Climate change projections and impacts for Marlborough

Prepared for Marlborough District Council

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Executive summary

The climate of Marlborough 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 concentrations of greenhouse gases in the atmosphere. The rate of future climate change depends on how fast atmospheric greenhouse gas concentrations continue to increase.

Envirolink and Marlborough District Council commissioned NIWA to undertake a review of climate change projections and impacts for the Marlborough region. This report addresses expected changes for a range of climate variables out to 2100 and draws heavily on climate model simulations from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. The following bullet points outline some key findings of this report:

- The projected temperature changes increase with time and greenhouse gas concentration pathway. Future annual average warming spans a wide range: 0.5-1.5°C by 2040, and 0.5-2.0°C (medium concentration pathway) or 2.0-3.5°C (high concentration pathway) by 2090.
- Annual average maximum temperatures are expected to increase by 0.5-1.5°C by 2040 under RCP4.5. By 2090, maximum temperatures are projected to increase by 1.0-3.0°C (medium concentration pathway) or 2.0-5.0°C (high concentration pathway).
- The average number of hot days is expected to increase with time and increasing greenhouse gas concentrations. The largest increases are projected for low elevation locations, where 1-15 more hot days are projected by 2040 (medium concentration pathway), and 15-65 more days are projected by 2090 (high concentration pathway).
- Annual average minimum temperatures are expected to increase by up to 1.0°C by 2040. By 2090, minimum temperatures are projected to increase by 0.5-1.0°C (medium concentration pathway) or 1.0-2.5°C (high concentration pathway).
- The average number of frost days is expected to decrease with time and greenhouse gas concentrations. The largest decreases are projected for high elevation and inland locations, where 1-20 fewer frost days are projected by 2040, and 10-60 fewer days by 2090 (high concentration pathway). Smaller decreases are generally projected for coastal locations because fewer frosts currently occur in these locations.
- Projected changes in rainfall show variability across Marlborough. By 2040 under both medium and high greenhouse gas concentration pathways, annual rainfall is expected to change by only a small amount for most of the region (±5%). By 2090, larger and more extensive changes to rainfall are projected at the seasonal scale. For some parts, summer decreases of up to 20% and winter increases of up to 40% are projected (high concentration pathway).
- Extreme, rare rainfall events are projected to become more severe in the future. Short duration rainfall events have the largest relative increases compared with longer duration rainfall events.
- Drought potential is projected to increase across Marlborough, with annual accumulated Potential Evapotranspiration Deficit (PED) totals increasing with time and

increasing greenhouse gas concentrations. By 2040, PED totals are projected to increase by 50-150 mm. By 2090, PED totals are projected to increase by 50-200 mm (medium concentration pathway) or 75-250 mm (high concentration pathway).

The effects of climate change on hydrological characteristics were examined by driving NIWA's national hydrological model with downscaled Global Climate Model outputs from 1971-2099 under different greenhouse gas concentration scenarios:

- Annual average discharge is projected to remain stable or slightly increase across both greenhouse gas concentration pathways and future time periods.
- Mean annual low flow (MALF) magnitudes are expected to decrease across both greenhouse gas concentration pathways and future time periods for most catchments. A decrease in MALF is expected to exceed 50% for most of the river systems in the region with increased greenhouse gas concentration and time.

One of the most certain consequences of increasing concentrations of atmospheric greenhouse gases and associated warming is the rising sea level. Rising sea level in past decades has already affected human activities and infrastructure in coastal areas is New Zealand, with a higher base mean sea level contributing to increased vulnerability to storms and tsunami.

- Rising sea level has already been observed in Marlborough. Absolute sea-level rise (SLR), calculated from satellite altimetry, shows the region is trending at an increase of around 4 mm/year (trend for 1993-present), which is close to the New Zealand-wide average of 4.4 mm/year (calculated up to the end of 2015).
- As sea levels rise, so will the probability of current high-water marks being exceeded, while the average recurrence interval of rare storm-tide event will become smaller. A 0.65 m SLR (estimated to be reached by 2070-2155) would mean that any coastal location currently affected by the present-day mean high water spring (MHWS-10 level), which is exceeded by only 10% of all high tides (tide only), will be exceeded by all high tides (under high greenhouse gas concentrations).

The following points summarise ongoing and potential future impacts of a changing climate on different sectors and environments in Marlborough:

- Increasing temperatures due to human-induced climate change will likely impact primary sector activities through increasing the incidence of pests and diseases. Increasing temperatures affect the rate of plant growth, which may affect the quality and quantity of harvested fruit and vegetable crops, as well as the productivity of forestry and pasture. Human health will also be affected by a changing climate due to the increasing prevalence of hot conditions and heatwaves. Warmer temperatures in the future may provide opportunities for new crops to be grown.
- A warmer atmosphere in the future is expected to result in increases to rainfall intensity. Increased rainfall intensity increases the risk of reduced quality of fruit and vegetables, as well as causing soil saturation issues for horticulture and agriculture. It also increases the risk of flooding events which have associated adverse impacts such as damage to infrastructure.

- Future reductions in rainfall and increases in drought severity may cause fire risk to increase in Marlborough, affecting forestry and the natural environment. With ongoing risk of wildfire, smoke taint may be an issue for crops such as wine grapes.
- Ongoing sea-level rise is likely to increase exposure of infrastructure and primary sector activities to extreme coastal flooding, as well as cause habitat loss at the coastal margins where ecosystems are not able to move further inland (coastal squeeze). Exposure is likely to increase over time in response to higher sea levels.
- Warming oceans will induce pressures on the distribution and abundance of marine species, and ocean acidification will affect species with carbonate shells (e.g. paua, oysters). In aquaculture, heatwaves can lead to reduced growth and yields, increased mortality, and an associated loss in revenue.
- Increased concentrations of atmospheric carbon dioxide should increase forest, pasture, crop, and horticulture productivity, if not limited by water availability.

1 Introduction

Climate change is already affecting New Zealand and the Marlborough region 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.

Envirolink and Marlborough District Council commissioned the National Institute of Water and Atmospheric Research (NIWA) to undertake a review of climate change projections and impacts for the Marlborough region (regional extent shown in Figure 1-1). 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 (Ministry for the Environment, 2018). The contents of this technical report include analysis of climate projections for the Marlborough region in greater detail than the national-scale analysis. Regional-scale climate projection maps have been provided for 15 different climate and hydrological variables and indices.

This technical report describes changes which are likely to occur over the 21st century to the climate of the Marlborough 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, rainfall and potential evapotranspiration deficit (a measure of drought potential). Projections for sea-level rise and river flows are also discussed. Commentary on climate change impacts and implications for some of the different environments and sectors of Marlborough are provided, including horticulture, human and ecosystem health, and forestry.

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; 2014c; 2014a; 2014b). Details specific to Marlborough 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 climate change information presented in this report is consistent with recently-updated national-scale climate change guidance produced for the Ministry for the Environment (2018), and sea-level rise information is consistent with the coastal hazards guidance manual published by Ministry for the Environment (2017).

The remainder of this chapter includes a brief introduction to 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 the Marlborough region.

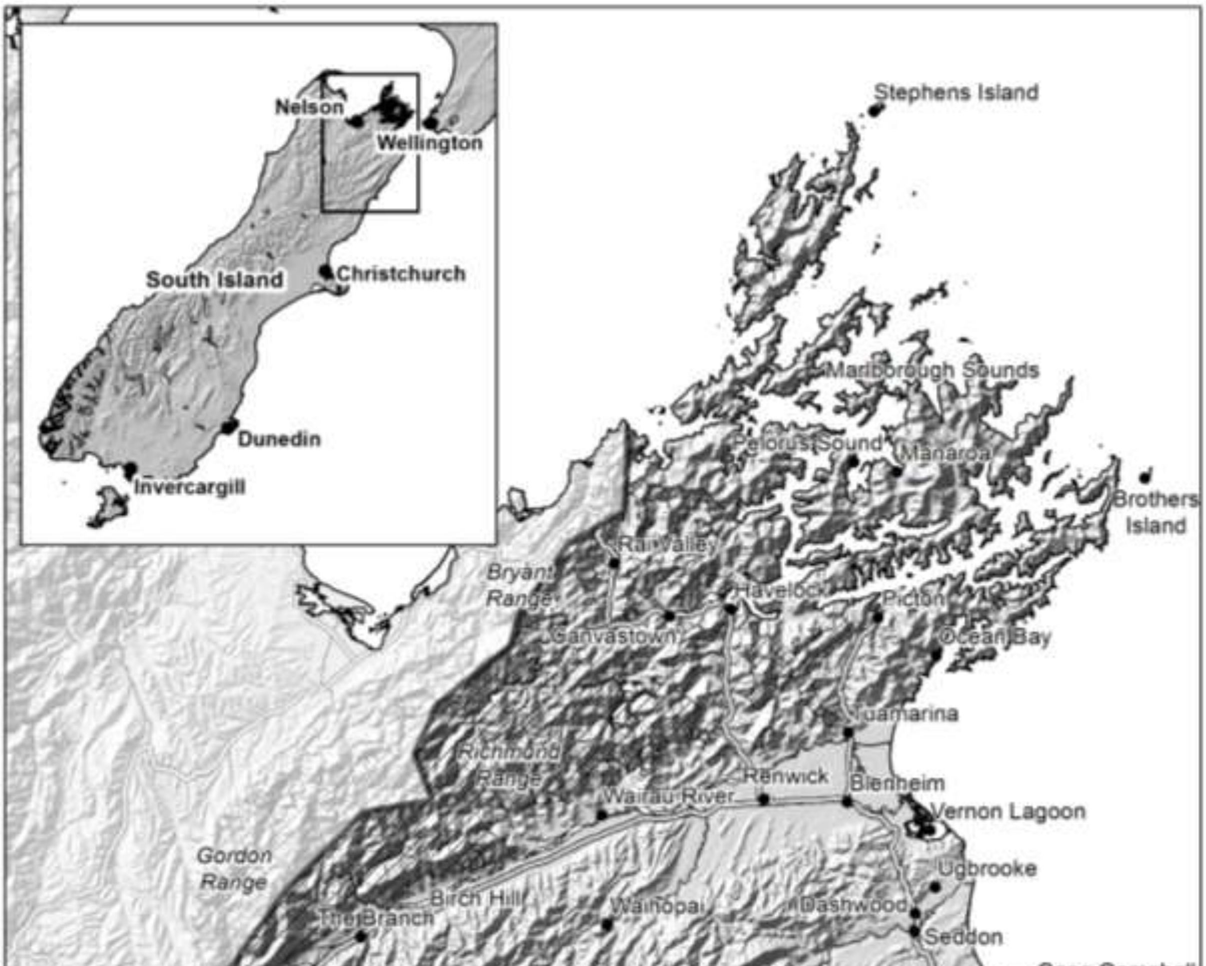


Figure 1-1: Marlborough regional boundary. Sourced from Chappell (2016).

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 already influencing the intensity and frequency of many extreme weather and climate events globally. Increases in average temperatures will result in related increases in the occurrence of extreme temperatures. The Earth's atmosphere has warmed by approximately 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. From the start of New Zealand's records (1901) to 2018, national mean coastal sea levels have risen 1.81 (±0.05) millimetres per year (MFE & STATS NZ, 2019).

Global 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 January 2020, the global carbon dioxide concentration of the atmosphere was 415.5 parts per million (NOAA, 2021). 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).

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 decreases in the north of the North Island (MFE & STATS NZ, 2020). 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). Frosts have become less common, while the number of warm days and heatwaves days is increasing (MFE & STATS NZ, 2020).

The region has exhibited warming to the present and is virtually certain to continue to do so. Based on observations, New Zealand's mean annual temperature has increased by an average of 1.04°C (± 0.25°C) per century since 1909 (Figure 1-2).

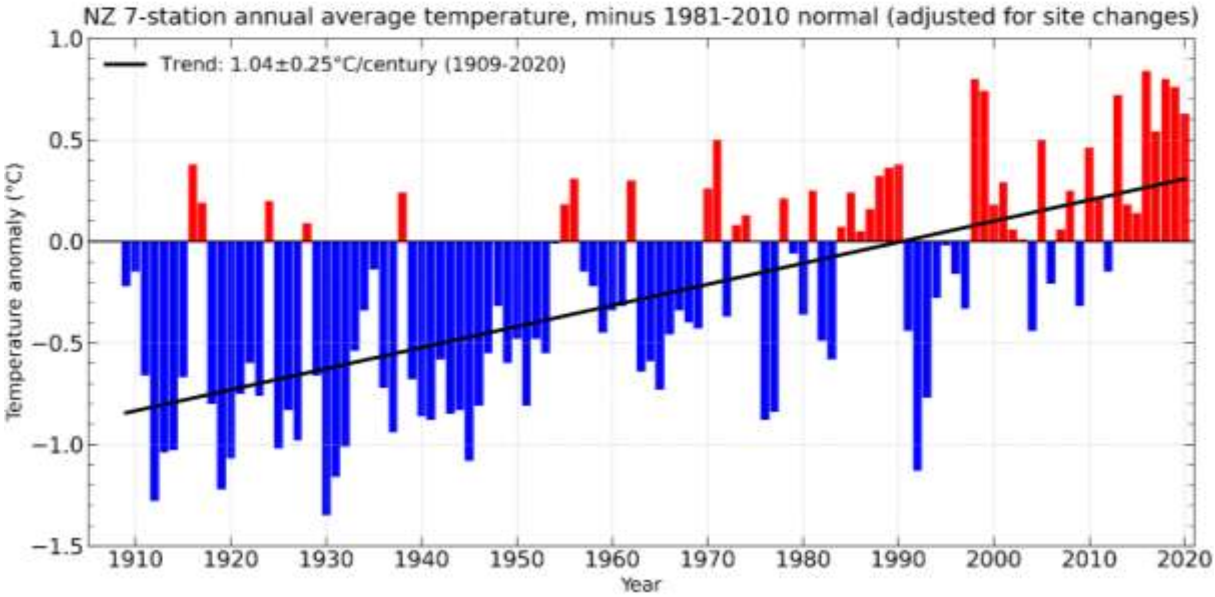


Figure 1-2: New Zealand national temperature series, 1909-2020. More information about the New Zealand seven-station temperature series can be found at https://www.niwa.co.nz/our-science/climate/information-and-resources/nz-temp-record/seven-station-series-temperature-data

Warming is projected to continue through the 21st century along with other changes in climate. Warming is expected to be associated with rising snow line elevations, more frequent hot extremes, less frequent cold extremes, and increasing extreme rainfall related to flood risk in many locations. Annual average rainfall is projected to decrease in the north and east of the North Island, and to increase in southern and western parts of the South Island (Ministry for the Environment, 2018). Fire hazard is projected to increase in many parts of New Zealand, especially on the eastern coast in the southern half of both islands (Watt *et al*., 2019). Regional sea level rise will very likely exceed the historical rate, consistent with global mean trends (Ministry for the Environment, 2017).

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 (2018).

1.2 Year to year climate variability and climate change

Key messages

- Natural variability is an important consideration in addition to the underlying climate change signal. It will continue to affect the year-to-year climate of New Zealand into the future.
- El Niño-Southern Oscillation is the 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 and 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.

Much of the material in this report focuses on the projected impact on the climate of the Marlborough region 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 Marlborough region will need to cope with the combination of both anthropogenic change and natural variability.

1.2.1 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, retention of warm ocean waters over the western Pacific. ENSO events occur on average 3 to 7 years apart, typically becoming established in April or May and persisting for about a year thereafter.

During El Niño events, the weakened trade winds usually 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, including the Marlborough region (Salinger and Mullan, 1999; Figure 1-3). During La Niña conditions, the strengthened trade winds usually cause New Zealand to experience more north-easterly airflow than normal, higher-than-normal temperatures (especially during summer), and wetter conditions in the north and east of the North Island, as well as coastal Marlborough (Figure 1-3).

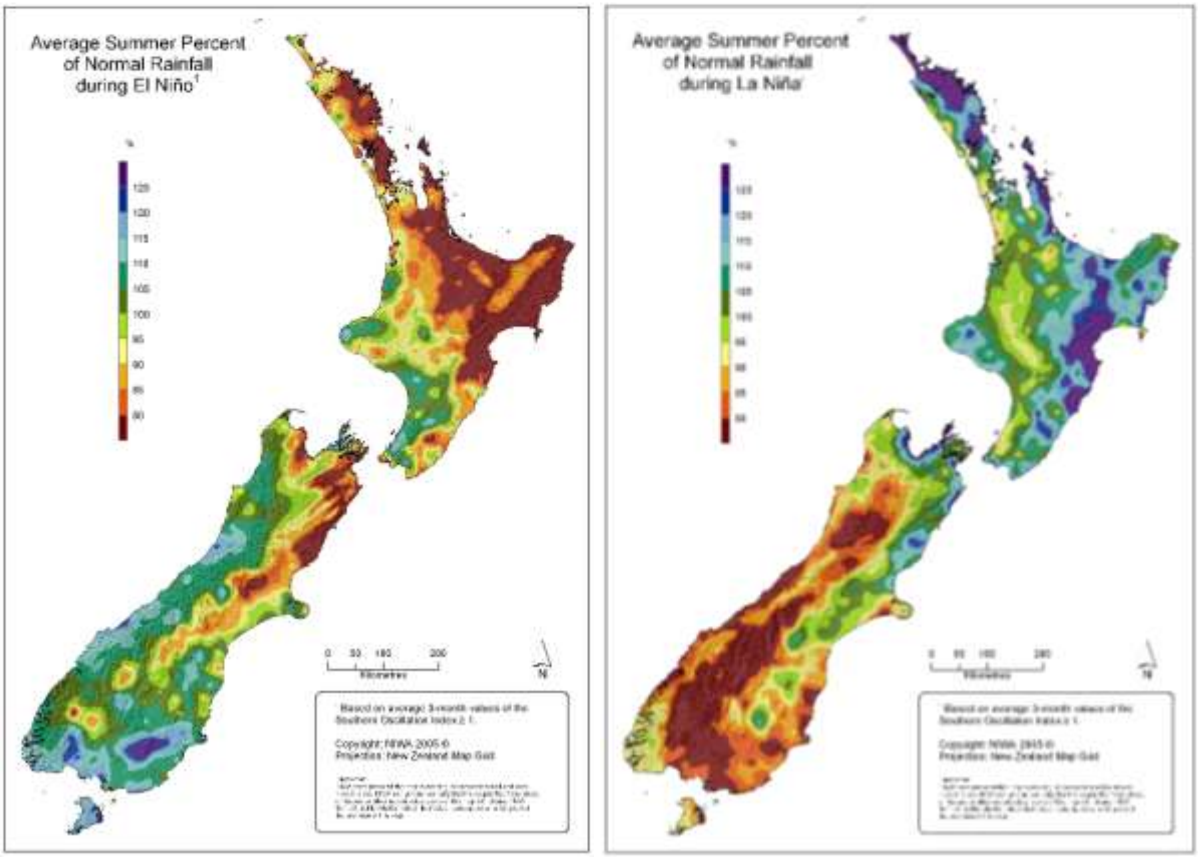


Figure 1-3: Average summer percentage of normal rainfall during El Niño (left) and La Niña (right). El Niño composite uses the following summers: 1963/64, 1965/66, 1968/69, 1969/70, 1972/73, 1976/77, 1977/78, 1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98, 2002/03. La Niña composite uses the following 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 due to increased moisture availability. However, there is uncertainty about future changes to the amplitude and spatial pattern of ENSO.

1.2.2 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 (including Marlborough). 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).

1.2.3 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.

1.2.4 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 1-4. The solid black line on the left-hand side represents the annual average temperature for New Zealand based on the average of a number of climate simulations forced by historic greenhouse gas concentrations. All the other line plots and shading refer to the modelled air temperature averaged over the New Zealand region from individual simulations. Post-2005, the coloured line plots show the annual temperature changes for the New Zealand region under four different scenarios of future greenhouse gas concentrations, with the heavier lines showing the six-model average temperature projections for each concentration scenario, and the lighter lines showing the results for each of the six downscaled climate models for both historical and future periods.

For the future 2006-2100 period, the models show very little warming trend after about 2030 under the low greenhouse gas concentration ("RCP2.6", blue shading) scenario, whereas temperature changes between +2.0°C and +3.5°C by 2100 are projected under the high concentration ("RCP8.5", red shading) scenario.

Figure 1-4 should not be interpreted as a set of specific predictions for individual years. However, it illustrates that although we expect a long term overall continuing upward trend in temperatures (other than for the RCP2.6 scenario), there will still be some relatively cool years. For this particular 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 concentration scenarios) is likely to be warmer than anything we currently experience. The strength of future anthropogenic trends in other climate variables will be smaller in relation to their large year-to-year variability, with the notable exception of sea-level rise.

