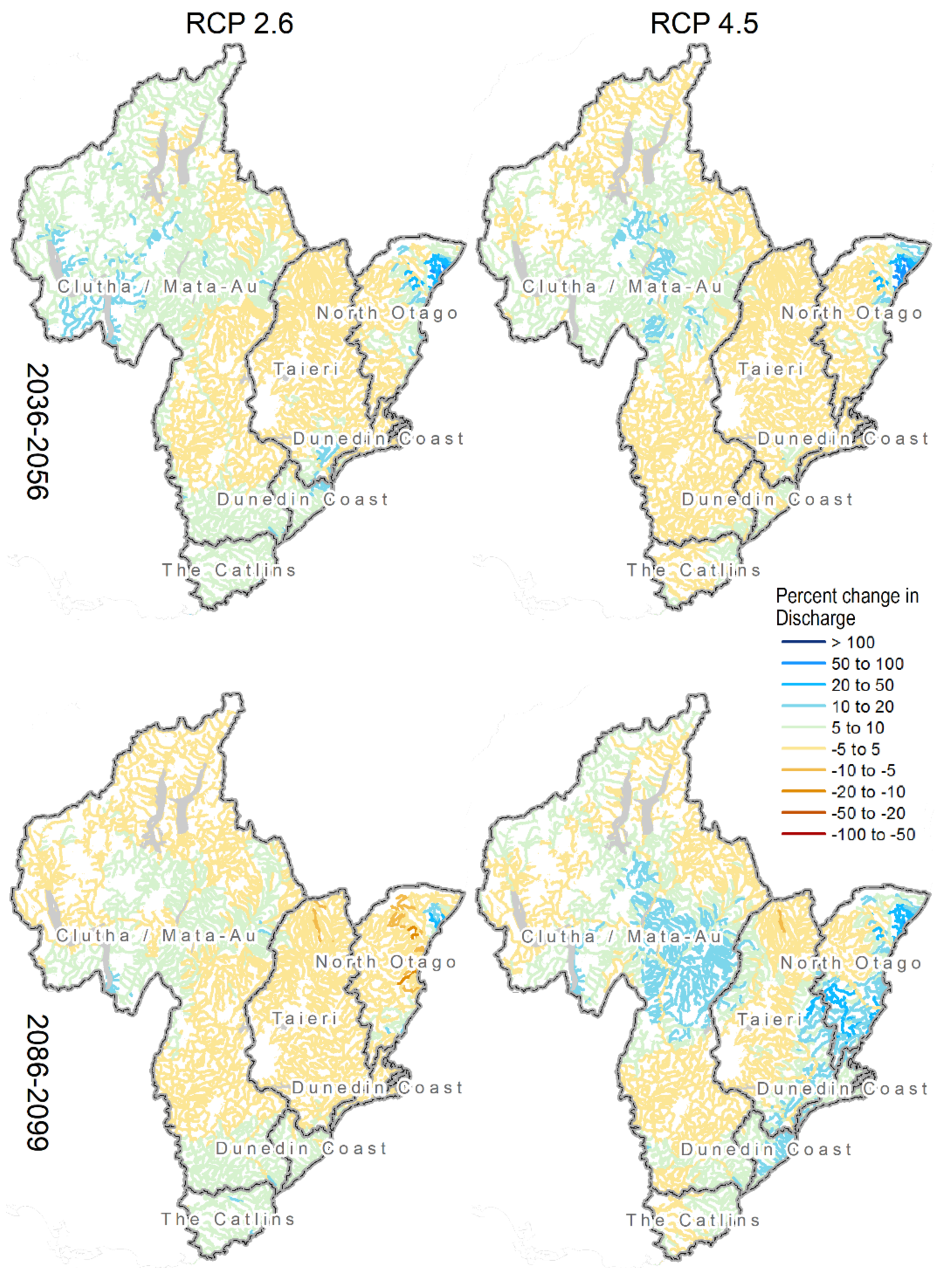


Figure 6-3: Percent changes in multi-model median of the mean discharge across Otago for mid (top) and late-century (bottom). Climate change scenarios: RCP2.6 (left panels) and RCP4.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

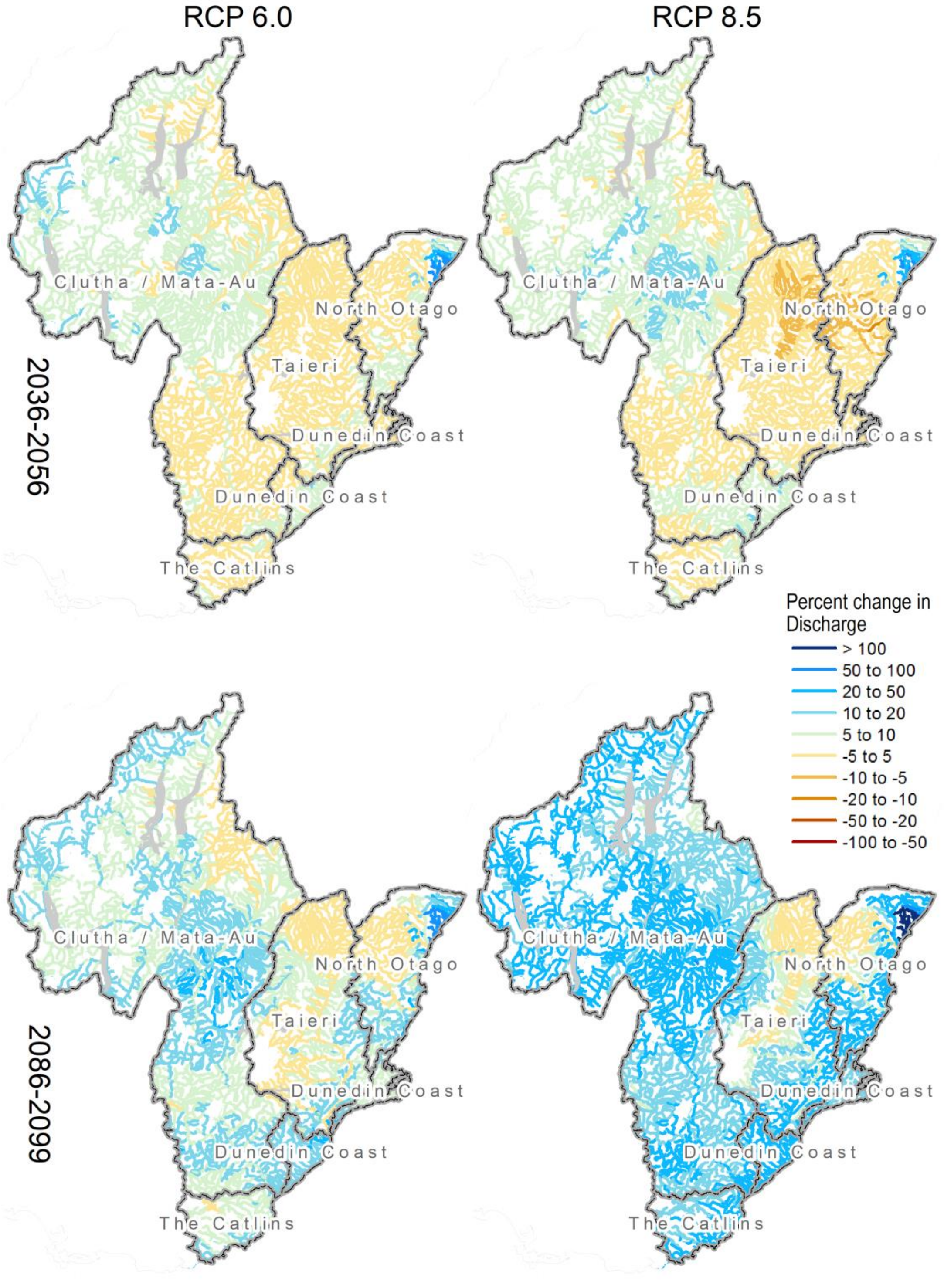


Figure 6-4: Percent changes in multi-model median of the mean discharge across Otago for mid (top) and late-century (bottom). Climate change scenarios: RCP6.0 (left panels) and RCP8.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

6.3 Mean annual flood

The projected future differences in the mean annual flood (MAF) for all four RCPs and two time periods are presented in Figure 6-5 and Figure 6-6. While there are some pockets of little change or decreasing MAF, in general Otago is projected to experience an increase in MAF, with some increases exceeding 100%. There is little difference among the RCPs during the mid-century period, but by late-century, the increases in MAF become larger and more extensive progressively from RCP4.5 to RCP8.5.

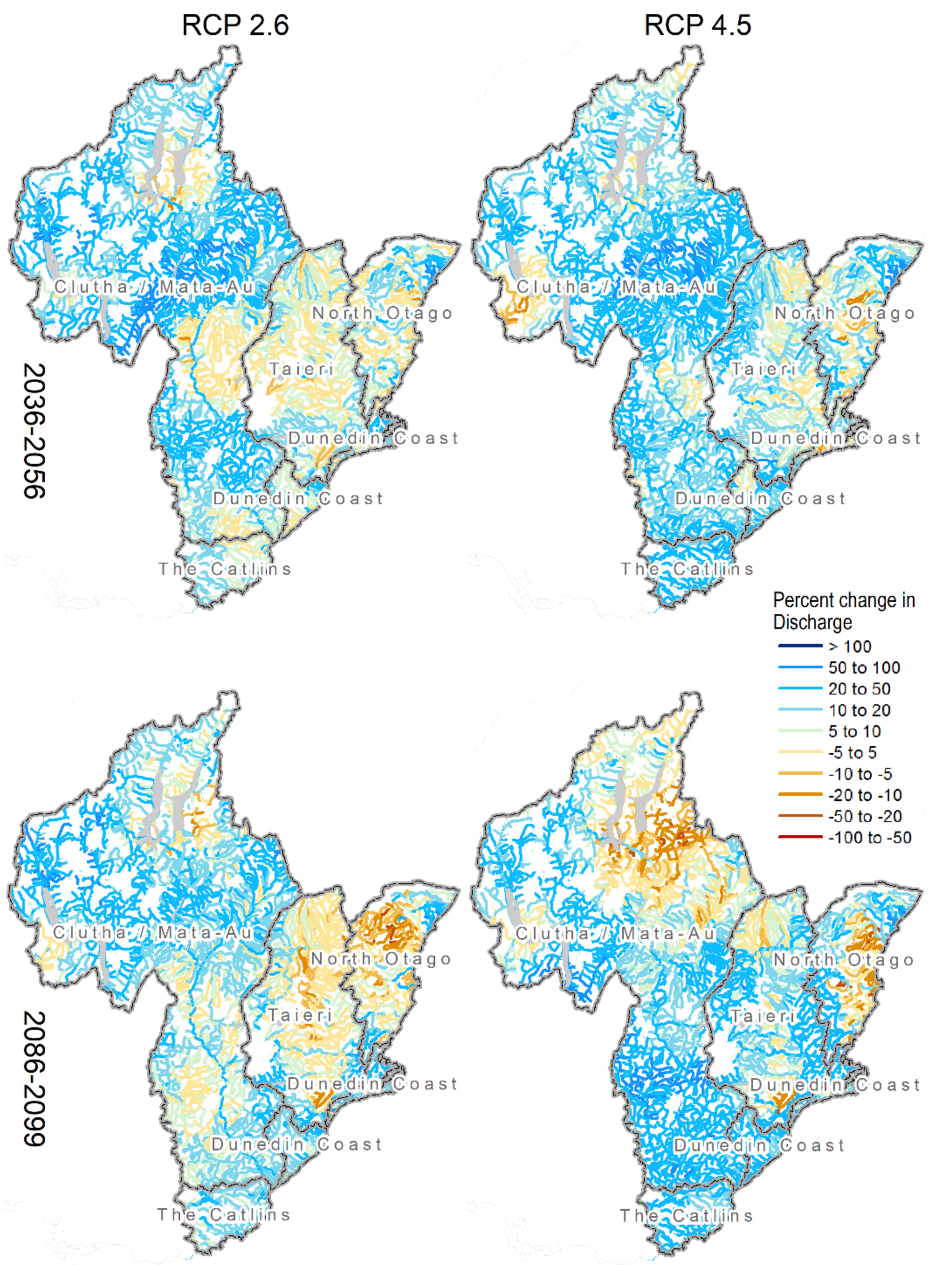


Figure 6-5: Percent changes in multi-model median of MAF across Otago for mid (top) and end of century (bottom). Climate change scenarios: RCP2.6 (left panels) and RCP4.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