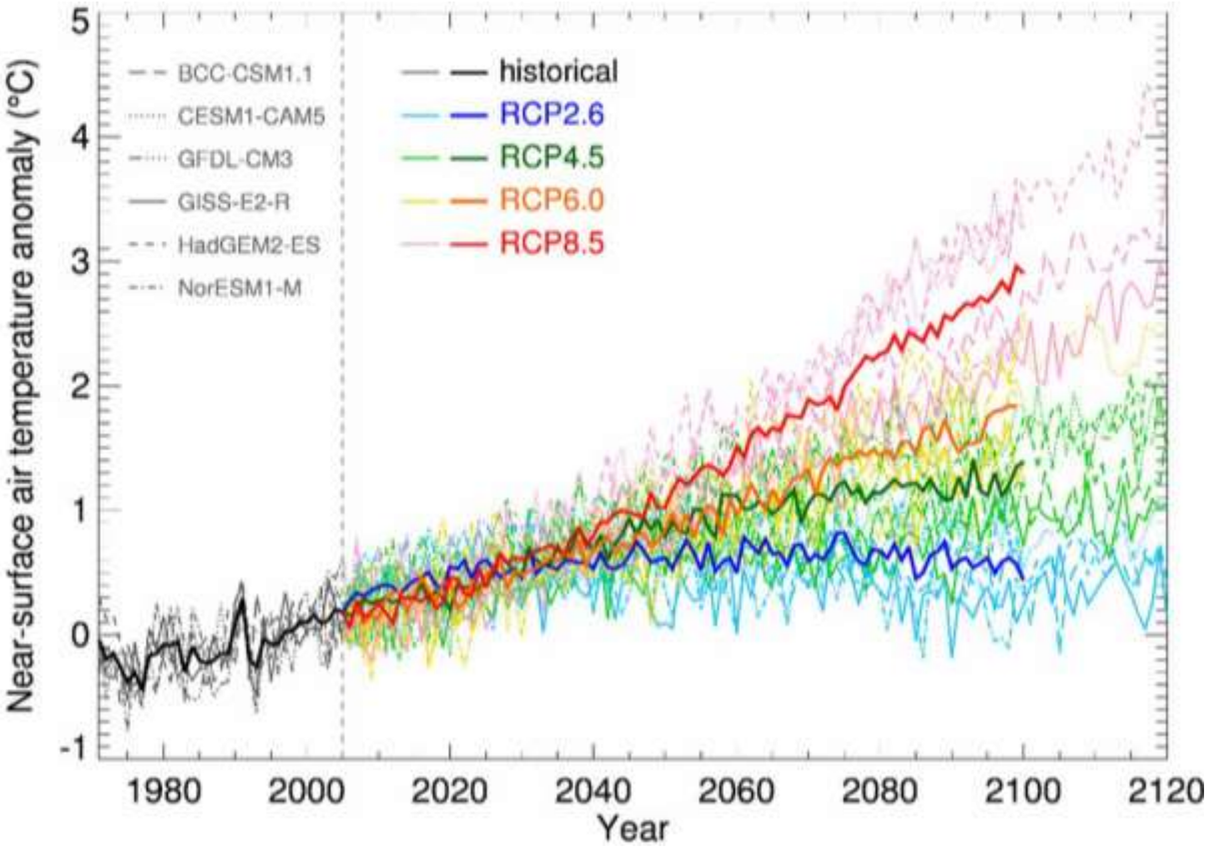


Figure 1-4: New Zealand air temperature - historical (black) and future projections for four RCPs and six downscaled climate models, illustrating future year-to-year variability. (See text for full explanation). From Ministry for the Environment (2018).

2 Methodology

2.1 Climate modelling

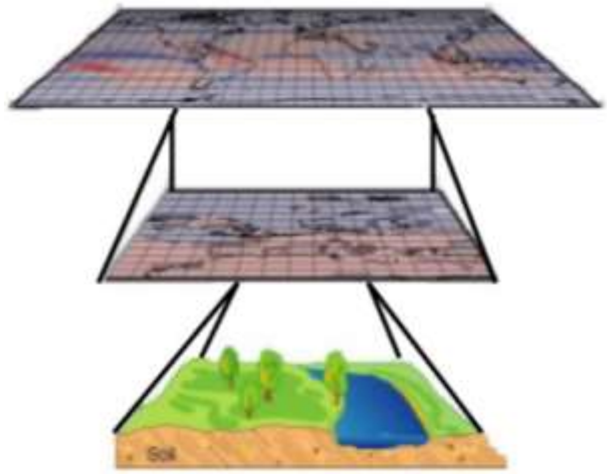
NIWA has used global climate model simulations from the IPCC Fifth Assessment to generate climate change projections for New Zealand using both dynamical (regional climate modelling, RCM) and statistical downscaling procedures. These are described in more detail in a climate guidance manual prepared for the Ministry for the Environment (2018), but a short explanation for the dynamical procedure is provided below. All climate variables and indices presented in this report are based on the dynamical downscaling approach.

Coupled global atmosphere-ocean general circulation models (GCMs) are used to generate climate change projections for prescribed future greenhouse gas concentration scenarios, and results from these models are available through the Fifth Coupled Model Inter-comparison Project (CMIP5) archive (Taylor *et al*., 2012). Simulations from six GCMs were selected by NIWA for dynamical modelling, and the bias corrected sea surface temperatures (SSTs) from these six CMIP5 models were used to drive a global atmosphere-only GCM, which in turn drives a higher resolution regional climate model (RCM) for the New Zealand domain. These CMIP5 models were chosen because they produced the most consistent results when compared to historical climate and circulation patterns in the New Zealand and Southwest Pacific region. Additional selection criteria for the parent global models was that they were the least similar to each other such that they spanned the likely range of model differences. The dynamical downscaling procedure involves forcing a higher-resolution regional climate model (RCM) with data from a coarser global model (GCM) at the lateral boundaries to obtain finer scale detail over a limited area.

The six GCMs chosen for the sea surface temperatures were BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISS-E2-R, HadGEM2-ES and NorESM1-M. The NIWA downscaling (RCM) produced simulations that contain daily climate variables, including precipitation and surface temperature, from 1971 through to 2100. The native resolution of the regional climate model is approximately 30 km (0.27 degrees). However, climate models are known to have considerable biases due to inadequate representation of some critical processes and features (e.g. clouds, precipitation). The daily precipitation projections, as well as daily maximum and minimum temperatures, were bias corrected so that the probability distributions from the RCM were aligned with those derived from the Virtual Climate Station Network (VCSN) data on the model resolution when the RCM is driven by the observed large scale circulation across New Zealand (known as 're-analysis' data, REAN; Sood, 2015). When the RCM is driven from the free-running GCMs, forced by CMIP5 sea surface temperatures (SSTs), additional biases occur due to biases in the large-scale circulation in the global model without data assimilation. Therefore, the climate variables from the RCM nested in the free running GCMs forced by historic greenhouse gas concentrations (RCPpast) are expected to have larger biases than where the lateral boundaries of the RCM are forced by reanalysis (REAN) data derived from observations.

The RCM output is then downscaled using interpolation and physically based models from ~30 km to a ~5 km grid at a daily time-step. The ~5 km grid corresponds to the VCSN grid[1]. Figure 2-1 shows a schematic for the dynamical downscaling method used in this report.

[1] 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 *et al*., 2006).



Global Climate Model: ~140 km

Regional Climate Model ~27 km

Bias corrected/downscaled RCM: ~5 km

Figure 2-1: Schematic diagram showing the dynamical downscaling approach.

The change in the mean climatologies of climate variables averaged from the six model simulations, the 6-model ensemble mean, is presented for the climate simulations rather than for any individual model. The model ensemble mean climatology of climate variables is a better representation of the corresponding climate change signal (also termed signal), since the averaging process reduces the internal variability of the climate system (also termed noise). This is particularly relevant where the signal to noise ratio is small. Though only a small number of model simulations (six) were possible due to large computing resources required for running climate model simulations, they were very carefully selected to cover a wide range of the larger CMIP5 model ensemble.

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 (2013). 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 represent and smoothen the natural variability of the selected period. The baseline maps (1986-2005) show modelled historical climate conditions from the same six models as the future climate change projection maps.

2.1.1 Representative Concentration Pathways

Assessing possible changes for our future climate due to human activity is challenging because climate projections strongly depend on estimates for future greenhouse gas concentrations. In turn, those concentrations depend on global greenhouse gas emissions that are driven by factors such as economic activity, population changes, technological advances and policies for mitigation and sustainable resource use. 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. In the 2013 IPCC Fifth Assessment Report, a selection of these scenarios were called Representative Concentrations Pathways (RCPs).

These representative pathways are abbreviated as RCP2.6, RCP4.5, RCP6.0, and RCP8.5, in the order of increasing radiative forcing in Watts/m^2 of area from increasing greenhouse gases (i.e. the change in net energy in the atmosphere due to greenhouse gas concentrations). RCP2.6 requires net global emissions to reduce to zero around the 3rd quarter of this century, leading to low anthropogenic greenhouse gas concentrations (also requiring removal of carbon dioxide from the atmosphere), and called the 'mitigation' pathway (and the scenario closest to the aspirational goal of the 2015 Paris Agreement of reducing global temperature rise below 2°C above pre-industrial times). RCP4.5 and RCP6.0 are two 'stabilisation' pathways (where greenhouse gas concentrations stabilise by 2100), and RCP8.5 represents continuing high global emissions without effective mitigation, which will lead to high greenhouse gas concentrations (a 'high end' pathway).

Therefore, the RCPs represent the outcomes of a range of 21st-century climate policies.

Table 2-1 shows the projected global mean surface air temperature for each RCP. The full range of projected globally averaged temperature increases for all pathways for 2081-2100 (relative to 1986-2005) is 0.3 to 4.8°C (Figure 2-2). Warming will likely continue beyond 2100 under all RCPs except RCP2.6. Warming will continue to exhibit inter-annual-to-decadal variability and will not be regionally uniform.

Table 2-1: 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 (°C)	Likely range (°C)	Mean (°C)	Likely range (°C)
RCP2.6	Mitigation pathway	1.0	0.4 to 1.6	1.0	0.3 to 1.7
RCP4.5	Stabilisation pathway	1.4	0.9 to 2.0	1.8	1.1 to 2.6
RCP6.0	Stabilisation pathway	1.3	0.8 to 1.8	2.2	1.4 to 3.1
RCP8.5	High end pathway	2.0	1.4 to 2.6	3.7	2.6 to 4.8

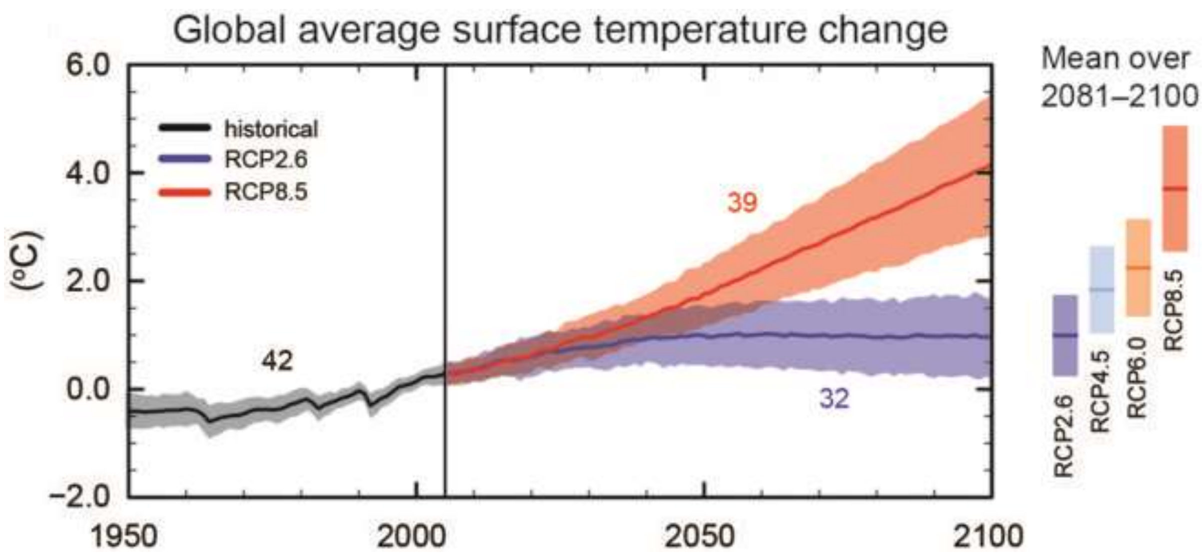


Figure 2-2: CMIP5 multi-model simulated time series from 1950-2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled historical evolution using historical reconstructed forcing. 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 greenhouse gas emissions will largely determine global mean surface warming by the late 21st century and beyond. Even if emissions are stopped, the inertia of many changes in global climate will continue for many centuries to come, with the longest lag effect being sea-level rise. This represents a substantial multi-century climate change commitment created by past, present and future emissions – particularly for coastal areas facing ongoing sea-level rise.

In this report, the downscaled results of the selected global climate models based on two RCPs (RCP4.5 and RCP8.5) are presented. The rationale for choosing these two scenarios was to present a 'high end' scenario if atmospheric greenhouse gas concentrations continue to rise at high rates (RCP8.5) and a scenario which could be realistic if moderate global action is taken towards mitigating greenhouse gas emissions (RCP4.5). Including all four RCP scenarios within the body of this report would make it unwieldy, but GIS datasets for climate projections of the four RCPs were provided to the Council. For sea-level rise, all four scenarios from the Ministry for the Environment (2017) coastal guidance, comprising RCP2.6, RCP4.5 and RCP8.5 (with a second high-end H^+ scenario to cover the potential for runaway polar ice sheet instabilities), are covered by the sea-level rise increments used for the exposure assessment.

2.2 Maps and tabulated climate projections

Downscaled climate projection data is presented as 5 km x 5 km square pixels over New Zealand. Data were downscaled only where low-resolution cells in the climate model consisted of land coverage and where they overlapped high-resolution cells on land. For display purposes, NIWA has undertaken interpolation to continue the climate projections to the coast for the climate change and historic climate maps presented in Section 4 to Section 7. The nearest neighbour interpolation method was used to do this, where the value of the empty coastal cell was estimated using the value of the nearest neighbouring cells. Because the values at these locations are estimates generated simply for presentation purposes (i.e. not a direct output of the climate change model), mapped climate change values at these coastal locations may go unmentioned in this report.

At the start of each subsection in Section 4 to Section 7, summary tables present an overview of the projected changes across Marlborough. These span the entire range of projections illustrated in the associated maps. As such, only isolated portions of the region may observe projected changes at the lower and upper limits of the range presented in the summary tables. The reader is referred to the maps for detailed projections, and also referred to the limitations (Section 2.4) associated with the interpretation of these maps.

Note that the historic maps are not provided for mean wind speed, surface solar radiation and relative humidity as these have not been bias-corrected, and therefore do not provide a reliable representation of the observed magnitude of these variables.

2.3 Hydrological modelling

To assess the potential impacts of climate change on agricultural water resources, 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 used 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, that is used commonly in New Zealand for catchment, regional and national scale hydrological modelling. 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 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).

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 digital river network aggregated up to Strahler catchment order three (approximate average catchment area of 7 km^2) used within previous national and regional scale assessments (Pearce *et al*., 2017; 2018); 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 two

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.

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). The periods analysed 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. Hydrological projections were analysed for the following hydrological statistics: Mean annual discharge and Mean annual low flow (MALF).

Because of TopNet assumptions, soil and land use characteristics within each computational subcatchment 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 approximate conditions across land uses. The data used in the hydrology section of the report is consistent with Collins and Zammit (2016).

2.4 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 show the average of six dynamically downscaled global climate models. This is a relatively small number of models for a quantitative probability assessment.
- The average of six models is used in this report, however data from individual models is available for further assessment if required in the future. The six models chosen represented historic climate conditions in New Zealand well, and span a range of future outcomes. The climate signal is better represented by ensemble averages since the uncertainty due to climate models and internal variability is much reduced.
- 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 low frequency climate variability (e.g. decadal signals from climate drivers like the Interdecadal Pacific Oscillation etc.). As climate data is subject to significant trends, a short period is more homogenous and representative. Moreover, 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 this report. The data have been bias-corrected, downscaled and interpolated from the 30 km regional climate model grid to the 5 km grid across New Zealand using physically based models and interpolation. Therefore, the data from these grid points does not correspond to on-the-ground observations. It is more appropriate to consider relative patterns rather than absolute values, e.g. the magnitude of change at different time periods and scenarios.

Although there are some limitations and caveats in the approach used here, considerable effort has been made to generate physically consistent climate change projections for New Zealand at unprecedented spatial and temporal resolution. A considerable research effort has also been dedicated to validating simulated climate variables, and thus the projections provide a good basis for risk assessments and adaptation plans.

3 Current and future climate of Marlborough

The main characteristic of the Marlborough climate is its dryness. Summer droughts are frequent, and the region is often swept by warm, dry northwesterlies. However, northern and elevated parts of Marlborough receive ample rainfall, with annual totals of more than 1500 mm common in these areas. The climate type is rather continental, with warm, dry summers and cool winters. However, this effect is significantly moderated in coastal areas. Snow lies throughout the winter on the mountain tops but is very rare in the main cropping areas near the east coast. Hail is not common, with eastern coastal areas being more susceptible. The main windflow over much of the region is from the northwest, while southwesterlies and northeasterlies predominate in the east. The most severe rain and wind conditions occur when the region is affected by intense depressions (low pressure systems) of tropical origin, but these occurrences are relatively rare. A feature of the climate, especially in the northeast of the region, is the relatively large amount of sunshine: Blenheim is one of the sunniest towns in New Zealand.

More information about the historic climate of Marlborough, outside of the information in this report, can be found in Chappell (2016).

4 Temperature

4.1 Mean temperature

Projected mean temperature changes (°C)

Annual:

Period	RCP4.5	RCP8.5
2040	+0.5-1.5	+0.5-1.5
2090	+0.5-2.0	+2.0-3.5

Seasonal:

	RCP4.5		RCP8.5	
	2040	2090	2040	2090
Summer	+0.5-1.5	+0.5-2.0	+0.5-1.5	+1.5-4.5
Autumn	+0.5-1.5	+1.0-2.0	+0.5-1.5	+2.0-4.0
Winter	Up to +1.0	+0.5-1.5	+0.5-1.0	+1.5-3.0
Spring	Up to +1.5	+0.5-2.0	+0.5-1.5	+1.5-4.0

Historic (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for mean temperature are shown in this section. The historic 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 historic maps are on a different colour scale to the future projection maps.

For the modelled historic period, coastal and low elevation portions of Marlborough have the highest annual and seasonal mean temperatures whereas areas further inland have the lowest mean temperatures, particularly those at high elevations (Figure 4-1 and Figure 4-2).

Representative concentration pathway (RCP) 4.5

By 2040, annual and seasonal mean temperatures are projected to increase by up to 1.5°C under RCP4.5 (Figure 4-3 to Figure 4-4). Only isolated inland areas to the southwest of the region see projected temperature increases of 1.0-1.5°C in summer, autumn and spring.

By 2090, annual mean temperatures are projected to increase by 0.5-2.0°C (Figure 4-3). At the seasonal scale, projected increases to mean temperature range from 0.5-2.0°C (Figure 4-5). The highest projected increases by 2090 under RCP4.5 are in the range of 1.5-2.0°C, and are restricted to the southwestern portions of Marlborough during summer, autumn and spring.

Representative concentration pathway (RCP) 8.5

By 2040, annual mean temperatures are projected to increase by 0.5-1.5°C (similar to RCP4.5; Figure 4-3). This is also the case for majority of the region at the seasonal scale, with southwestern parts of the region are projected to increase by 1.0-1.5°C during summer, autumn and spring (Figure 4-6).

By 2090, annual mean temperatures under RCP8.5 are projected to be around 2.0-3.5°C higher for Marlborough (Figure 4-3). At the seasonal scale, projected increases to mean temperatures are generally higher for summer (up to 3.5-4.5°C in southwestern high elevation inland areas) and autumn, with the majority of the region projected to increase by 2.0-3.5°C (Figure 4-7). Conversely, projected warming is generally lower for winter, with most of the region projected to increase by 1.5-3.0°C.