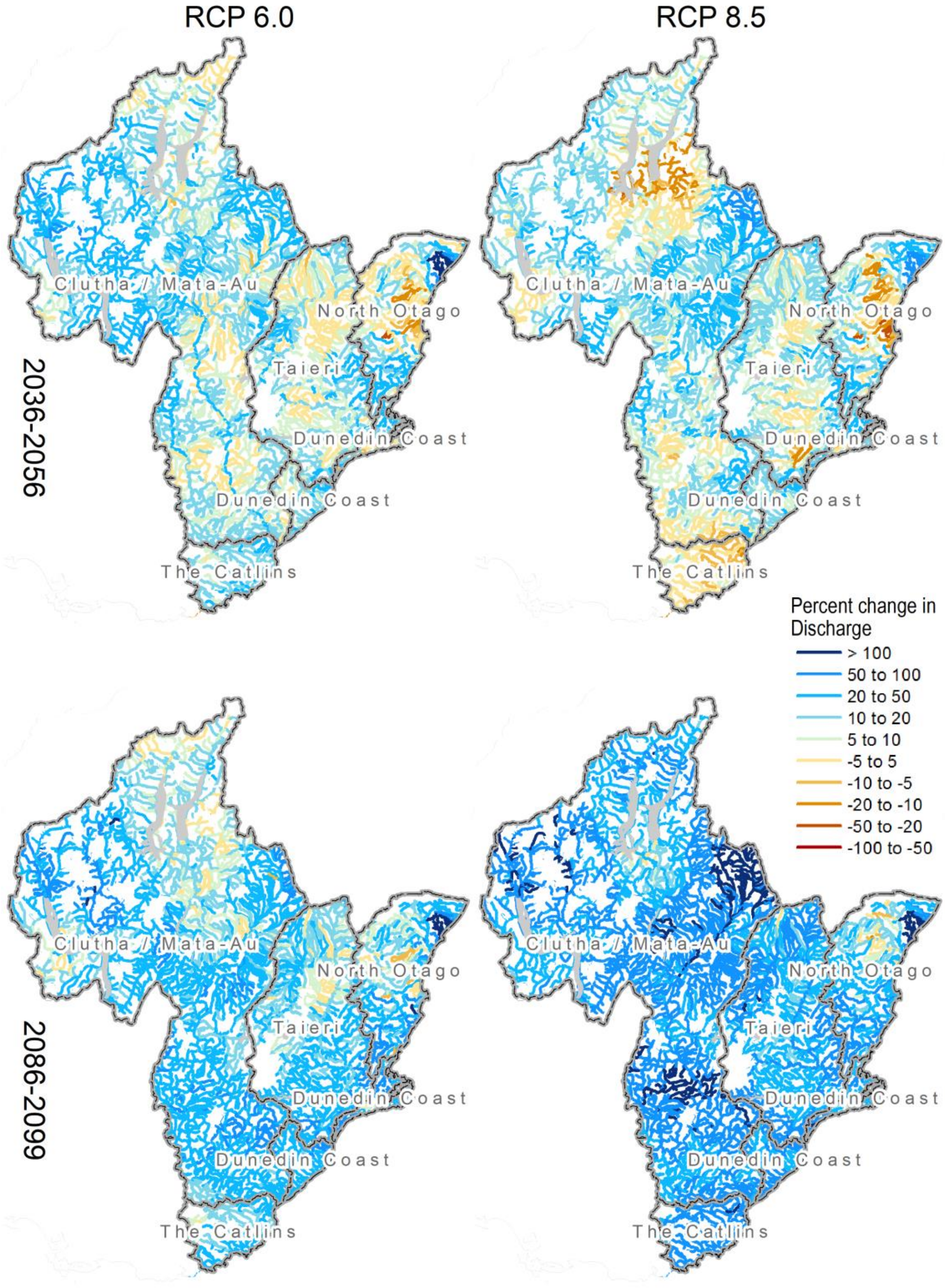


Figure 6-6: Percent changes in multi-model median of MAF across Otago for mid (top) and end of century (bottom). Climate change scenarios: RCP6.0 (left panels) and RCP8.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

The increase in MAF is a change that is largely consistent with the changes to rainfall presented in Ministry for the Environment (2018), especially regarding the 99th percentile of daily rainfall. Analysis of flow records indicates that MAF has a strong correspondence with observed mean annual rainfall (Henderson et al., 2018). It is noteworthy that flood design standards for significant infrastructure are usually made based on events with annual exceedance probabilities much smaller than that represented by MAF (i.e. much rarer events like the 1-in-100-year flood event). Analysis of RCM rainfall projections undertaken for the High Intensity Rainfall Design project (Carey-Smith et al., 2018), has shown that rainfall events with small annual exceedance probability are projected to increase ubiquitously across the country in a way that scales with increasing temperatures. As such, MAF, with its relatively common (annual) occurrence, should not be considered a comprehensive metric for the possible impact of climate change on large, rare floods in New Zealand.

6.4 Surface water supply reliability

Surface water supply reliability refers to the duration of time river water abstraction is unconstrained[4]. The projected future differences in the surface water supply reliability for all four RCPs and two time periods are presented in Figure 6-7 and Figure 6-8. Little appreciable change in reliability is projected across most of the Otago region, with most parts of the region exhibiting slight increases but some with slight decreases. Mountain ranges between North Otago and Taieri FMU are expected to experience an increase in reliability increasing with radiative forcing, while the headwaters of North Otago FMU are expected to experience the largest decrease in flow reliability.

[4] Surface water supply reliability is the fraction of time that the flow is equal to or below the threshold for minimum flows (based on the Proposed National Environmental Standard for Ecological Flows), and in this case without accounting for any water takes. This ranges from 0 to 1 (or 0 to 100 per cent) and is often between 0.9 and 1.0 for New Zealand's rivers. Note that this statistic only considers surface water flows, not groundwater.

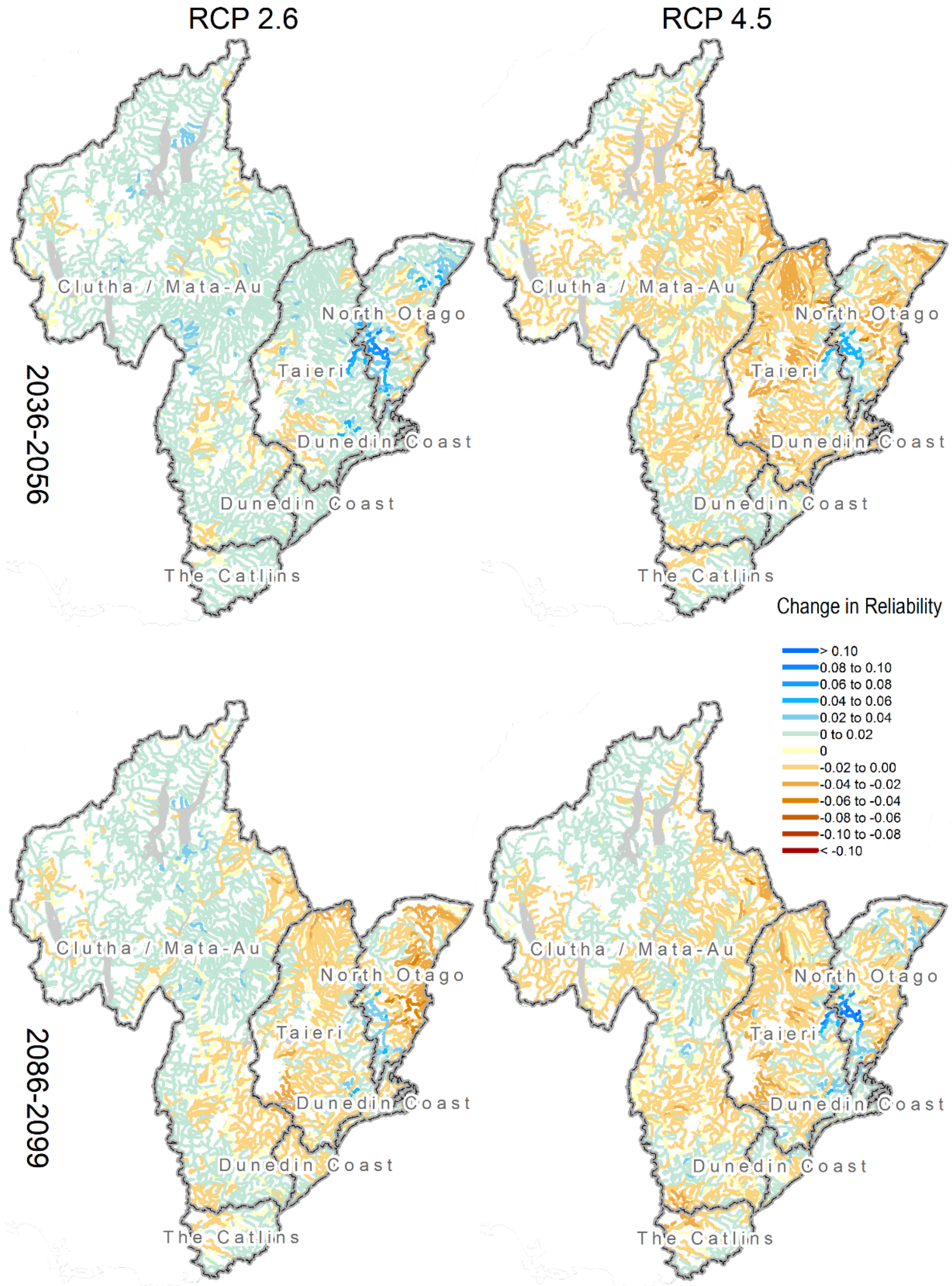


Figure 6-7: Absolute changes in multi-model median of surface water supply reliability across Otago for mid (top) and end of century (bottom). Climate change scenarios: RCP2.6 (left panels) and RCP4.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

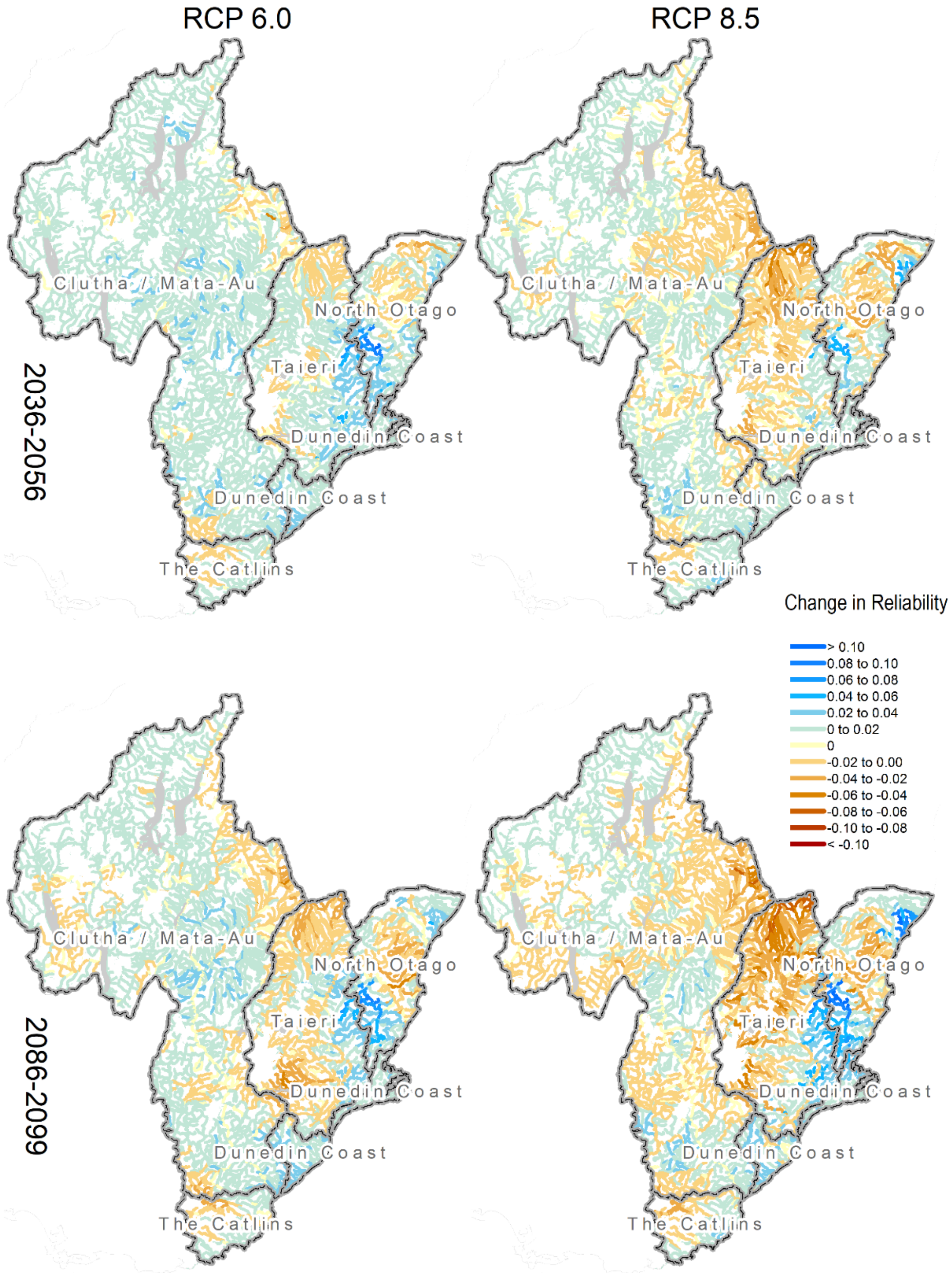


Figure 6-8: Absolute changes in multi-model median of surface water supply reliability across Otago for mid (top) and end of century (bottom). Climate change scenarios: RCP6.0 (left panels) and RCP8.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

7 Limitations

As with any modelling exercise, there are limitations on the results and use of the data. This section outlines some of these limitations and caveats that should be considered when using the results in this report.

- The maps and tables presented in this report (except the model confidence sections 3.1.1 and 4.1.1) show the average of six dynamically downscaled global climate models. This is a relatively small number of models and a clear shift in the distribution of potential future outcomes is not available. This is particularly important when considering extremes (e.g. extreme hot days, extreme rainfall), where the models considered here may not accurately capture how rare events are changing.
- The average of six models is used in this report, which gives no indication of the range of results that the models project. However, the six models chosen represented historic climate conditions in New Zealand well, and span a range of future outcomes. Using the average balances out the errors that may be apparent in each model.
- The time periods chosen for historic and future projection span 20-year periods. This is seen as a relatively short timeframe to understand average conditions in the historic period and in the future, as there is likely an influence of underlying climate variability (e.g. decadal signals from climate drivers like the El Niño-Southern Oscillation etc.). However, the IPCC uses 20-year periods so we have followed that approach for consistency.
- Care needs to be taken when interpreting grid-point-scale projections such as those presented in the tables in this report. The underlying climate data are Virtual Climate Station data, which are interpolated from physical climate stations. Therefore, the data from these grid points may be slightly different to on-the-ground observations, due to the interpolation procedure (particularly if the grid point is surrounded by multiple different stations or if there are no stations nearby). It is useful to look at broader patterns between grid points, e.g. coast vs. inland, and the magnitude of change at different time periods and scenarios, when considering the values.

Although there are limitations and caveats to the approach used here, these climate change projections are the best currently available for New Zealand. A considerable amount of research time has been dedicated to undertaking the modelling and validation of the results, and the projections provide context to base risk assessments and adaptation plans on.

8 Summary and conclusions

This report presents climate change projections for Otago. Present-day climatic conditions are presented to provide a context for future changes. The future changes discussed in this report consider differences between the historical period 1986-2005 and two future time-slices, 2031-2050 and 2081-2100. Note, the modelled differences between two time periods should not be attributed solely to climate change, as natural climate variability is also present and may add to or subtract from the climate change effect. The effect of natural variability has been reduced by averaging results from six GCM simulations, but it will still be present.

It is internationally accepted that further climate changes will result from increasing amounts of anthropogenically produced greenhouse gases in the atmosphere. The influence from anthropogenic greenhouse gas contributions to the global atmosphere is the dominant driver of climate change conditions, and it will continue to become more dominant if there is no slowdown in emissions, according to the IPCC. In addition, the climate will vary from year to year and decade to decade owing to natural variability.

Notably, future climate changes depend on the pathway taken by the global community (i.e. through mitigation of greenhouse gas emissions or a 'business as usual' approach). The global climate system will respond differently to future pathways of greenhouse gas concentrations. The representative concentration pathway approach taken here reflects this variability through the consideration of multiple scenarios (i.e. RCP4.5, the mid-range scenario, and RCP8.5, the business-as-usual scenario). The six climate models used to project New Zealand's future climate were chosen by NIWA because they produced the most accurate results when compared to historical climate and circulation patterns in the New Zealand and southwest Pacific region. They were as varied as possible to span the likely range of model sensitivity. The average of outputs from all six models (known as the 'ensemble average'), is presented in the climate change projection maps in this report. The ensemble-average was presented as this usually performs better in climate simulations than any individual model (the errors in different models are compensated).

Changes to Otago's future climate are likely to be significant. An increase in extreme hot days, a reduction in frost days and larger extreme rainfall events are some of the main impacts. The following list summarises the projections of different climate variables in Otago:

1. The projected Otago temperature changes increase with time and emission scenario. Future annual average warming spans a wide range: 0.5-1.5°C by 2040, and 0.5-3.5°C by 2090. Diurnal temperature range (i.e., difference between minimum and maximum temperature of a given day) is expected to increase with time and emission scenarios.