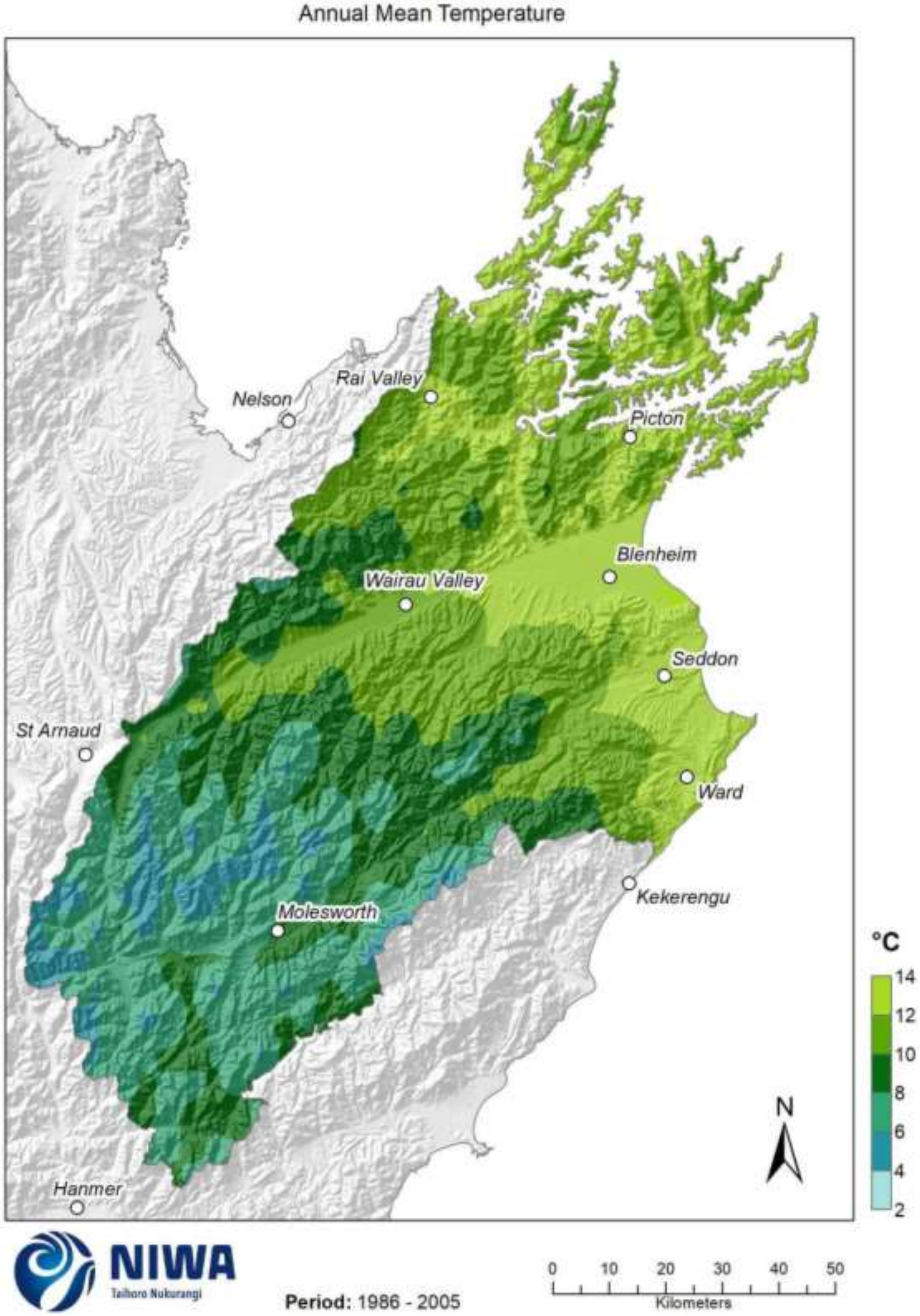


Figure 4-1: Modelled annual mean temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

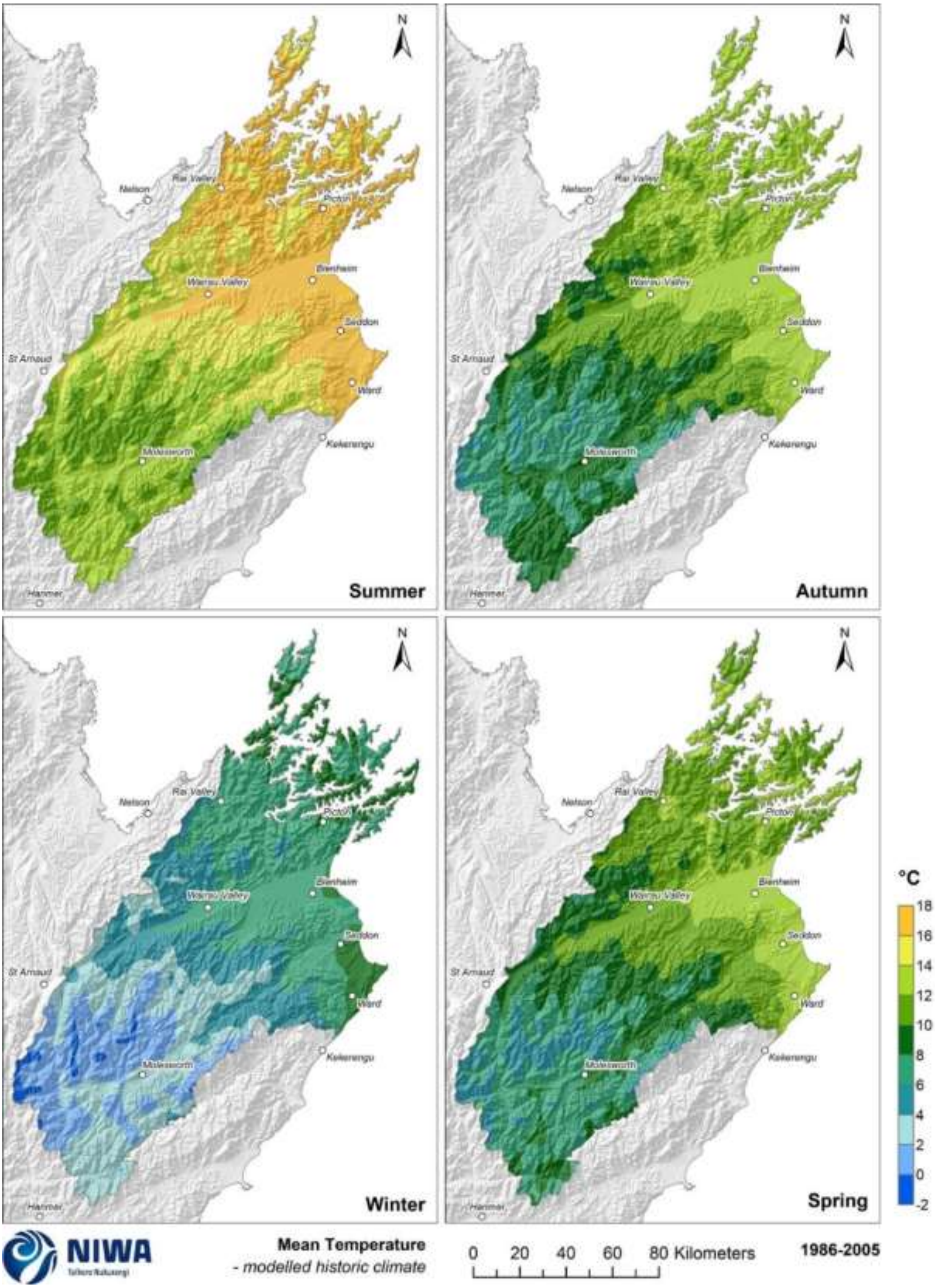


Figure 4-2: Modelled seasonal mean temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

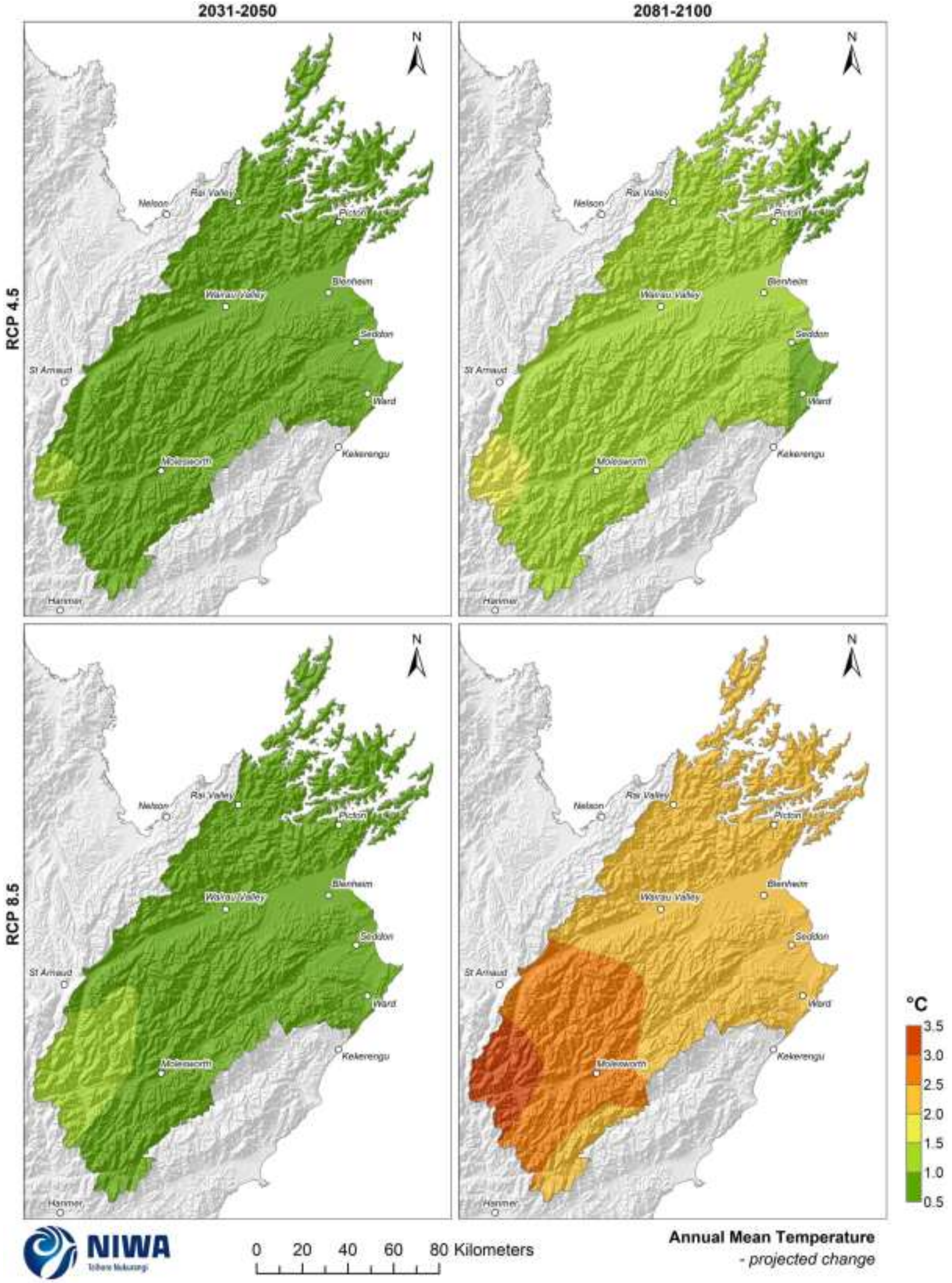


Figure 4-3: Projected annual mean temperature changes by 2040 and 2090 under RCP4.5 and RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

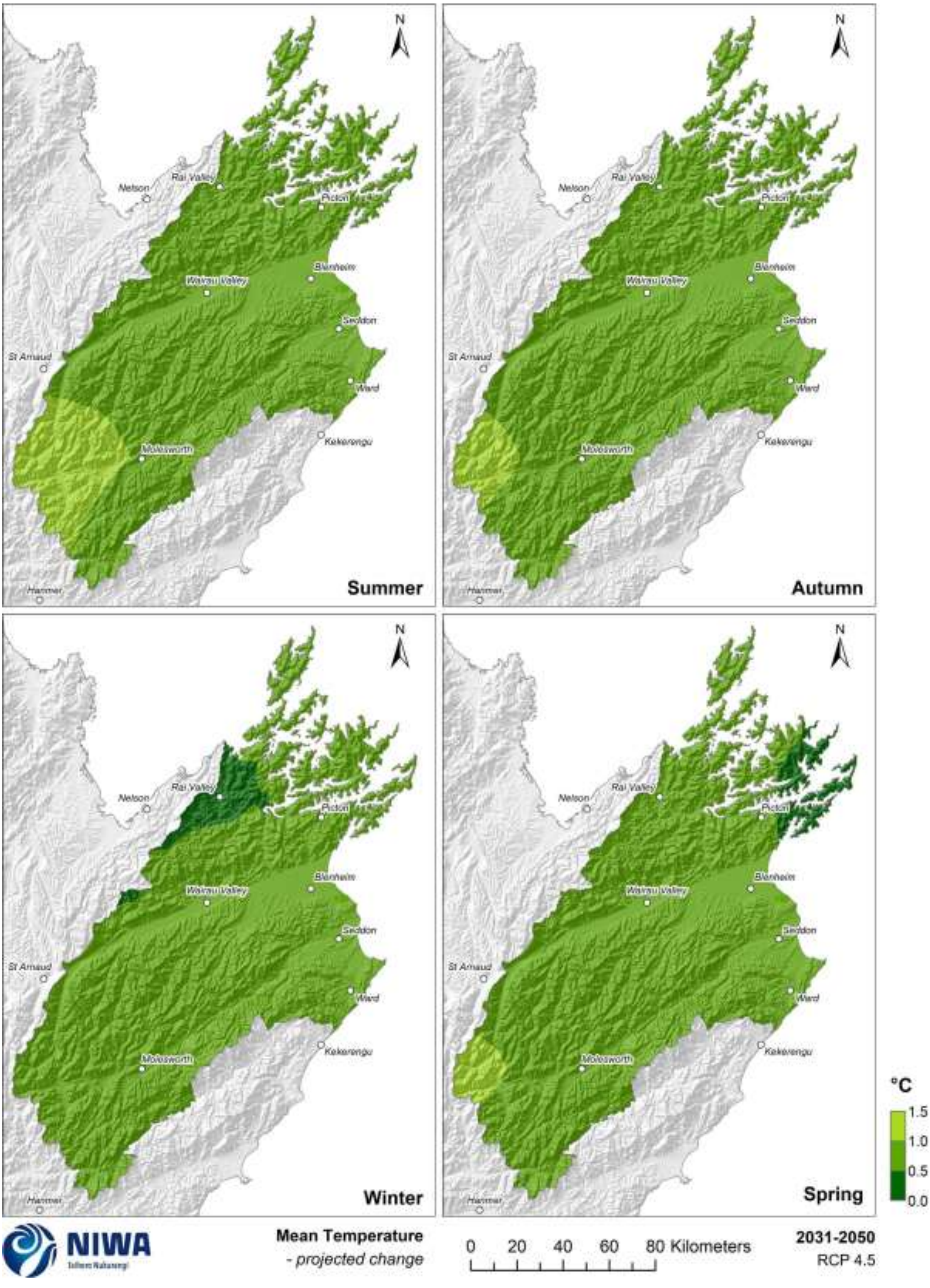


Figure 4-4: Projected seasonal mean temperature changes by 2040 under RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

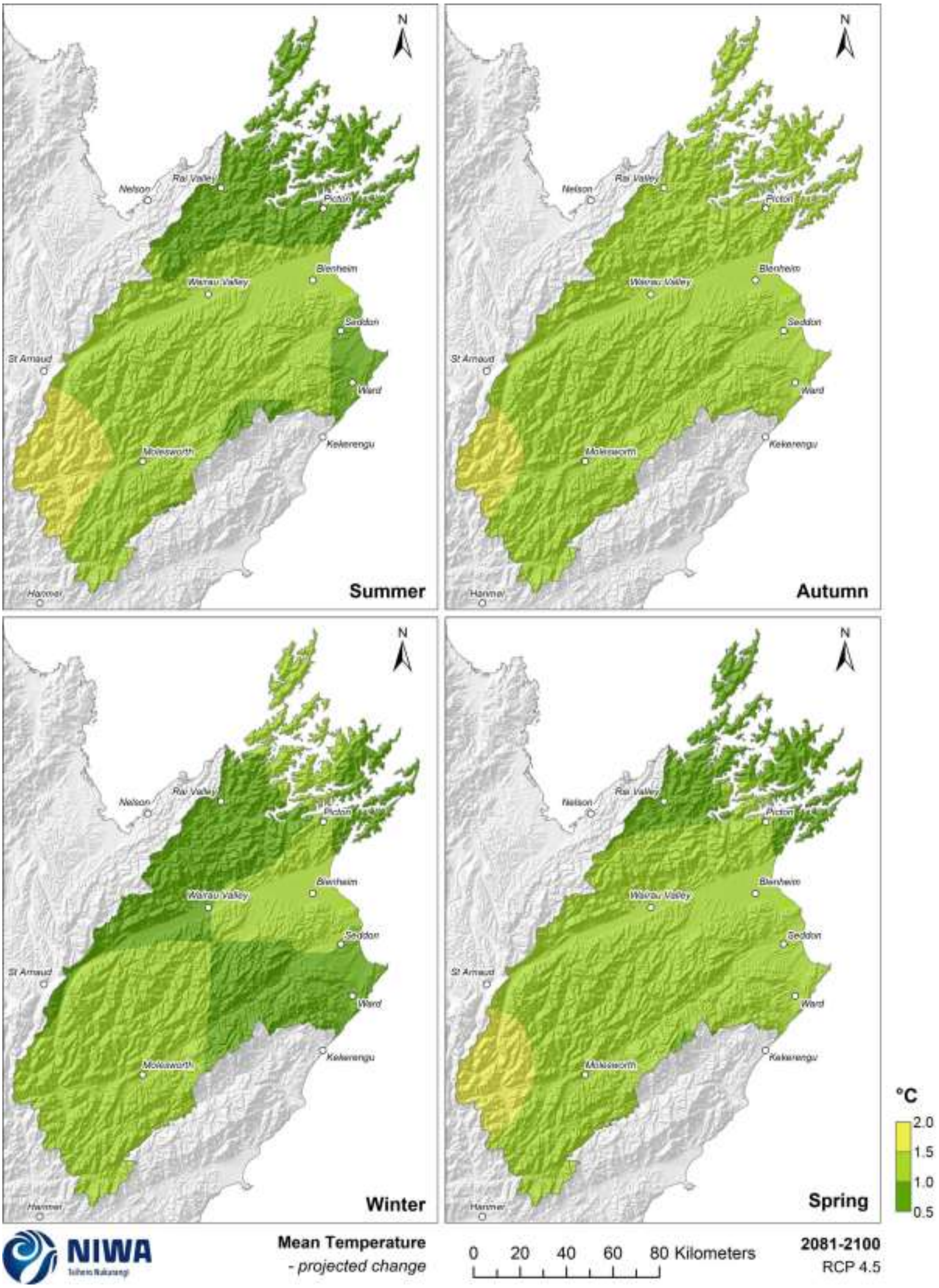


Figure 4-5: Projected seasonal mean temperature changes by 2090 under RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