2. Changes in extreme temperatures reflect the changes in the average annual signal. The average number of extreme hot days is expected to increase with time and scenario, with considerable variability between coastal and southernmost parts of Otago compared to Central Otago. For example, coastal and southern parts of Otago are projected to observe 0.1-4 more extreme hot days per year in future. In contrast, the number of extreme hot days in Central Otago are projected to increase by 30-40 days by 2090 under RCP8.5. As expected, the number of frost days is expected to decrease throughout the region. Largest decreases are expected in inland areas; 10-15 fewer frost days per year by 2040, and 20-40 fewer frost days per year by 2090.

3. Projected changes in rainfall show variability across the Otago region. Annual rainfall is expected to slightly increase by mid-century (0-10%), while the increase spans 10-20% (with a larger increase in the western part of the region) at the end of the century. Seasonally the largest increases are projected during winter, with 20-40% increases expected by the end of the century under RCP8.5. Summer precipitation is expected to decrease around Ranfurly and Middlemarch (5-10% decrease at the end of the century under RCP8.5).

4. The number of heavy rain days (i.e., days where the total precipitation exceeds 25 mm) is projected to see little change for most of the Otago region at all time slices and RCPs. The exception is far western parts of Otago, where a 5-15 day increase in heavy rain days is projected for the end of the century under RCP8.5.

5. Extreme, rare rainfall events are projected to become more severe in the future under all four climate change scenarios. Short duration rainfall events have the largest relative increases compared with longer duration rainfall events. The depth of a current 1:100-year 1-hour duration rainfall event is projected to increase by approximately 35% by 2090 under RCP8.5.

6. By mid-century the number of dry days per year are expected to decrease near the coast and parts of Central Otago (1-4 fewer dry days per year), with increases of 1-6 more annual dry days for many remaining parts of Otago. By the end of the century, a decrease in annual dry days of 2-6 days is projected for coastal and some central parts of Otago, with increases of 2-10 more dry days per year for many remaining parts of Otago.

7. The number of snow days reduces everywhere, with the largest reduction in the coldest mountainous areas where there are a relatively large number of snow days in the present climate.

8. The future magnitude of the 99th percentile daily mean wind speed is projected to decrease about the eastern coast of Otago, and increase for inland areas about Central Otago and the Southern Lakes.

9. The effects of climate change on hydrological characteristics were examined by driving NIWA's national hydrological model with downscaled Global Climate Model (GCM) outputs from 1971-2099 under different global warming scenarios. Using a combination of six GCMs and four warming scenarios allows us to consider a plausible range of future trajectories of greenhouse gas emissions and climatic responses. The changing climate over this century is projected to lead to the following hydrological effects:

   - By the end of the century and with increased emissions, average annual flows are expected to increase across the region (above 50% across all FMUs except headwaters of Taieri and North Otago).

   - Low flow (expressed as Q95% flow) changes are expected to be variable across the Otago region. Low flows are usually increasing with radiative forcing in the headwaters and slightly decreasing elsewhere. Large decrease in low flow is expected with time and increased radiative forcing for North Otago and Taieri FMUs.

- Floods (characterised by the Mean Annual Flood) are expected to become larger everywhere, with increases up to 100% in some locations by the end of the century.
- Change in surface water supply reliability are characterised by little appreciable change across Otago by mid-century, with Taieri FMU experiencing the largest decrease in flow reliability. Late-century, however, the decreases in the Taieri headwaters become slightly more accentuated, particularly under a high emissions scenario.

9 Glossary of abbreviations and terms

99th percentile	The top 1 percent of a population.
Adaptation	The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.
Air mass	A widespread body of air, the approximately homogeneous properties of which (1) have been established while that air was situated over a region of the Earth's surface, and (2) undergo specific modifications while in transit away from the source region.
Annual exceedance probability (AEP)	The probability of a given event (e.g. flood or sea level or wave height) being equalled or exceeded in elevation, in any given calendar year. AEP can be specified as a fraction (e.g., 0.01) or a percentage (e.g., 1%).
Anomaly	The deviation of a variable from its value averaged over a reference period.
Anthropogenic	Human-induced; man-made. Resulting from or produced by human activities.
Anthropogenic emissions	Emissions of greenhouse gases, greenhouse gas precursors, and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use changes, livestock production, fertilization, waste management, and industrial processes.
AOGCM	Atmosphere-ocean global climate model – a comprehensive climate model containing equations representing the behaviour of the atmosphere, ocean and sea ice and their interactions.
AR4	IPCC Fourth Assessment Report 2007.
AR5	5th Assessment Report of IPCC – published in 2013/14 covering three Working Group Reports and a Synthesis Report.
ARI	Average recurrence interval. The average or expected value of the periods between exceedances of a given rainfall total accumulated over a given duration. It is implicit in this definition that the periods between exceedances are generally random, e.g. a 50-year ARI rain event doesn't necessarily occur only once every 50 years.
Atmosphere	The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium and radiatively active greenhouse gases such as carbon dioxide (0.035% volume mixing ratio) and ozone. In addition, the atmosphere contains the greenhouse gas water vapour, whose amounts are highly variable but typically around 1% volume mixing ratio. The atmosphere also contains clouds and aerosols.

Augmentation factor	The percentage increase of rainfall per degree of warming contained within depth-duration-frequency tables in this report.
Baseline/reference	The baseline (or reference) is the state against which change is measured. A baseline period is the period relative to which anomalies are computed.
BCC-CSM1.1	The Beijing Climate Centre Climate System Model version 1.1. A fully coupled global climate-carbon model. Part of CMIP5.
Bias correction	Procedures designed to remove systematic climate model errors.
Biogeochemical	Relating to or denoting the cycle in which chemical elements and simple substances are transferred between living systems and the environment.
Brown Haze	A local or regional scale phenomena that causes a poor atmospheric visibility mostly associated with high pollution levels, also known as smog.
Business as Usual (BAU)	Business as usual projections assume that operating practices and policies remain as they are at present. Although baseline scenarios could incorporate some specific features of BAU scenarios (e.g., a ban on a specific technology), BAU scenarios imply that no practices or policies other than the current ones are in place. RCP8.5 is known as the 'business as usual' climate change scenario.
Carbon dioxide (CO2)	A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas and coal of burning biomass, of land use changes and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1.
Carbon sequestration	Carbon sequestration is the process involved in carbon capture and the long-term storage of atmospheric carbon dioxide. Carbon sequestration involves long-term storage of carbon dioxide or other forms of carbon to mitigate or defer global warming.
CESM1-CAM5	The Community Earth System Model, version 5 of the Community Atmosphere Model primarily developed at the National Center for Atmospheric Research in the USA. Part of CMIP5.
Climate	Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, rainfall and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate change	Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.
Climate change scenario	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.
Climate model	A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented or the level at which empirical parametrizations are involved. Coupled Atmosphere–Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near or at the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and inter-annual climate predictions.
Climate projection	A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.

Climate system	The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land use change.
Climate variability	Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).
Climate variable	An element of the climate that is liable to vary or change e.g. temperature, rainfall.
CMIP5	Coupled Model Inter-comparison Project, Phase 5, which involved coordinating and archiving climate model simulations based on shared model inputs by modelling groups from around the world. This project involved many experiments with coupled atmosphere-ocean global climate models, most of which were reported on in the IPCC Fifth Assessment Report, Working Group I. The CMIP5 dataset includes projections using the Representative Concentration Pathways.
Cold nights	In this report, a cold night (or frost) is defined when the daily minimum temperature is below 0°C.
Confidence	The validity of a finding based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement. Confidence is expressed qualitatively.
Diurnal temperature range	The difference between the maximum and minimum temperature during a 24-hour period.
Downscaling (statistical, dynamical)	Deriving local climate information (at the 5 kilometre grid-scale in this report) from larger-scale model or observational data. Two main methods exist – statistical and dynamical. Statistical methods develop statistical relationships between large-scale atmospheric variables (e.g., circulation and moisture variations) and local climate variables (e.g., rainfall variations). Dynamical methods use the output of a regional climate/weather model driven by a larger-scale global model.

Drought (meteorological, hydrologic)	A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term; therefore, any discussion in terms of rainfall deficit must refer to the rainfall-related activity that is under discussion. For example, shortage of rainfall during the growing season impinges on crop production or ecosystem function in general (due to soil moisture drought, also termed agricultural drought), and during the runoff and percolation season primarily affects water supplies (hydrological drought). Storage changes in soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in rainfall. A period with an abnormal rainfall deficit is defined as a meteorological drought. A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.
Emission scenario	A plausible representation of the future development of emissions of substances that act as radiative forcing factors (e.g., greenhouse gases, aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships.
Ensemble	A collection of model simulations characterizing a climate prediction or projection. Differences in initial conditions and model formulation result in different evolutions of the modelled system and may give information on uncertainty associated with model error and error in initial conditions in the case of climate forecasts and on uncertainty associated with model error and with internally generated climate variability in the case of climate projections.
ENSO	El Niño-Southern Oscillation. A natural global climate phenomenon involving the interaction between the tropical Pacific and the atmosphere, but has far-reaching effects on the global climate, especially for countries in the Pacific rim. ENSO is the strongest climate signal on time scales of one to several years, characteristically oscillating on a 3-7-year timescale. The quasi-periodic cycle oscillates between El Niño (unusually warm ocean waters along the tropical South American coast and west-central equatorial Pacific) and La Niña (colder-than-normal ocean waters off South America and along the central-east equatorial Pacific).
ESM	Earth system model. Refers to an AOGCM that also includes interactions with biological processes and natural cycles of chemical components such as ozone, carbon dioxide, nitrogen, and sulphur.
Extra-tropical cyclone or mid-latitude cyclone	A large-scale (of order 1000 km) storm in the middle or high latitudes having low central pressure and fronts with strong horizontal gradients in temperature and humidity. A major cause of extreme wind speeds and heavy rainfall especially in wintertime.
Extreme hot days	In this report, an extreme hot day is defined as a day with a maximum temperature over 30°C.

Flood	The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.
Flow reliability	The fraction of time river flow is below a minimum flow threshold related to water abstraction (based on the Proposed National Environmental Standard for Ecological Flows). Flow reliability reflects the frequency of drought conditions.
GCM	Global climate model. These days almost all GCMs are AOGCMs (atmosphere-ocean global climate models). See also climate model.
GFDL-CM3	The Coupled physical model version 3, developed by the Geophysics Fluid Dynamics Laboratory at NOAA in the USA. Part of CMIP5.
GIS	A geographic information system (GIS) is a system designed to capture, store, manipulate, analyse, manage, and present all types of geographical information for informing decision making.
GISS-E2-R	The E2-R climate model developed by NASA Goddard Institute for Space Studies in the USA. Part of CMIP5.
Global mean surface temperature	An estimate of the global mean surface air temperature. However, for changes over time, only anomalies, as departures from a climatology, are used, most commonly based on the area-weighted global average of the sea surface temperature anomaly and land surface air temperature anomaly.
Greenhouse effect	The radiative effect of all infrared-absorbing constituents in the atmosphere. Greenhouse gases, clouds, and (to a small extent) aerosols absorb terrestrial radiation emitted by the Earth's surface and elsewhere in the atmosphere. These substances emit infrared radiation in all directions, but, everything else being equal, the net amount emitted to space is normally less than would have been emitted in the absence of these absorbers. This is because of the decline of temperature with altitude in the troposphere and the consequent weakening of emission. An increase in the concentration of greenhouse gases increases the magnitude of this effect; the difference is sometimes called the enhanced greenhouse effect. The change in a greenhouse gas concentration because of anthropogenic emissions contributes to an instantaneous radiative forcing. Surface temperature and troposphere warm in response to this forcing, gradually restoring the radiative balance at the top of the atmosphere.

Greenhouse gas (GHG)	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are many entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO2, N2O and CH4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).
Groundwater recharge	The process by which external water is added to the zone of saturation of an aquifer, either directly into a geologic formation that traps the water or indirectly by way of another formation.
Gully erosion	The removal of soil along drainage lines by surface water runoff. Once started, gullies will continue to move by headward erosion or by slumping of the side walls unless steps are taken to stabilise the disturbance.
HadGEM2-ES	Climate model developed by the UK Met Office Hadley Centre, from the UK Unified Model. Part of CMIP5.
HIRDS	High Intensity Rainfall Design System (http://hirds.niwa.co.nz). HIRDS uses a regionalized index-frequency method to predict rainfall intensities at ungauged locations and returns depth-duration-frequency tables for rainfall at any location in New Zealand. Temperature increases can be inserted and corresponding increases in rainfall for each duration and frequency are calculated.
Humidity	Specific humidity is the ratio of the mass of water vapour to the total mass of the system (water plus air) in a parcel of moist air. Relative humidity is the ratio of the vapour pressure to the saturation vapour pressure (the latter having a strong dependence on temperature).
Hydrologic drought	Hydrologic drought occurs when low water supply becomes evident, especially in streams, reservoirs, and groundwater levels, usually after an extended period of meteorological drought.
Industrial Revolution	A period of rapid industrial growth with far reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of fossil fuels and emission of, in particular, fossil carbon dioxide.

IPCC	Intergovernmental Panel on Climate Change. This body was established in 1988 by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) to objectively assess scientific, technical and socioeconomic information relevant to understanding the scientific basis of risk of human induced climate change, its potential impacts and options for adaptation and mitigation. Its latest reports (the Fifth Assessment) were published in 2013/14 (see www.ipcc.ch/).
IPO	Interdecadal Pacific Oscillation – a long timescale oscillation in the ocean–atmosphere system that shifts climate in the Pacific region every one to three decades.
Likelihood	The chance of a specific outcome occurring, where this might be estimated probabilistically.
Mean annual flood	The average of the maximum flood discharges experienced in a river over a period, which should have a recurrence interval of once every 2.33 years.
Mean annual low flow	The mean of the lowest 7-day average flows in each year of a projection period.
Mean discharge	The average annual streamflow or discharge of a river.
Mean sea level (MSL)	The surface level of the ocean at a point averaged over an extended period such as a month or year. Mean sea level is often used as a national datum to which heights on land are referred. Mean sea level changes with the averaging period used, due to climate variability and long-term sea-level rise.
Mitigation (of climate change)	A human intervention to reduce the sources or enhance the sinks of greenhouse gases.
Model spread	The range or spread in results from climate models, such as those assembled for Coupled Model Intercomparison Project Phase 5 (CMIP5). Does not necessarily provide an exhaustive and formal estimate of the uncertainty in feedbacks, forcing or projections even when expressed numerically, for example, by computing a standard deviation of the models' responses. To quantify uncertainty, information from observations, physical constraints and expert judgement must be combined, using a statistical framework.
NIWA	National Institute of Water and Atmospheric Research Ltd.
NorESM1-M	The Norwegian Earth System Model. Part of CMIP5.
Orographic rainfall	Precipitation that is produced when moist air is lifted as it moves over a mountain range. As the air rises and cools, orographic clouds serve as the source of the precipitation, most of which falls upwind of the mountain ridge.