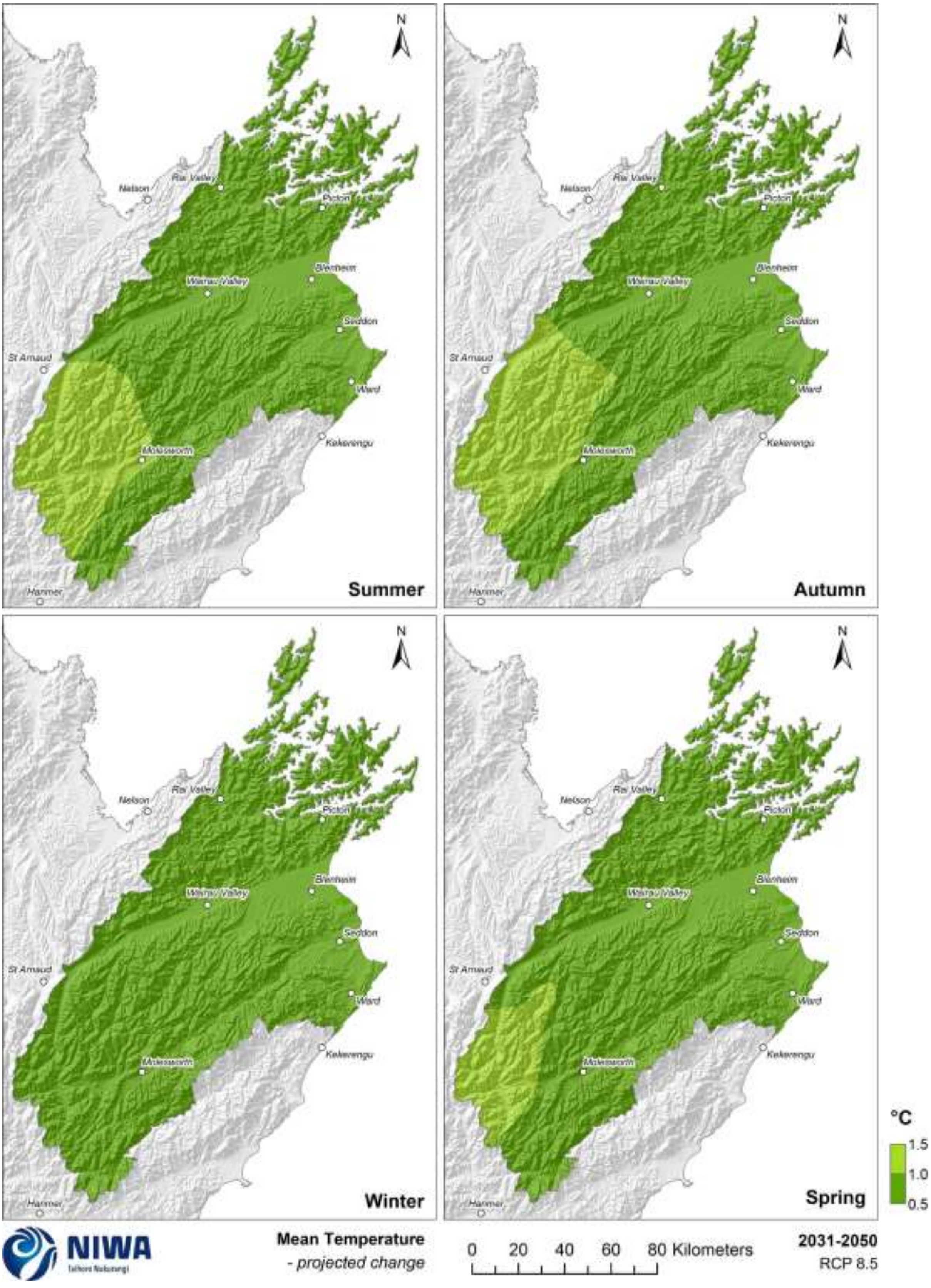


Figure 4-6: Projected seasonal mean temperature changes by 2040 under RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

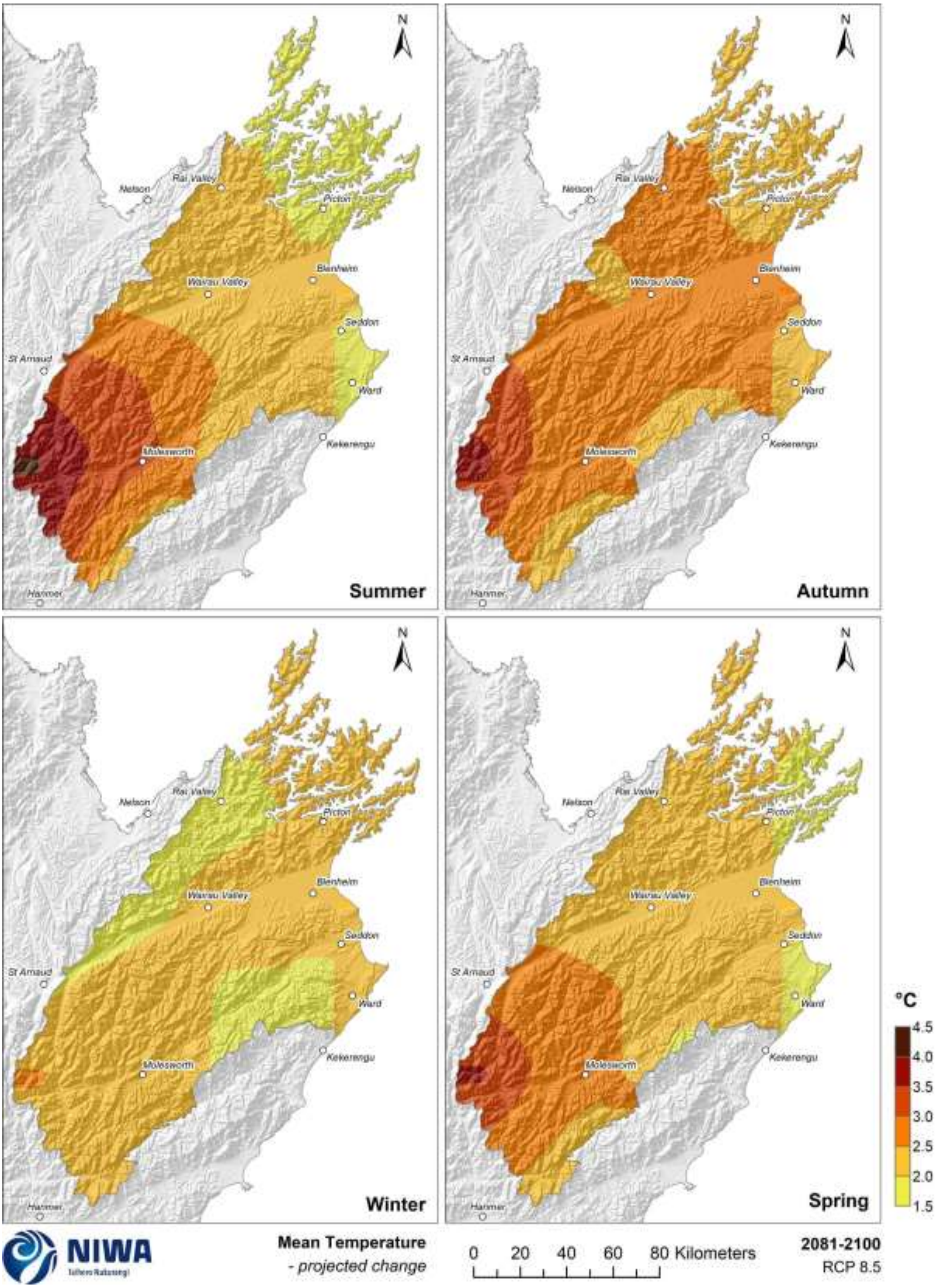


Figure 4-7: Projected seasonal mean temperature changes by 2090 under RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

4.2 Maximum temperature

Projected mean temperature changes (°C)

Annual:

Period	RCP4.5	RCP8.5
2040	+0.5-1.5	+0.5-2.0
2090	+1.0-3.0	+2.0-5.0

Seasonal:

	RCP4.5		RCP8.5	
	2040	2090	2040	2090
Summer	+0.5-2.0	+0.5-3.0	+0.5-3.0	+1.5-7.0
Autumn	+0.5-1.5	+1.0-3.0	+0.5-2.0	+2.0-5.0
Winter	+0.5-1.5	+0.5-2.0	+0.5-1.5	+2.0-4.0
Spring	+0.5-2.0	+1.0-3.0	+0.5-2.0	+2.0-6.0

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

For the historic period, coastal and low elevation portions of Marlborough have the highest annual and seasonal mean maximum temperatures (16-18°C at the annual scale; Figure 4-8), particularly about Blenheim (18-20°C at the annual scale). Inland high elevation areas have the lowest mean maximum temperatures.

Representative concentration pathway (RCP) 4.5

By 2040, annual mean maximum temperatures are projected to increase by 0.5-1.5°C under RCP4.5 (Figure 4-10). At the seasonal scale, winter and autumn maximum temperatures are projected to increase by 0.5-1.5°C, while increases for the remaining two seasons range from 0.5-2.0°C (Figure 4-11).

By 2090, projected changes to annual mean maximum temperatures are slightly higher than 2040, with increases of 0.5-2.0°C for the region (Figure 4-10). Autumn and spring maximum temperatures are projected to increase by 1.0-3.0°C, while summer is projected to have maximum temperature increases ranging from 0.5-3.0°C.

Representative concentration pathway (RCP) 8.5

By 2040, annual mean maximum temperatures are projected to increase by 0.5-2.0°C under RCP8.5 (Figure 4-10). At the seasonal scale, projected increases are similar to RCP4.5 by 2040, although summer maximum temperatures are projected to increase by 0.5-3.0°C with greatest projected change occurring in the southwest of the region (Figure 4-13).

By 2090, projected increases to maximum temperatures are considerable, and much greater than under RCP4.5, with annual increases of 2.0-5.0°C projected for Marlborough (Figure 4-10). At the seasonal scale, summer maximum temperatures are projected to increase by the most across the region, with increases of 1.5-7.0°C (Figure 4-14). Winter is projected to generally experience the smallest increases, although they are still considerable, with projected increases of 2.0-4.0°C. Greatest increases in maximum temperature are projected over southwestern parts of Marlborough.

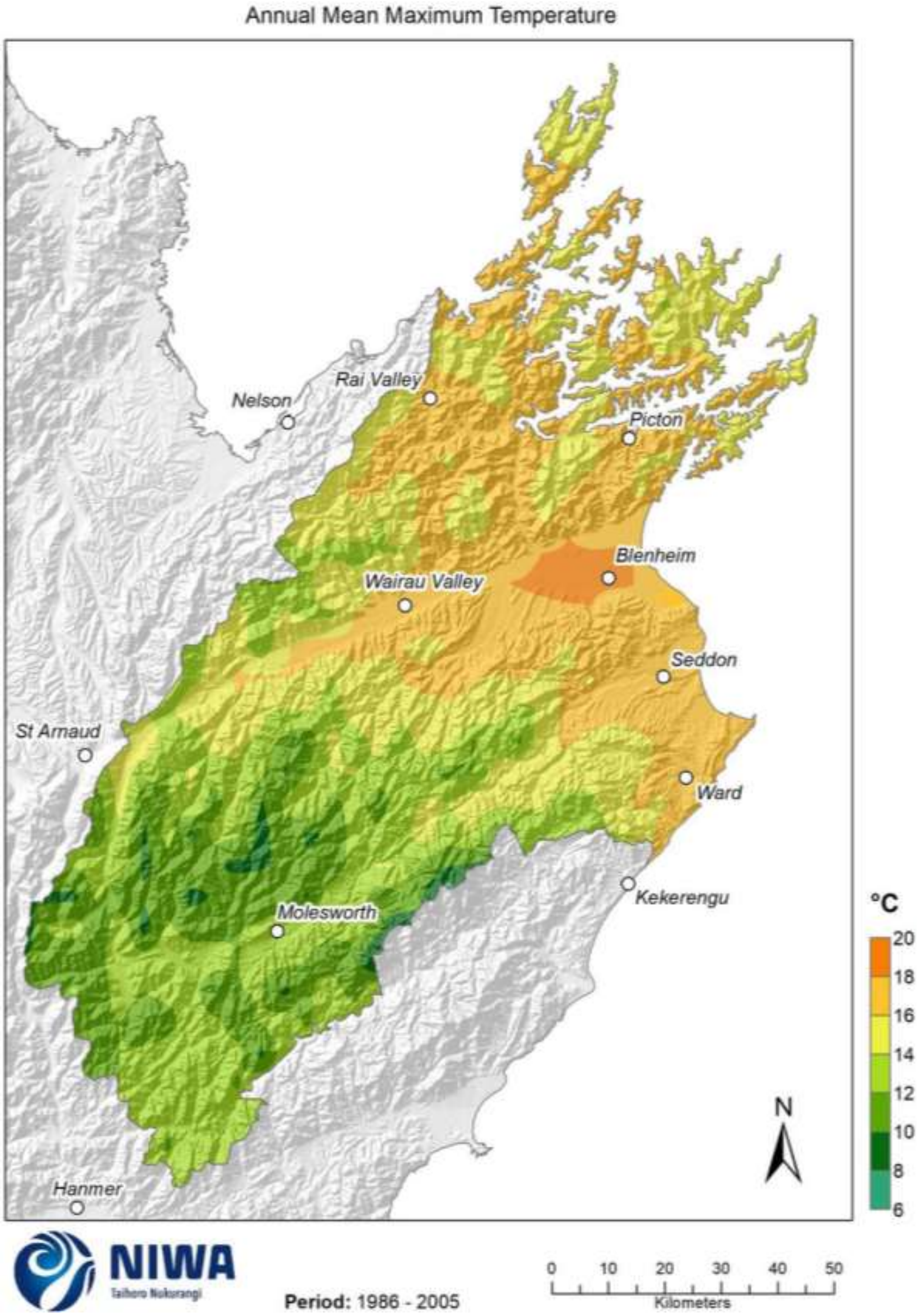


Figure 4-8: Modelled annual mean maximum temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

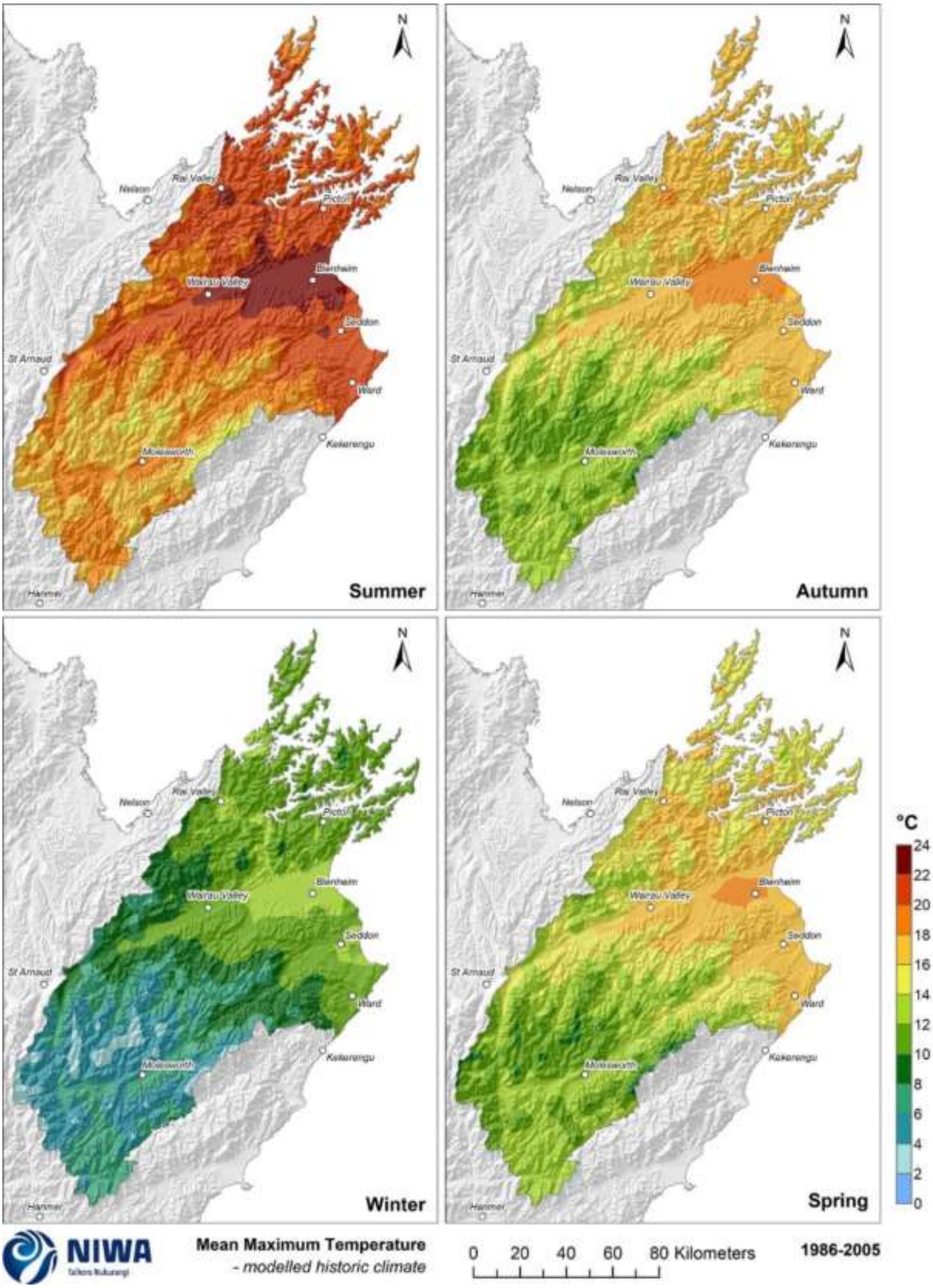


Figure 4-9: Modelled seasonal mean maximum temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

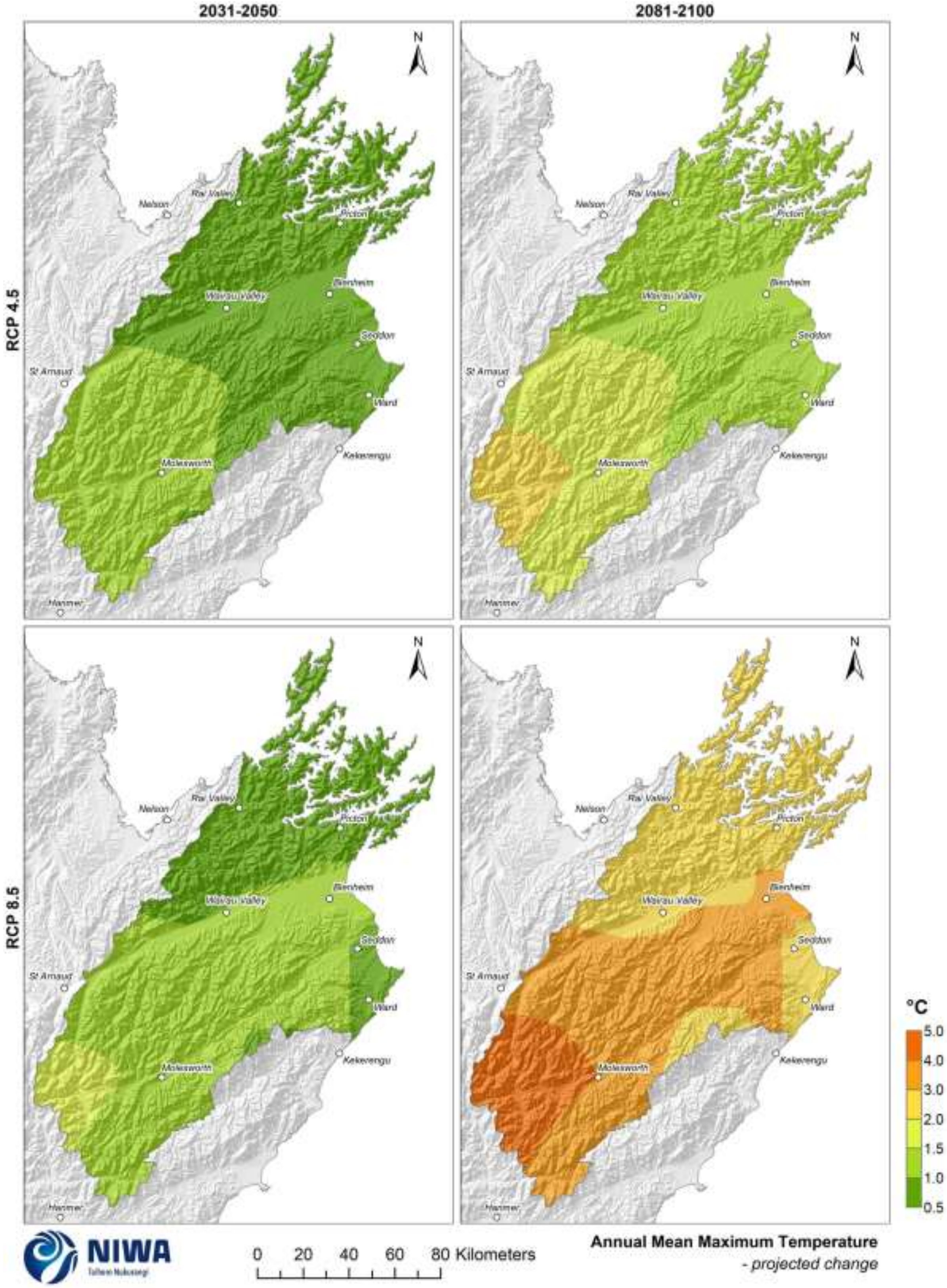


Figure 4-10: Projected annual mean maximum temperature changes by 2040 and 2090 under RCP4.5 and RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

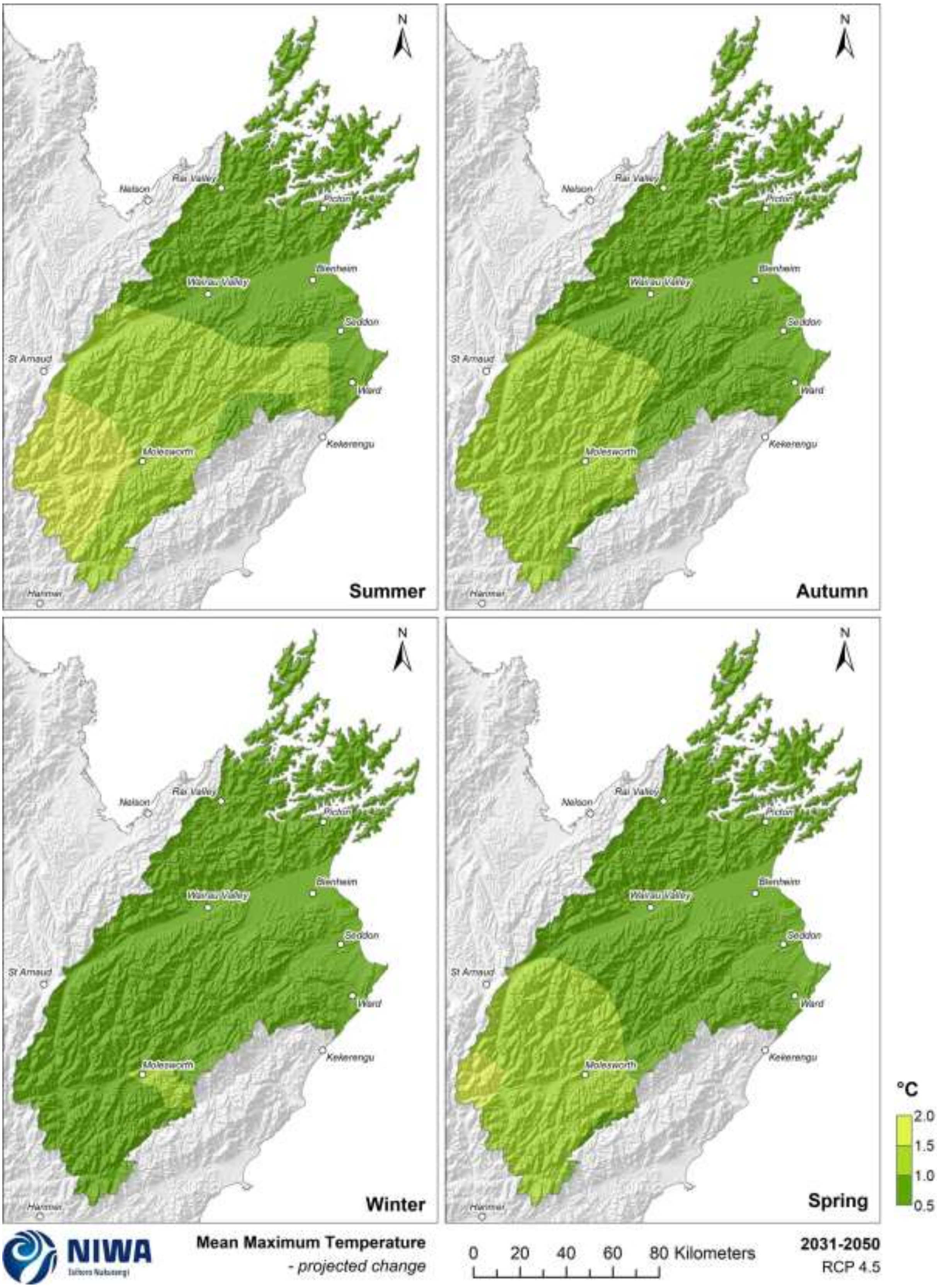


Figure 4-11: Projected seasonal mean maximum temperature changes by 2040 under RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

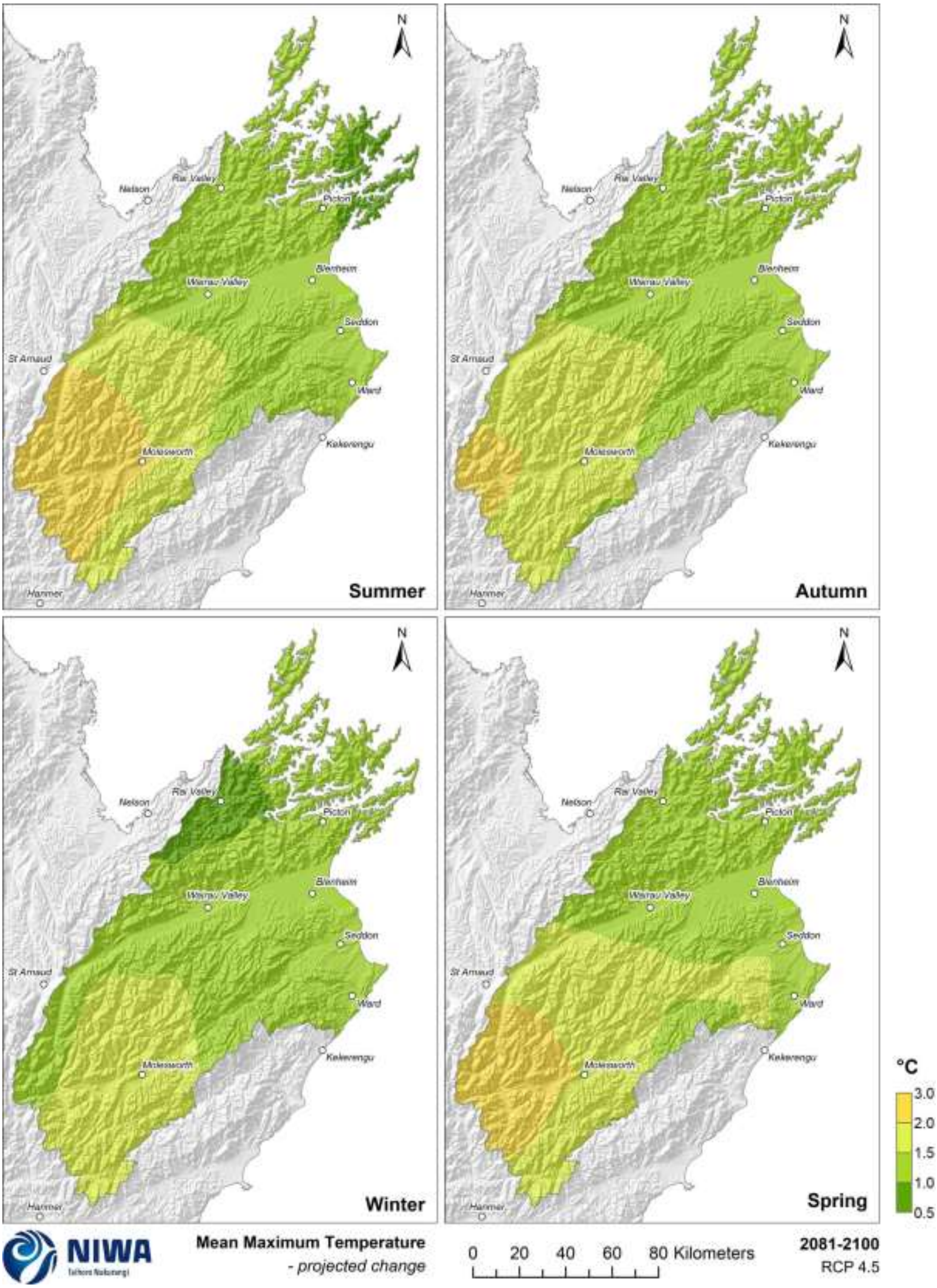


Figure 4-12: Projected seasonal mean maximum temperature changes by 2090 under RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

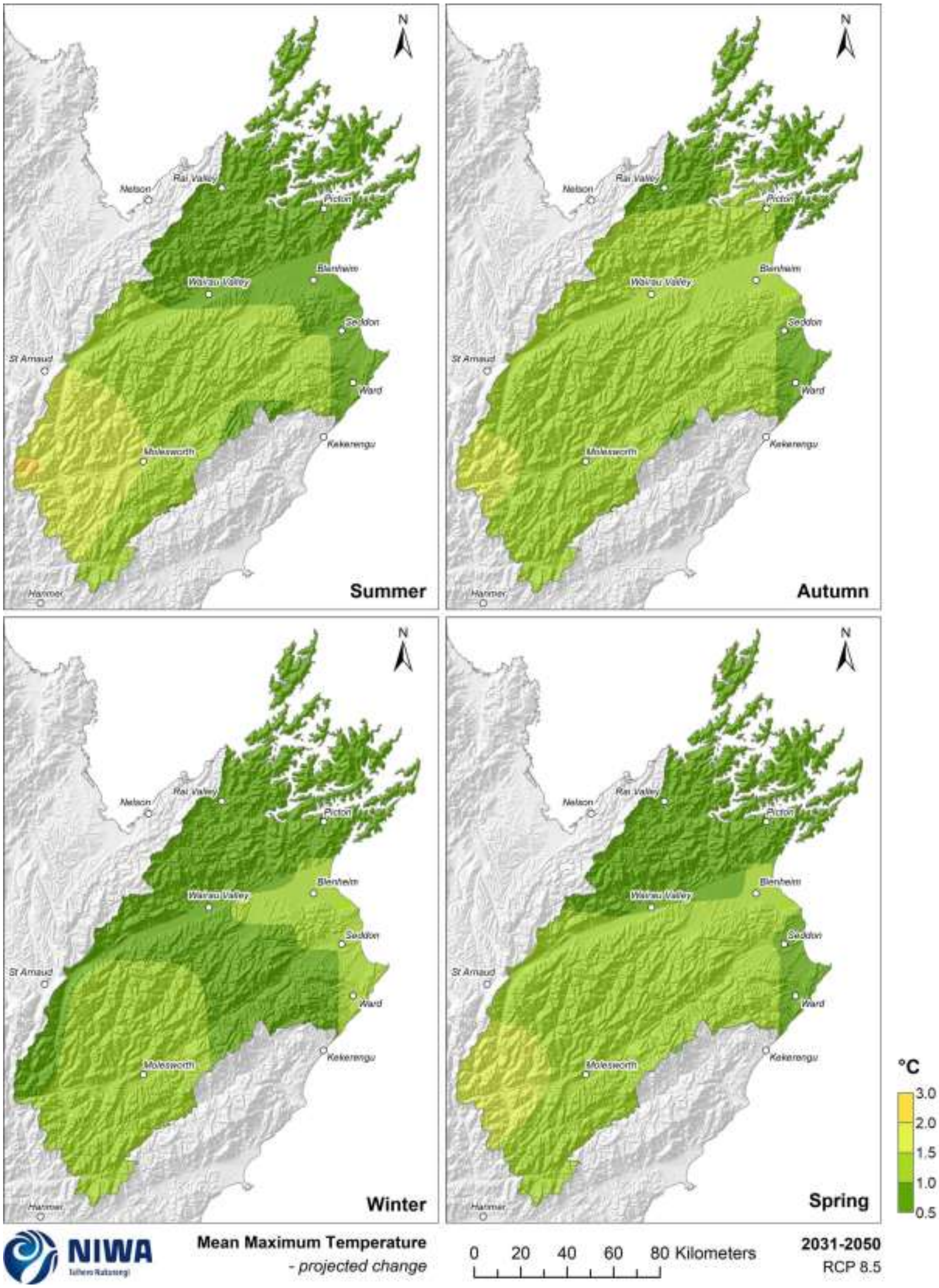


Figure 4-13: Projected seasonal mean maximum temperature changes by 2040 under RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

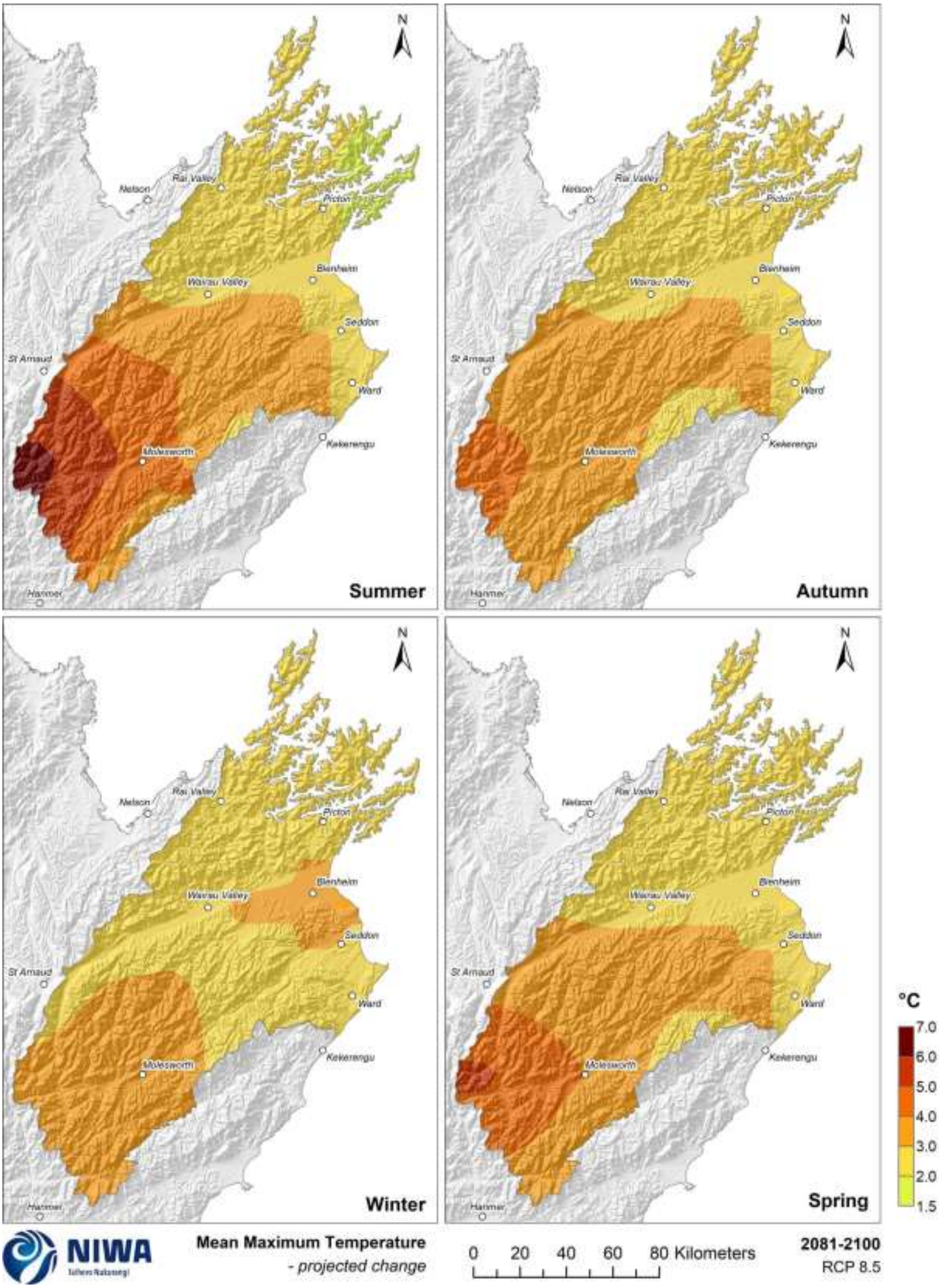


Figure 4-14: Projected seasonal mean maximum temperature changes by 2090 under RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

4.3 Minimum temperature

Projected minimum temperature changes (°C)

Annual:

Period	RCP4.5	RCP8.5
2040	Up to +1.0	Up to +1.0
2090	+0.5-1.0	+1.0-2.5

Seasonal:

	RCP4.5		RCP8.5	
	2040	2090	2040	2090
Summer	Up to +1.0	+0.5-1.0	Up to +1.0	+1.0-2.0
Autumn	Up to +1.0	+0.5-1.5	+0.5-1.0	+1.5-3.0
Winter	Up to +1.0	Up to +1.0	Up to +1.0	+0.5-2.0
Spring	Up to +1.0	+0.5-1.5	Up to +1.0	+1.0-2.0

Minimum temperatures are generally recorded in the early hours of the morning, and therefore are known as night-time temperatures. Historic (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for mean minimum temperature are shown in this section. The historic 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 historic period, in units of °C. Note that the historic maps are on a different colour scale to the future projection maps.

For the historic period, coastal portions of Marlborough have the highest annual and seasonal mean minimum temperatures (8-10°C at the annual scale; Figure 4-15). Winter mean minimum temperatures between 0°C and -4°C are observed for inland and high elevation parts of Marlborough Figure 4-16.

Representative concentration pathway (RCP) 4.5

By 2040, annual and seasonal mean minimum temperatures are projected to increase by up to 1.0°C under RCP4.5 (Figure 4-17 and Figure 4-18).

By 2090, increases to annual mean minimum temperatures of 0.5-1.0°C are projected for Marlborough (Figure 4-17). Autumn and spring minimum temperatures are projected to increase by 0.5-1.5°C, while summer is projected to have minimum temperature increases ranging from 0.5-1.0°C (Figure 4-19).

Representative concentration pathway (RCP) 8.5

By 2040, annual mean minimum temperatures are projected to increase by up to 1.0°C under RCP8.5 in Marlborough (Figure 4-17). At the seasonal scale, projected increases are similar to RCP4.5 by 2040, with autumn minimum temperatures projected to increase by 0.5-1.0°C for the region, and remaining seasons projected to increase by up to 1.0°C (Figure 4-20).

By 2090, projected increases to minimum temperatures are greater than under RCP4.5, with annual increases of 1.0-2.5°C projected for Marlborough (Figure 4-17). At the seasonal scale, autumn minimum temperatures are projected to increase the most compared with the other seasons (+1.5-3.0°C; Figure 4-21). Increases of 1.0-2.0°C are projected for summer and spring.

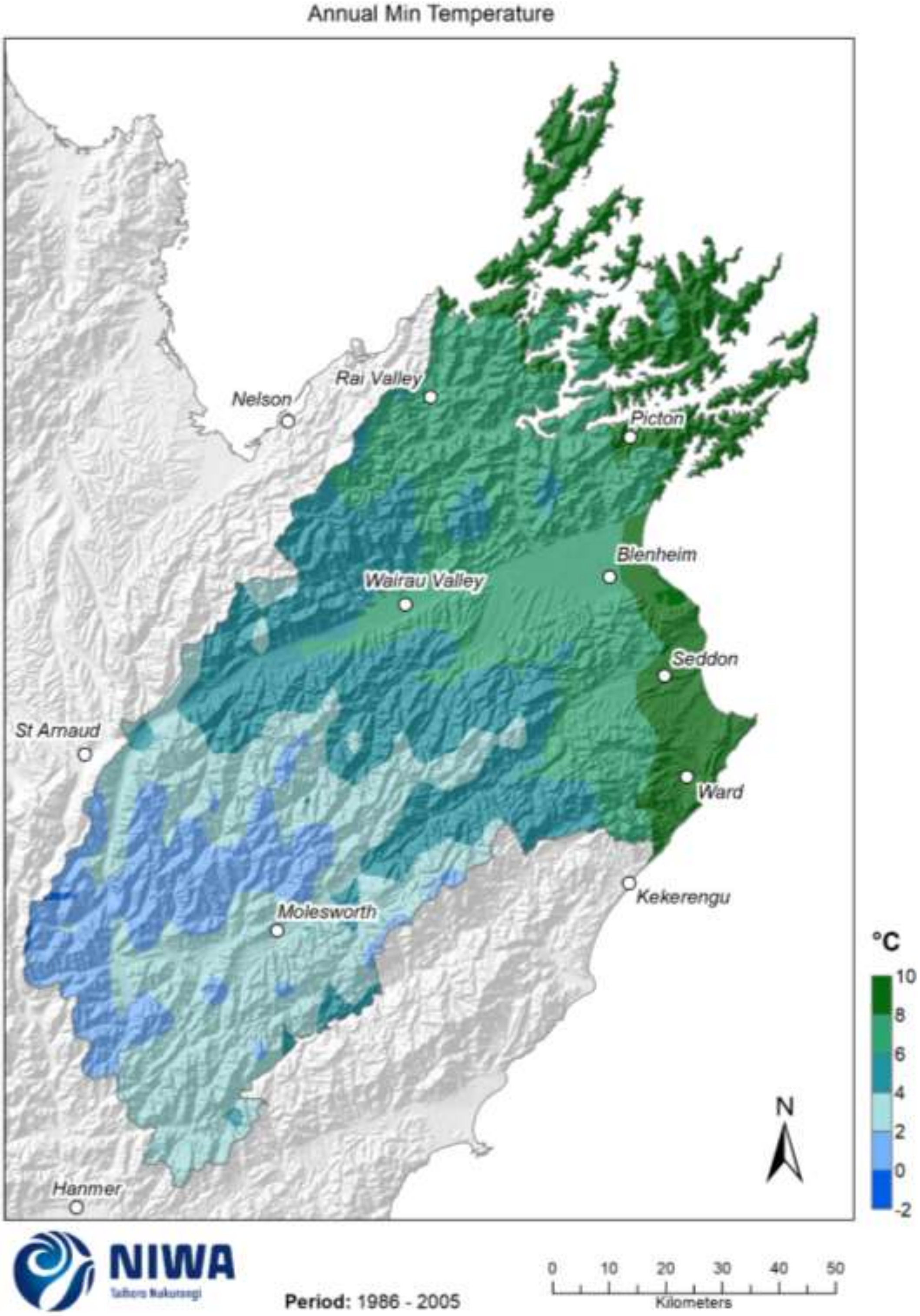


Figure 4-15: Modelled annual mean minimum temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