Ozone	Ozone, the triatomic form of oxygen (O3), is a gaseous atmospheric constituent. In the troposphere, it is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Tropospheric ozone acts as a greenhouse gas. In the stratosphere, it is created by the interaction between solar ultraviolet radiation and molecular oxygen (O2). Stratospheric ozone plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.
Paris agreement	The Paris Agreement aims to respond to the global climate change threat by keeping a global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C.
Percentiles	The set of partition values which divides the total population of a distribution into 100 equal parts, the 50th percentile corresponding to the median of the population.
Precipitation	Describes all forms of moisture that falls from clouds (rain, sleet, hail, snow, etc). 'Rainfall' describes just the liquid component of precipitation.
Pre-industrial	Conditions at or before 1750. See also Industrial revolution.
Projection	A numerical simulation (representation) of future conditions. Differs from a forecast; whereas a forecast aims to predict the exact time-dependent conditions in the immediate future, such as a weather forecast a future cast aims to simulate a time-series of conditions that would be typical of the future (from which statistical properties can be calculated) but does not predict future individual events.
Radiative forcing	A measure of the energy absorbed and retained in the lower atmosphere. More technically, radiative forcing is the change in the net (downward minus upward) irradiance (expressed in W/m2, and including both short-wave energy from the sun, and long-wave energy from greenhouse gases) at the tropopause, due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the sun.
Regional Climate Model (RCM)	A numerical climate prediction model run over a limited geographic domain (here around New Zealand), and driven along its lateral atmospheric boundary and oceanic boundary with conditions simulated by a global climate model (GCM). The RCM thus downscales the coarse resolution GCM, accounting for higher resolution topographical data, land-sea contrasts, and surface characteristics. RCMs can cater for relatively small-scale features such as New Zealand's Southern Alps.
Representative Concentration Pathways (RCPs)	Representative concentration pathways. They describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. 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 W/m2, respectively)

Resolution	In climate models, this term refers to the physical distance (metres or degrees) between each point on the grid used to compute the equations. Temporal resolution refers to the time step or time elapsed between each model computation of the equations.
Return period	An estimate of the average time interval between occurrences of an event (e.g., flood or extreme rainfall) of (or below/above) a defined size or intensity.
SAM	Southern Annular Mode. Represents the variability of circumpolar atmospheric jets that encircle the Southern Hemisphere that extend out to the latitudes of New Zealand. Positive phases of SAM are associated with relatively settled weather in New Zealand, whereas negative phases are associated with unsettled weather over the country.
Scenario	In common English parlance, a 'scenario' is an imagined sequence of future events. The IPCC Fifth Assessment describes a 'climate scenario' as: A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. The word 'scenario' is often given other qualifications, such as 'emission scenario' or 'socio-economic scenario'. For the purpose of forcing a global climate model, the primary information needed is the time variation of greenhouse gas and aerosol concentrations in the atmosphere.
Sea surface temperature (SST)	The sea surface temperature is the subsurface bulk temperature in the top few metres of the ocean, measured by ships, buoys and drifters.
Seven-station series	This refers to seven long-term temperature records used to assess New Zealand's warming on the century time-scale. The sites are located in Auckland, Wellington, Masterton, Nelson, Hokitika, Lincoln, and Dunedin.
Simulation	Simulation is the imitation of the operation of a real-world process or system over time. The act of simulating something first requires that a model be developed; this model represents the key characteristics, behaviours and functions of the selected physical or abstract system or process. The model represents the system itself, whereas the simulation represents the operation of the system over time.
SOI	Southern Oscillation Index, representing seesaws of atmospheric pressure in the tropical Pacific, one pole being at Tahiti and the other at Darwin, Australia. Extreme states of this index are indicative of El Niño or La Niña events in the equatorial Pacific. Typically, El Niño events produce more south-westerly flow than usual over New Zealand and associated cooler conditions, with more rainfall in western parts and frequently drought conditions in the east. La Niña events produce more high pressures over the South Island and warmer north-easterly airflow over the North Island, sometimes with drought conditions in the South Island.

Spatial and temporal scales	Climate may vary on a large range of spatial and temporal scales. Spatial scales may range from local (less than 100,000 km2), through regional (100,000 to 10 million km2) to continental (10 to 100 million km2). Temporal scales may range from seasonal to geological (up to hundreds of millions of years).
SRES	Special Report on Emissions Scenarios (SRES) was published by the IPCC in 2000. The greenhouse gas emissions scenarios described in this report were used in the IPCC Third Assessment Report (2001) and IPCC Fourth Assessment Report (2007).
Storm tracks	Originally, a term referring to the tracks of individual cyclonic weather systems, but now often generalized to refer to the main regions where the tracks of extratropical disturbances occur as sequences of low (cyclonic) and high (anticyclonic) pressure systems
Surface temperature	Air temperatures measured near or 'at' the surface (usually 1.5 m above the ground).
Synoptic	Weather patterns viewed at a scale of 1000 km or more to be able to see features such as high and low pressure systems.
TopNet	A semi-distributed hydrological model for simulating catchment water balance and river flow, developed by NIWA.
Trend	In this report, the word trend designates a change, generally monotonic in time, in the value of a variable.
Tropical cyclone	A strong, cyclonic-scale disturbance that originates over tropical oceans. Distinguished from weaker systems (often named tropical disturbances or depressions) by exceeding a threshold wind speed. A tropical storm is a tropical cyclone with 1-minute average surface winds between 18 and 32 m s–1. Beyond 32 m s–1, a tropical cyclone is called a hurricane, typhoon, or cyclone, depending on geographic location.
Uncertainty	A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts).
VCSN	Virtual Climate Station Network. Made up of observational datasets of a range of climate variables: maximum and minimum temperature, rainfall, relative humidity, solar radiation, and wind. Daily data are interpolated onto a 0.05° longitude by 0.05° latitude grid (approximately 4 kilometres longitude by 5 kilometres latitude), covering all New Zealand (11,491 points). Primary reference to the spline interpolation methodology is Tait et al (2006).

Appendix A Climate modelling methodology

Key messages

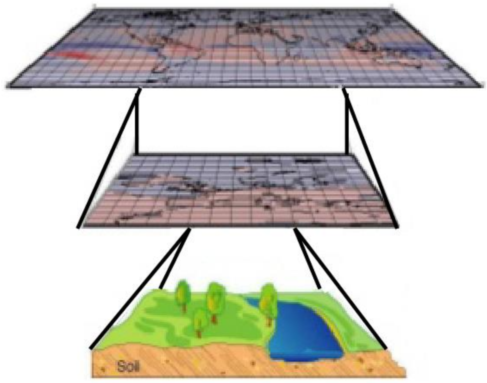
- Climate model simulation data from the IPCC Fifth Assessment has been used to produce climate projections for New Zealand.
- Six climate models were chosen by NIWA for dynamical downscaling. These models were chosen because they produced the most accurate results when compared to historical climate and circulation patterns in the New Zealand and southwest Pacific region.
- Downscaled climate change projections are at a 5 km x 5 km resolution over New Zealand.
- Climate projection maps and the historic baseline maps present the average of the six downscaled models.
- Climate projections are presented as a 20-year average for two future periods: 2031-2050 (termed '2040') and 2081-2100 (termed '2090'). All maps show changes relative to the baseline climate of 1986-2005 (termed '1995').

NIWA has used climate model simulation data from the IPCC Fifth Assessment to update climate change scenarios for New Zealand through both regional climate model (dynamical) and statistical downscaling processes. The downscaling processes are described in detail in a climate guidance manual prepared for the Ministry for the Environment (2018a), but a short explanation is provided below. Dynamical downscaling results are presented for all variables in this report, and statistical downscaling results are also presented for mean temperature and rainfall projections.

Global climate models (GCMs) are used to make future climate change projections for each future scenario, and results from these models are available through the Fifth Coupled Model Inter-comparison Project (CMIP5) archive (Taylor et al., 2012). Six GCMs were selected by NIWA for dynamical downscaling, and the sea surface temperatures (SSTs) from these six CMIP5 models used to drive an atmospheric global model, which in turn drives a higher resolution regional climate model (RCM) nested over New Zealand. These CMIP5 models were chosen because they produced the most accurate results when compared to historical climate and circulation patterns in the New Zealand and southwest Pacific region. In addition, they were chosen because they were as varied as possible in the parent global model to span the likely range of model sensitivity. For climate simulations, dynamical downscaling utilises a high-resolution climate model to obtain finer scale detail over a limited area based on a coarser global model simulation.