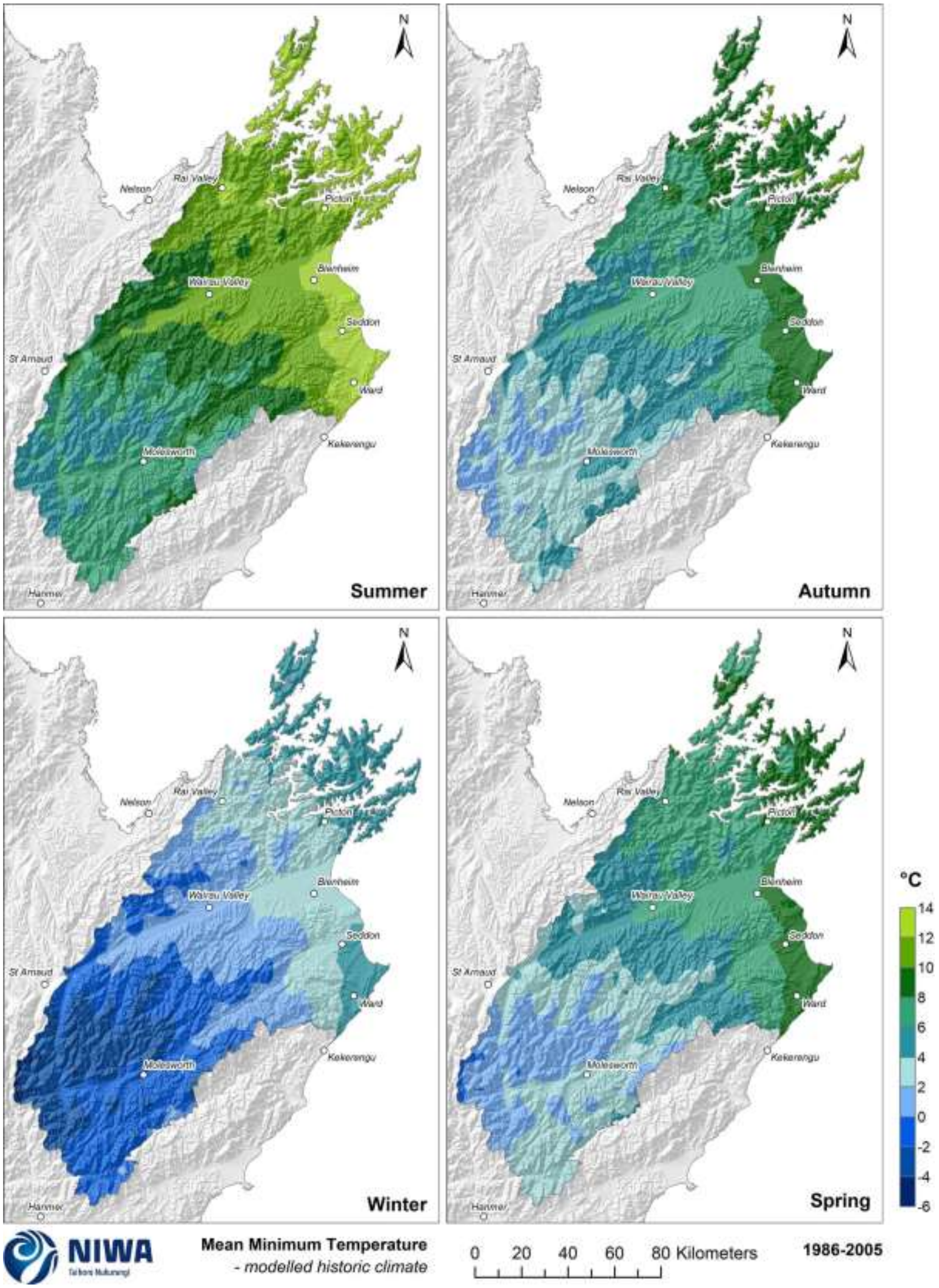


Figure 4-16: Modelled seasonal mean minimum temperature, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

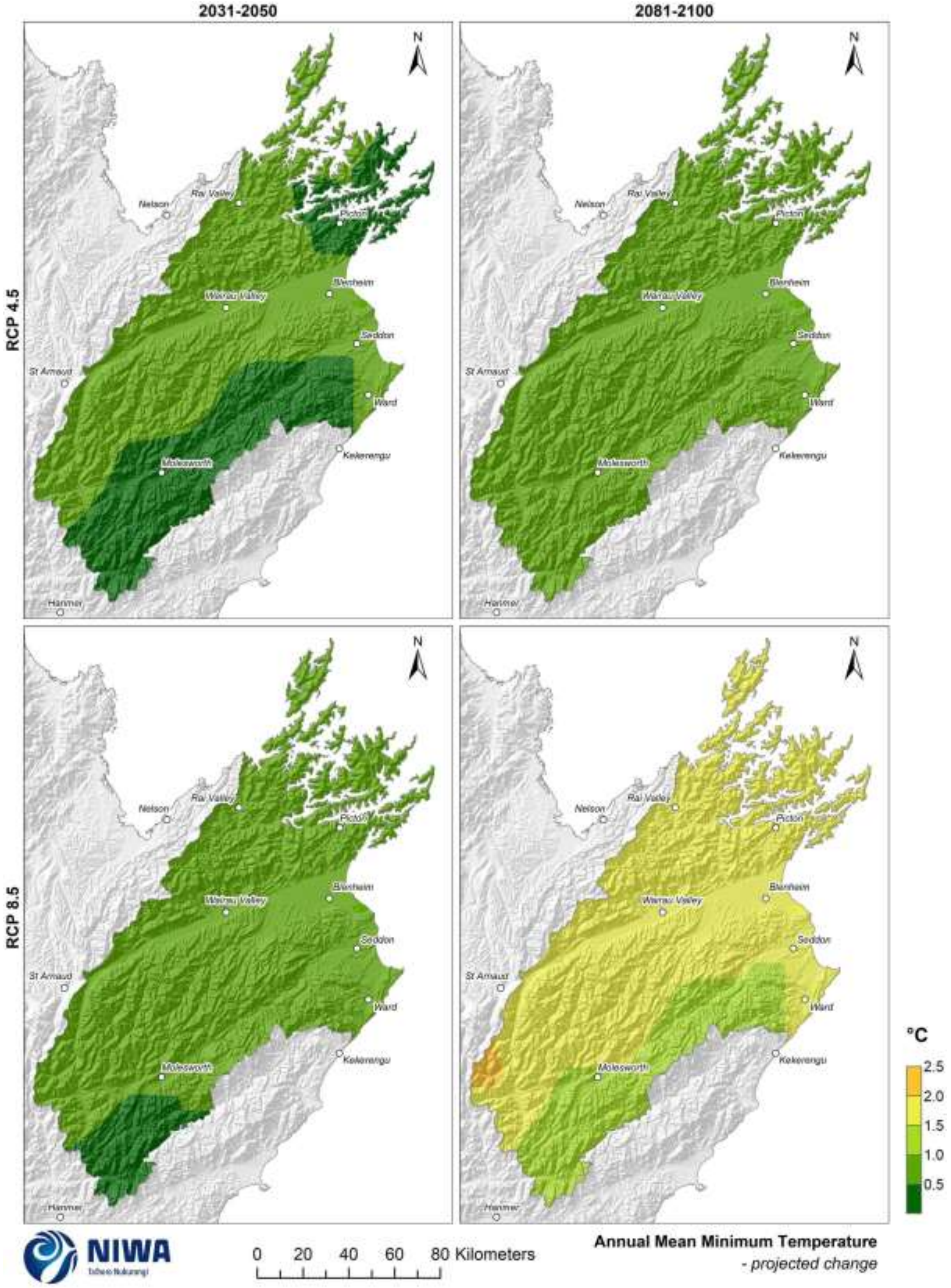


Figure 4-17: Projected annual mean minimum temperature changes by 2040 and 2090 under RCP4.5 and RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

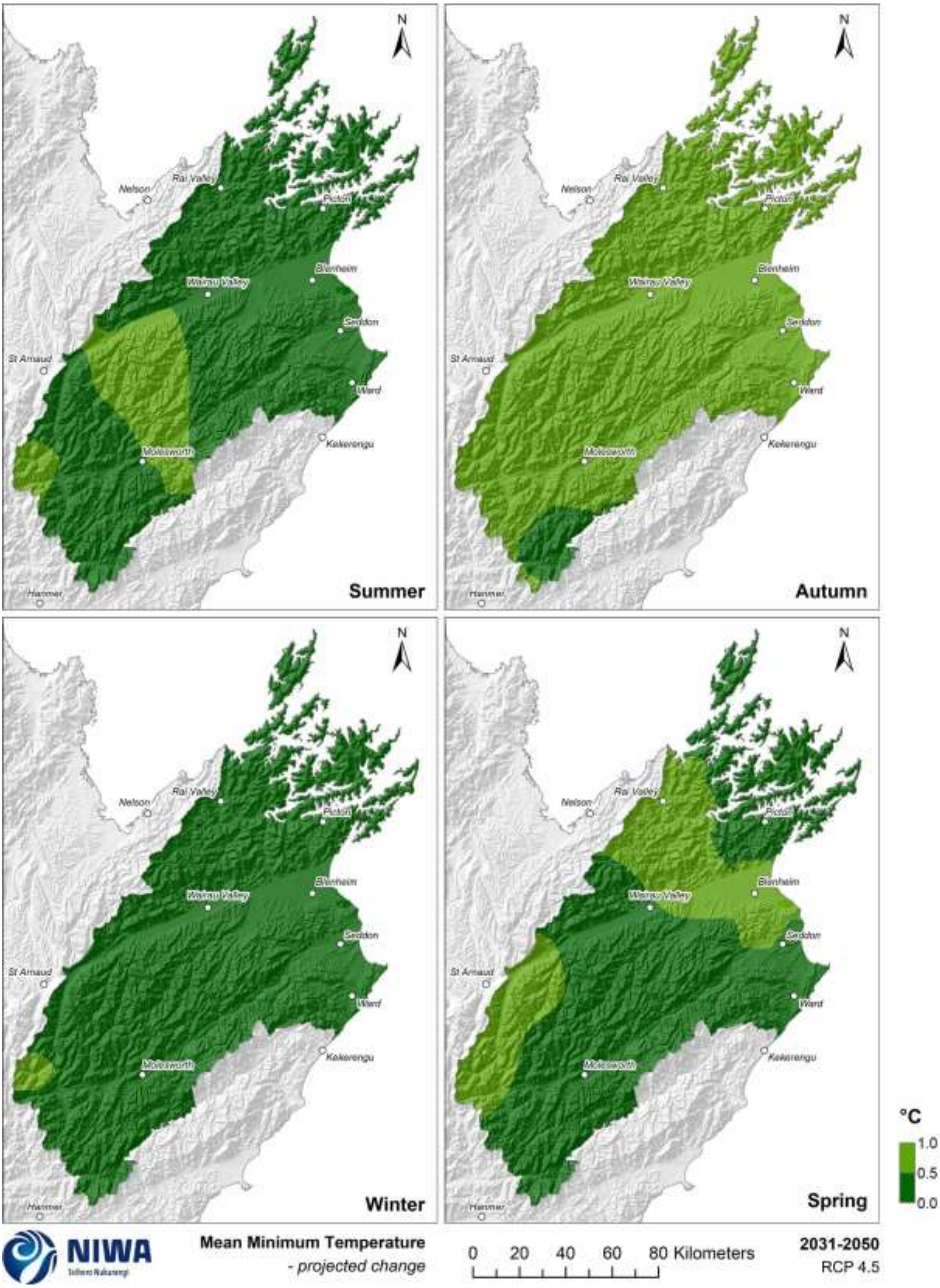


Figure 4-18: Projected seasonal mean minimum temperature changes by 2040 under RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

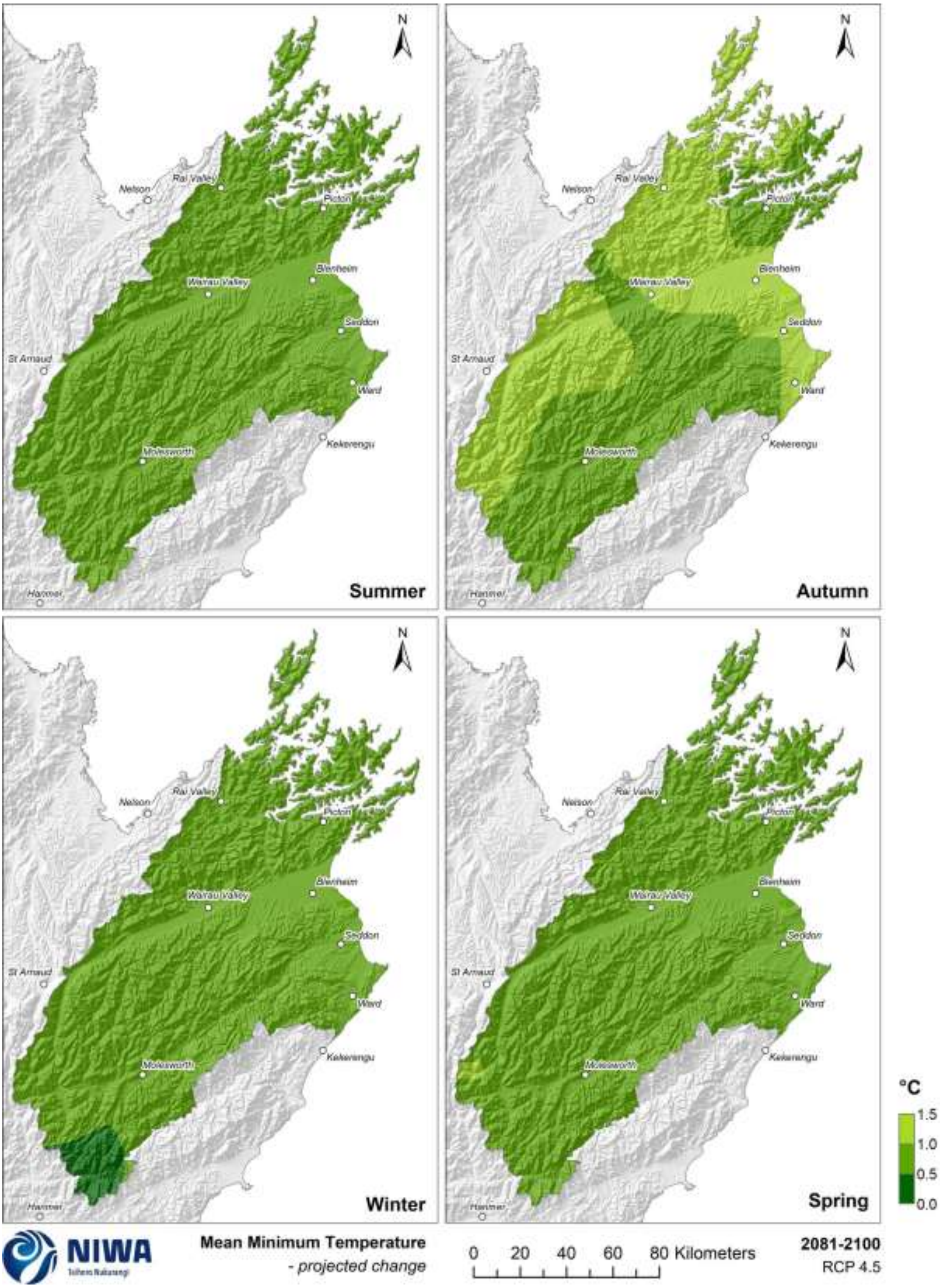


Figure 4-19: Projected seasonal mean minimum temperature changes by 2090 under RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

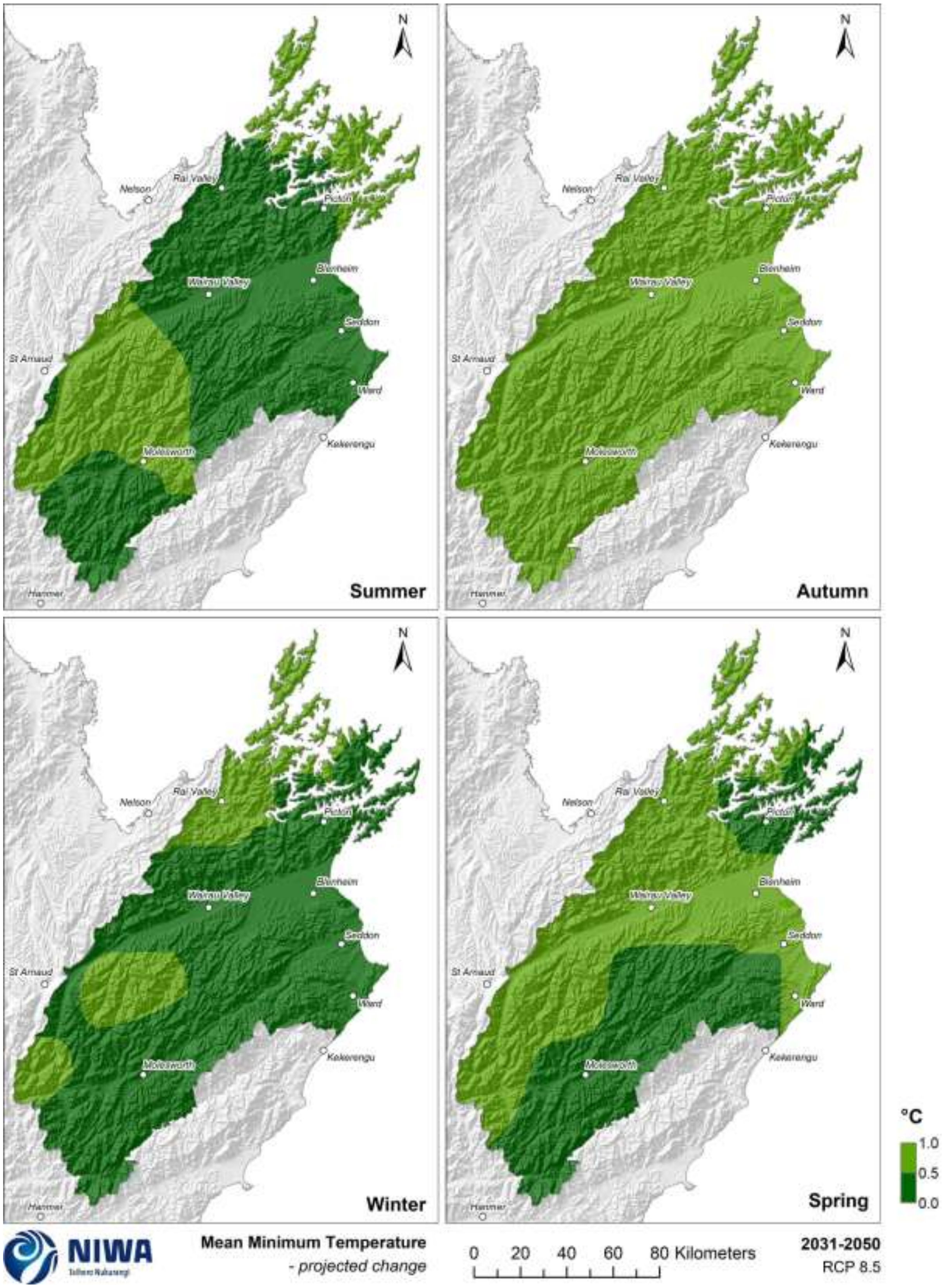


Figure 4-20: Projected seasonal mean minimum temperature changes by 2040 under RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

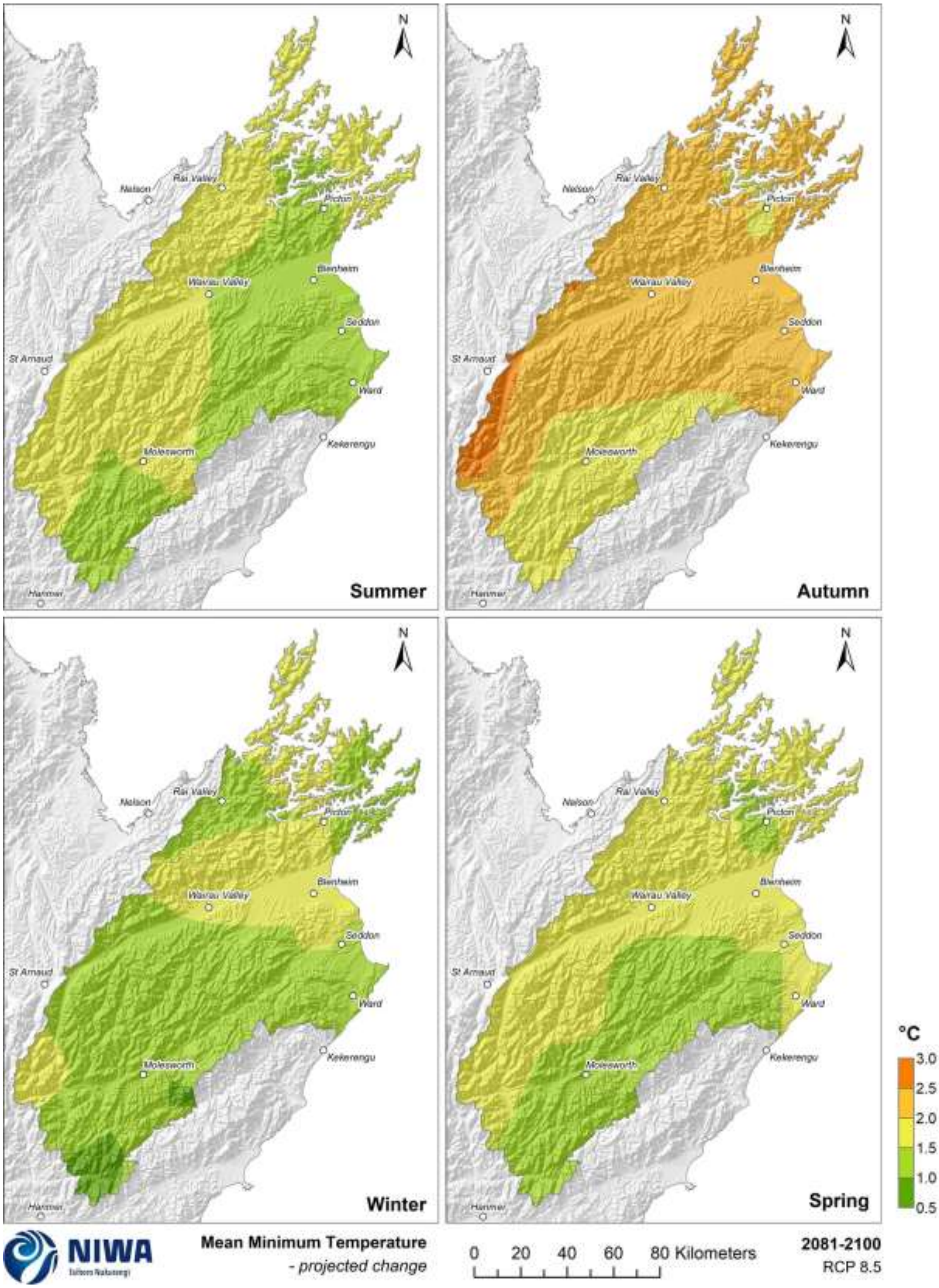


Figure 4-21: Projected seasonal mean minimum temperature changes by 2090 under RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

4.4 Diurnal temperature range

Projected diurnal temperature range changes (°C)

Annual:

Period	RCP4.5	RCP8.5
2040	Up to +1.0	Up to +2.0
2090	Up to +2.0	Up to +3.0

Diurnal temperature range is the difference between the daily maximum temperature and the daily minimum temperature. Diurnal temperature ranges are largest in dry desert areas and smallest in humid tropical areas of the world. Diurnal temperature range may change over time due to land use change, cloud cover, urban heat effects, and greenhouse gases.

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

The historic diurnal temperature range is highest at low elevation and inland locations, and lowest about coastal areas (Figure 4-22). This is largely a result of the moderating influence of the sea on daily maximum and minimum temperatures. The annual diurnal temperature range varies from 11-12°C about Blenheim and Wairau Valley, to 7-9°C near Ward and other coastal areas.

Representative concentration pathway (RCP) 4.5

By 2040, increases in diurnal temperature range of up to 1.0°C are projected throughout Marlborough (Figure 4-23). By 2090, increases of up to 2.0°C are projected for Marlborough, with greatest increases towards the southwest of the region.

Representative concentration pathway (RCP) 8.5

By 2040, increases in diurnal temperature range of up to 2.0°C are projected throughout Marlborough (Figure 4-23). By 2090, diurnal temperature range increases of up to 3.0°C are projected for Marlborough, with largest increases of 2.0-3.0°C for the inland area around Molesworth.

The projected increases in diurnal temperature range (under both RCP4.5 and RCP8.5) are due to higher projected increases in maximum temperatures compared to minimum temperatures. Further research is needed to establish the robustness of these differences in projected maximum and minimum temperatures, and the consequent effect on diurnal temperature range (MFE, 2018).

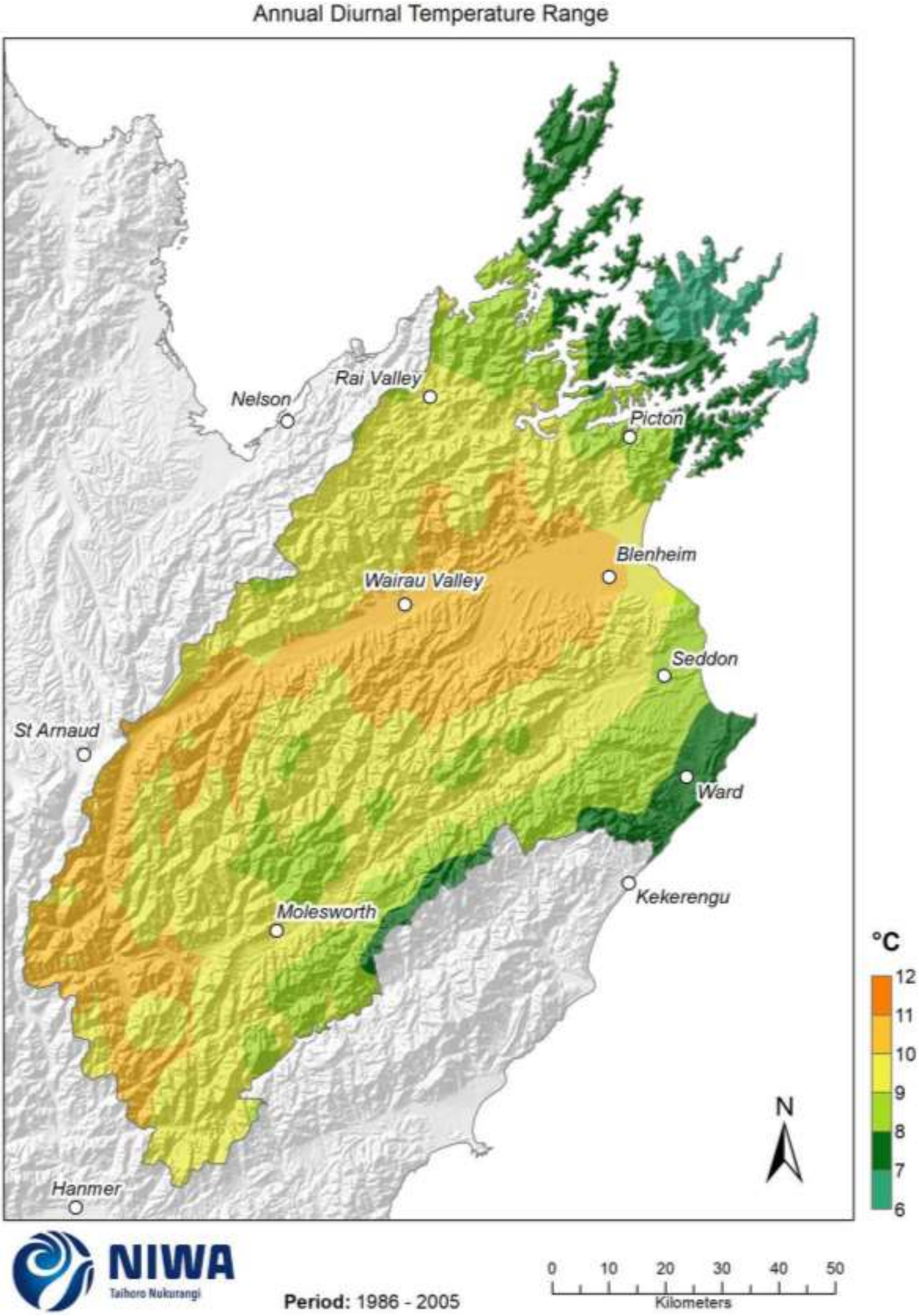


Figure 4-22: Modelled annual diurnal temperature range (Tmax minus Tmin), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km

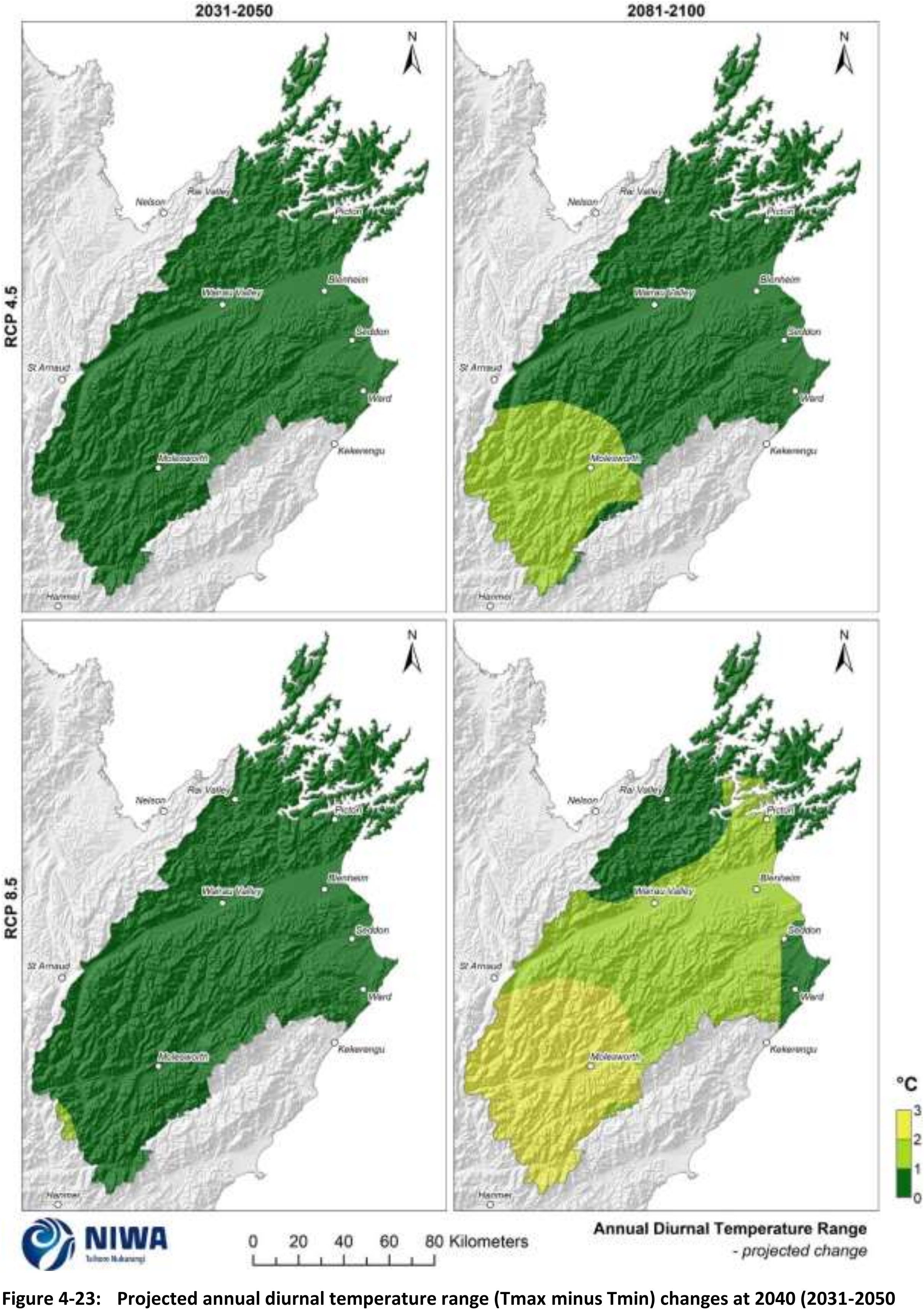


Figure 4-23: Projected annual diurnal temperature range (Tmax minus Tmin) changes at 2040 (2031-2050 average) and 2090 (2081-2100) for RCP4.5 and RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

4.5 Frost days

Projected frost day changes (days)

Annual:

Period	RCP4.5	RCP8.5
2040	Up to 20 fewer	1-20 fewer
2090	Up to 40 fewer	1-60 fewer

A frost day is defined in this report when the modelled daily minimum temperature is equal to or lower than 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.

Historic (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for frost days are shown in this section. The historic 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 the historic period. Note that the historic maps are on a different colour scale to the future projection maps.

For the modelled historic period, coastal portions of Marlborough (where minimum temperatures are generally higher) have the lowest number of frost days (Figure 4-24). This is largely the result of the influence of the sea, which moderates daily extreme temperatures compared to inland locations. Inland and mountainous parts of the region have the highest number of frost days, with 50-150 days per year typical about and west of Molesworth. Wairau Valley observes between 25-50 frost days per year on average for the modelled historic period, with 10-25 frost days per year about Blenheim.

Representative concentration pathway (RCP) 4.5

By 2040, decreases to frost days are projected throughout Marlborough (Figure 4-25), with highest decreases of 10-20 days projected towards the southwest of the region. Decreases of 5-10 days are projected about Wairau Valley, with decreases of 1-5 days projected about Blenheim, Seddon and Ward.

By 2090, decreases of 5-20 frost days are projected for most of the region. Decreases of 1-5 days are projected about Seddon and Ward (Figure 4-25). Larger decreases are projected for southwestern parts of the region, with isolated decreases of 20-40 days projected.

Representative concentration pathway (RCP) 8.5

By 2040, the projected pattern of change under RCP8.5 is very similar to that projected for the same time period under RCP4.5 (Figure 4-25).

By 2090, decreases of 1-60 frost days are projected for Marlborough (Figure 4-25). This would result in frosts becoming an uncommon occurrence for many areas of Marlborough near the coast. Decreases of 40-60 days are projected west of Molesworth.

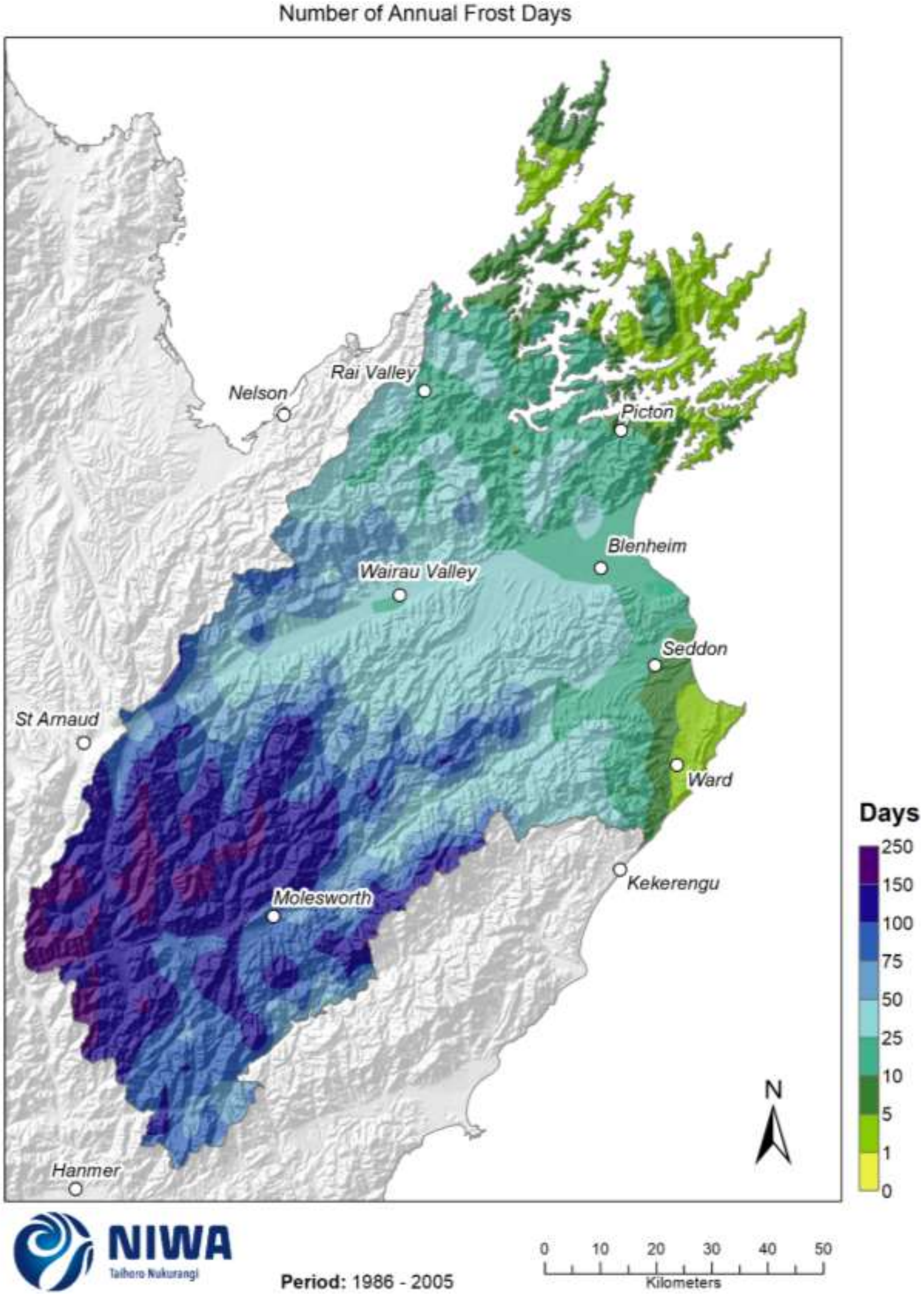


Figure 4-24: Modelled annual number of frost days (daily minimum temperature ≤0°C), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km

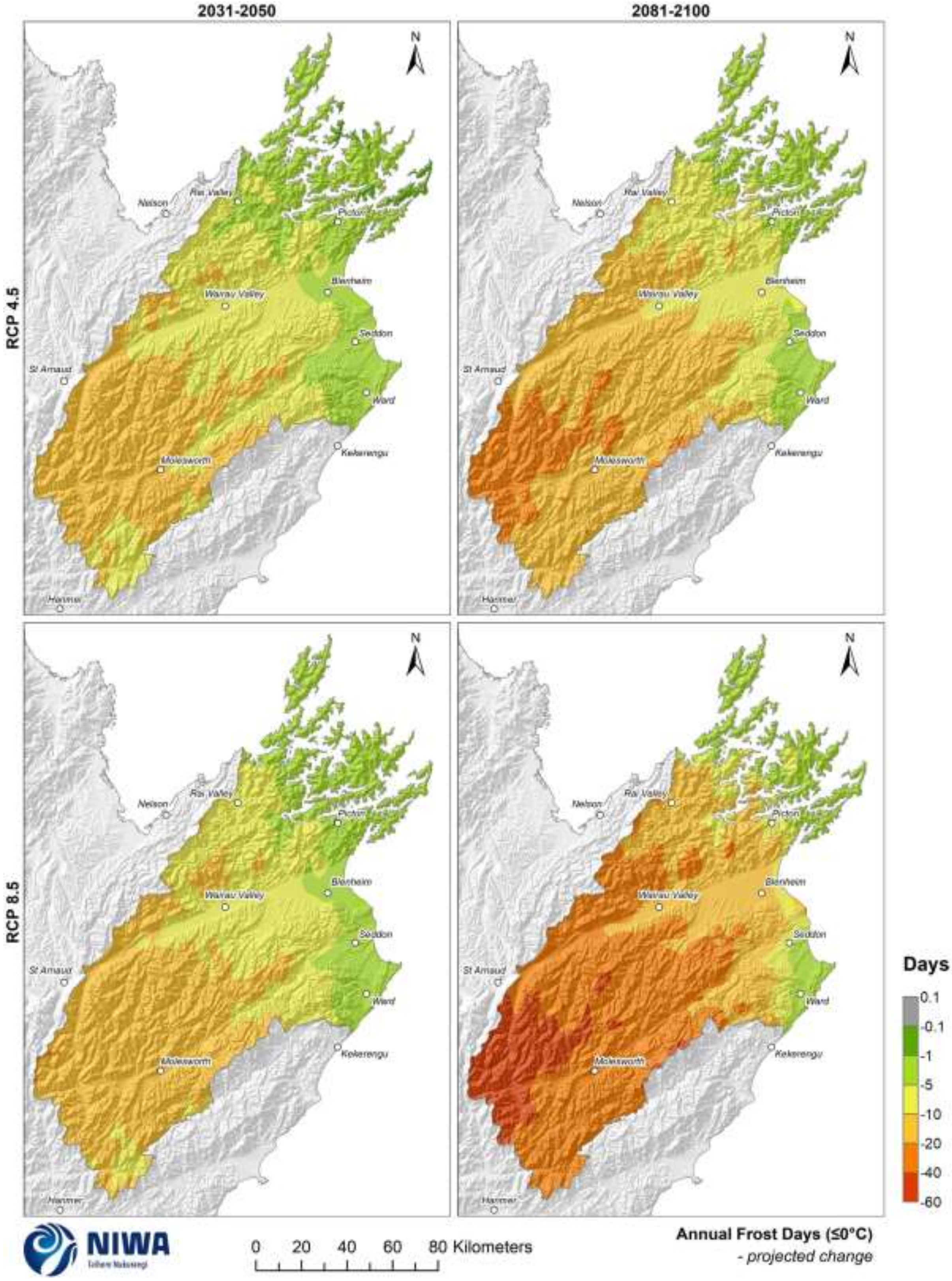


Figure 4-25: Projected annual number of frost days (daily minimum temperature ≤0°C) changes by 2040 and 2090 under RCP4.5 and RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

4.5.1 Frost season length

This section provides an analysis of the changing length of frost seasons for a specific location in Marlborough (-45.525, 173.775: approximately halfway between Blenheim and Wairau Valley). Daily climate model data between 1972 and 2100 were analysed to understand trends in frost occurrence and seasonality of frosts. Data from six dynamically downscaled global climate models (the same models used for the other projections in this report) were used, for RCP4.5 and RCP8.5.