The six GCMs chosen for dynamical downscaling were BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISS-E2-R, HadGEM2-ES and NorESM1-M. The NIWA downscaling (GCM then RCM) produced simulations that contained hourly precipitation results from 1970 through to 2100. The native resolution of the regional climate model is 27 km and there are known biases in the precipitation fields derived from this model. The daily precipitation projections, as well as daily maximum and minimum temperatures, have been bias-corrected so that their statistical distributions from the RCM matches those from the Virtual Climate Station Network (VCSN) when the RCM is driven by the observed sequence of weather patterns across New Zealand (known as 're-analysis' data). When the RCM is driven from the free-running GCM, forced only by CMIP5 SSTs, there can be an additional bias in the distribution of weather patterns affecting New Zealand, and the RCM output data for the historical climate will therefore not match the observed distributions exactly.

The RCM output is then downscaled statistically (by interpolation from the model 27 km grid) to a ~5 km x ~5 km resolution with a daily time-step. The ~5 km grid corresponds to the VCSN grid[5]. Figure 9-1 shows a schematic for the dynamical downscaling method used in this report.



Global Climate Model: ~140 km

Regional Climate Model 27 km

Bias corrected/downscaled RCM: 5 km

Figure 9-1: Schematic showing dynamical downscaling method used in this report.

Statistical downscaling uses statistical relationships to relate the large-scale climate simulation outputs (which are gridded) to regional, catchment or local station scales. The statistical downscaling is very fast, and so has been applied to a much larger number of CMIP5 GCMs (up to 41) than the dynamical downscaling).

The climate change projections from each of the six dynamical models are averaged together, creating what is called an ensemble-average. The ensemble-average is mapped in this report, because the models were chosen to cover a wide range of potential future climate conditions. The ensemble-average was presented as this usually performs better in climate simulations than any individual model (the errors in different models are compensated).

Climate projections are presented as a 20-year average for two future periods: 2031-2050 (termed '2040') and 2081-2100 (termed '2090'). All maps show changes relative to the baseline climate of 1986-2005 (termed '1995'), as used by IPCC. Hence the projected changes by 2040 and 2090 should be thought of as 45-year and 95-year projected trends. Note that the projected changes use 20-year averages, which will not entirely remove effects of natural variability. The baseline maps (1986-2005) show modelled historic climate conditions from the same six models as the future climate change projection maps.

[5] Virtual Climate Station Network, a set of New Zealand climate data based on a 5 km by 5 km grid across the country. Data have been interpolated from 'real' climate station records (TAIT, A., HENDERSON, R., TURNER, R. & ZHENG, X. G. 2006. Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. *International Journal of Climatology,* 26**,** 2097-2115.)

Appendix B Hydrological modelling methodology

Key messages

- NIWA's TopNet model was used in this study. TopNet is a spatially semi-distributed, time-stepping model of water balance. The model is driven by time-series of precipitation and temperature, and additional weather elements where available.
- TopNet was run continuously from 1971 to 2100, with the spin-up period 1971 excluded from the analysis. The climate inputs were stochastically disaggregated from daily to hourly time steps.
- The simulation results comprise time-series of modelled river flow for each computational sub-catchment, and for each of the six GCMs and four RCPs considered.
- Hydrological projections are presented as the average for two future periods: 2036-2056 (termed 'mid-century') and 2086-2099 (termed 'late-century'). All maps show changes relative to the baseline climate (1986-2005 average).

To assess the potential impacts of climate change on agricultural water resources and flooding, a hydrological model is required that can simulate soil moisture and river flows continuously and under a range of different climatic conditions, both historical and future. Ideally the model would also simulate complex groundwater fluxes but there is no national hydrological model capable of this at present. Because climate change implies that environmental conditions are shifting from what has been observed historically, it is advantageous to use a physically based hydrological model over one that is more empirical, with the assumption that a better representation of the biophysical processes will allow the model to perform better outside the range of conditions under which it is calibrated.

The hydrological model we will use in this study is NIWA's TopNet model (Clark et al. 2008), which is routinely used for surface water hydrological modelling applications in New Zealand. It is a spatially semi-distributed, time-stepping model of water balance. It is driven by time-series of precipitation and temperature, and of additional weather elements where available. TopNet simulates water storage in the snowpack, plant canopy, rooting zone, shallow subsurface, lakes and rivers. It produces time-series of modelled river flow (without consideration of water abstraction, impoundments or discharges) throughout the modelled river network, as well as evapotranspiration, and does not consider irrigation. TopNet has two major components, namely a basin module and a flow routing module.

The model combines TOPMODEL hydrological model concepts (Beven et al. 1995) with a kinematic wave channel routing algorithm (Goring 1994) and a simple temperature based empirical snow model (Clark et al. 2008). As a result, TopNet can be applied across a range of temporal and spatial scales over large watersheds using smaller sub-basins as model elements (Ibbitt and Woods 2002; Bandaragoda et al. 2004). Considerable effort has been made during the development of TopNet to ensure that the model has a strong physical basis and that the dominant rainfall-runoff dynamics are adequately represented in the model (McMillan et al. 2010). TopNet model equations and information requirements are provided by Clark et al. (2008) and McMillan et al. (2013).

For the development of the national version of TopNet used in here, spatial information in TopNet was provided by national datasets as follows:

- Catchment topography based on a nationally available 30 m Digital Elevation Model (DEM).
- Physiographical data based on the Land Cover Database version two and Land Resource Inventory (Newsome et al. 2012).
- Soil data based on the Fundamental Soil Layer information (Newsome et al. 2012).
- Hydrological properties (based on the River Environment Classification version one (REC1) (Snelder and Biggs 2002)[6].

The method for deriving TopNet's parameters based on GIS data sources in New Zealand is given in Table 1 of Clark et al. (2008). Due to the paucity of some spatial information at national/regional scales, some soil parameters are set uniformly across New Zealand.

To carry out the simulations required for this study, TopNet was run continuously from 1971 to 2100, with the spin-up period 1971 excluded from the analysis. The climate inputs were stochastically disaggregated from daily to hourly time steps. As the GCM simulations are "free-running" (based only on initial conditions, not updated with observations), comparisons between present and future hydrological conditions can be made directly (as each GCM is characterised by specific physical assumptions and parameterisation), but this also means that simulated hydrological hindcasts do not track observational records.

Hydrological simulations are based on the REC 1 network aggregated up to Strahler[7] catchment order three (approximate average catchment area of 7 km^2) used within previous national and regional scale assessments (Pearce et al. 2017a, b); residual coastal catchments of smaller stream orders remain included. The simulation results comprise hourly time-series of various hydrological variables for each computational sub-catchment, and for each of the six GCMs and four RCPs considered. To manage the volume of output data, only river flows information was preserved; all the other state variables and fluxes can be regenerated on demand.

Because of TopNet assumptions, soil and land use characteristics within each computational sub-catchment are homogenised. Essentially this means that the soil characteristics and physical properties of different land uses, such as pasture and forest, will be spatially averaged, and the hydrological model outputs will be an approximation of conditions across land uses.

[6] Due to time constraints associated with this project, it is not possible to assess the potential impact of climate change on the Digital River Network 3 available for the Otago region.

[7] Strahler order describes river size based on tributary hierarchy. Headwater streams with no tributaries are order 1; 2nd order streams develop at the confluence of two 1st order tributaries; stream order increases by 1 where two tributaries of the same order converge.

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