The number of frost days as well as the length of the frost season (first to last frost date per year) declines under both RCPs in the future (Figure 4-26). By 2100 under RCP8.5, the location in Marlborough is projected to experience approximately 15 frost days per year – about half experienced there currently. Beyond about 2060 the RCP4.5 decreasing trend in number of frost days flattens off, whereas the RCP8.5 trend in number of frost days continues to decline. Both RCP4.5 and RCP8.5 series exhibit high inter-annual variability.

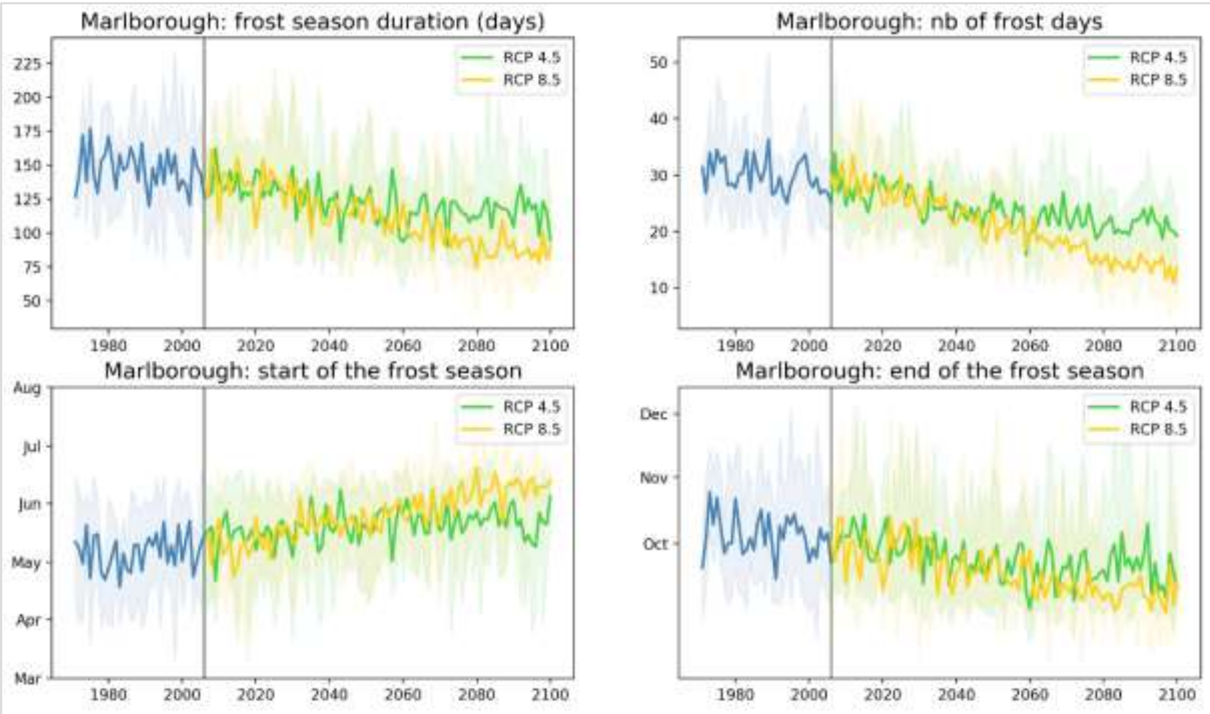


Figure 4-26: Frost season changes for a Marlborough location. Top-left: frost season duration; top-right: number of frost days; bottom-left: date of the first frost of the season; bottom-right: date of the last frost of the season. Bold lines show the average of six global climate models for two RCPs, dynamically downscaled to New Zealand (5km x 5km resolution). The blue line is the historic period (pre-2005). The shading is the minimum and maximum model result. Location selected: -41.525, 173.775 (WGS84).

To further illustrate the changing dates of the frost seasons in Marlborough, Figure 4-27 shows the distribution of model results for the start date of the frost season for 2040 (2031-2050) and 2090 (2081-2100), under RCP4.5 and RCP8.5. This result clearly shows the movement of the start of the frost season to be later in the calendar year (moving from early May, on average, in the historic period to early June, on average, by 2090 under RCP8.5). Note, however, that there is a large degree of variability in the historic start dates of the frost season (ranging from as early as early March to as late as mid-June) as well as the future projected frost season start dates (mid-April to early July under RCP8.5 at 2090).

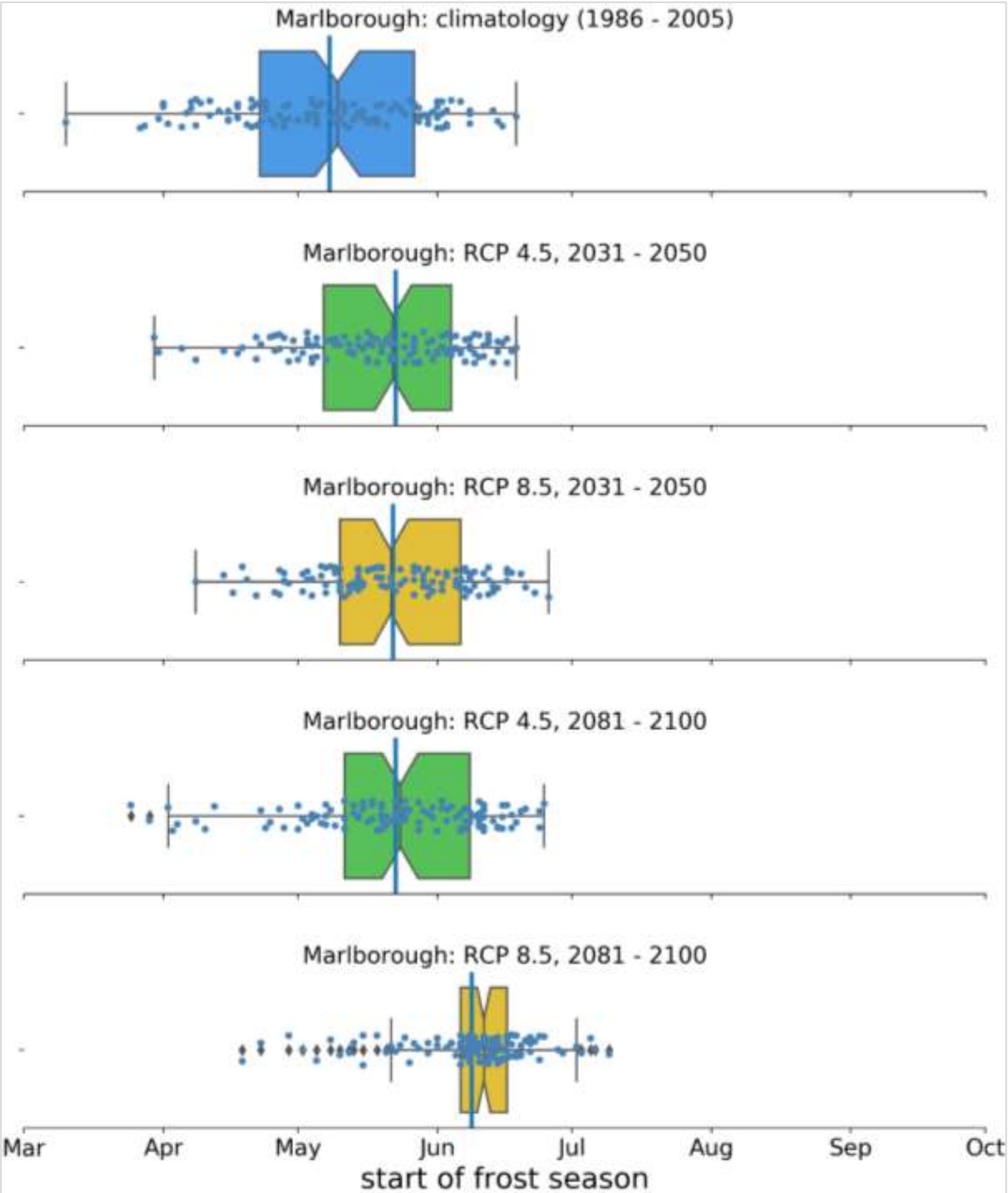


Figure 4-27: Projections for the start date of the frost season at a Marlborough location, for the historic period 1986-2005, RCP4.5 and RCP8.5 at 2040 and 2090. Box plots show the 5th and 95th percentile frost season start dates (end whiskers), the 25th and 75th percentile range (box bounds), and the median (line in middle of the box). The blue dots are the individual model results and the vertical blue line is the average of all results. Location selected: -41.525, 173.775 (WGS84).

Figure 4-28 shows the distribution of model results for the end date of the frost season for 2040 (2031-2050) and 2090 (2081-2100), under RCP4.5 and RCP8.5. The end date of the frost season is projected to move earlier in the calendar year (from early October, on average, in the historic period, to early September, on average, by 2090 under RCP8.5). There is high variability around the average for the end dates, ranging from as early as mid-August to as late as early December for the historic period, and mid-August to late October for RCP8.5 at 2090.

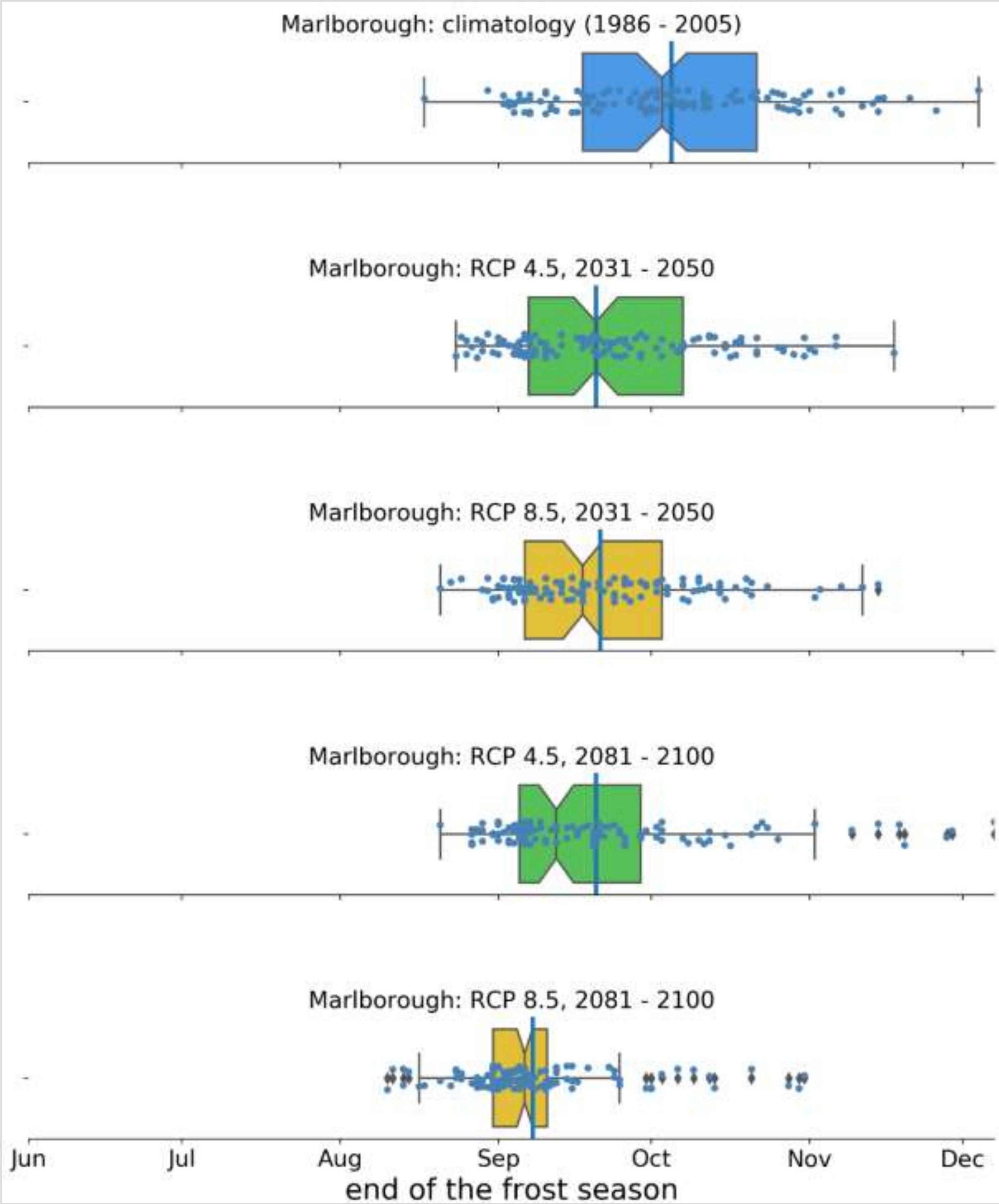


Figure 4-28: Projections for the end date of the frost season at a Marlborough location, for the historic period 1986-2005, RCP4.5 and RCP8.5 at 2040 and 2090. Box plots show the 5th and 95th percentile frost season end dates (end whiskers), the 25th and 75th percentile range (box bounds), the median (line in middle of the box). The blue dots are the individual model results and the vertical blue line is the average of all results. Location selected: -41.525, 173.775 (WGS84).

4.6 Hot days

Projected hot day changes

Annual:

Period	RCP4.5	RCP8.5
2040	Up to 15 more	Up to 25 more
2090	Up to 25 more	Up to 65 more

In this report, a hot day is considered to occur when the maximum temperature is 25°C or higher. Historic (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for hot days are shown in this section. The historic maps show annual average number of hot days and the future projection maps show the change in the number of hot days compared with the historic average. Note that the historic maps are on a different colour scale to the future projection maps.

For the historic period, hot days occur most regularly about Blenheim. Here, the annual number of hot days averages 30-40 days per year (Figure 4-29). Other coastal and low elevation areas typically observe 10-30 hot days per year. Hot days are uncommon in Marlborough's high elevation terrain.

Representative concentration pathway (RCP) 4.5

By 2040, increases to hot days are projected throughout Marlborough (Figure 4-30), with highest increases of 5-15 days projected for most coastal and lower elevations of the region.

By 2090, increases of 5-25 hot days are projected for most of the region. Largest increases of 15-25 hot days are projected about Blenheim and Wairau Valley (Figure 4-30).

Representative concentration pathway (RCP) 8.5

By 2040, the projected pattern of change under RCP8.5 is similar to that projected for the same time period under RCP4.5. The main difference is a higher projected increase of 15-25 hot days about Blenheim (Figure 4-30).

By 2090, considerable increases of up to 65 hot days are projected for Marlborough (Figure 4-30). Largest increases of 45-65 days are projected about Blenheim, Wairau Valley and other low elevation locations. This is the equivalent of approximately 6-9 additional weeks of hot days compared to the historic climate.

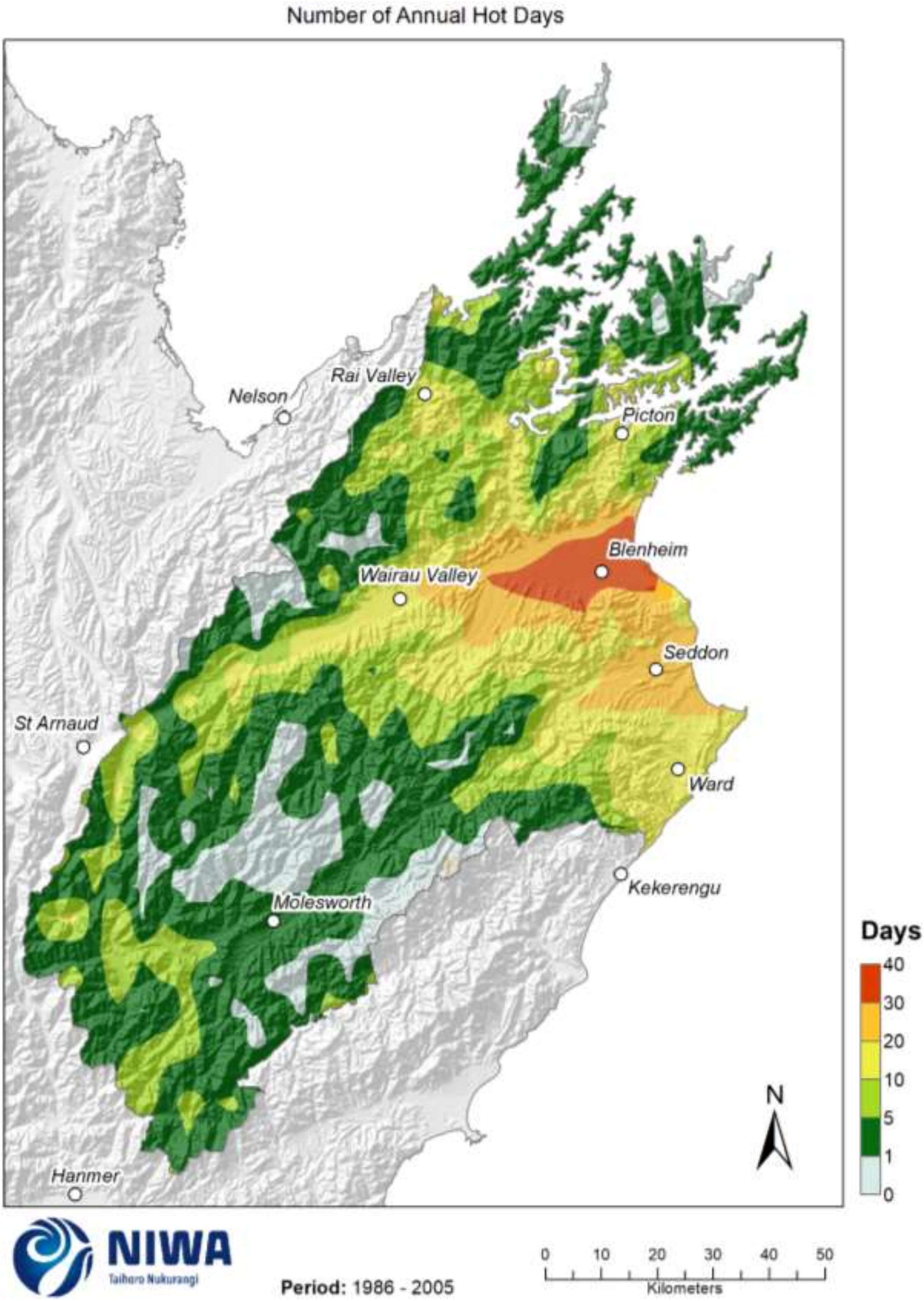


Figure 4-29: Modelled annual number of hot days (days with maximum temperature ≥25°C), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

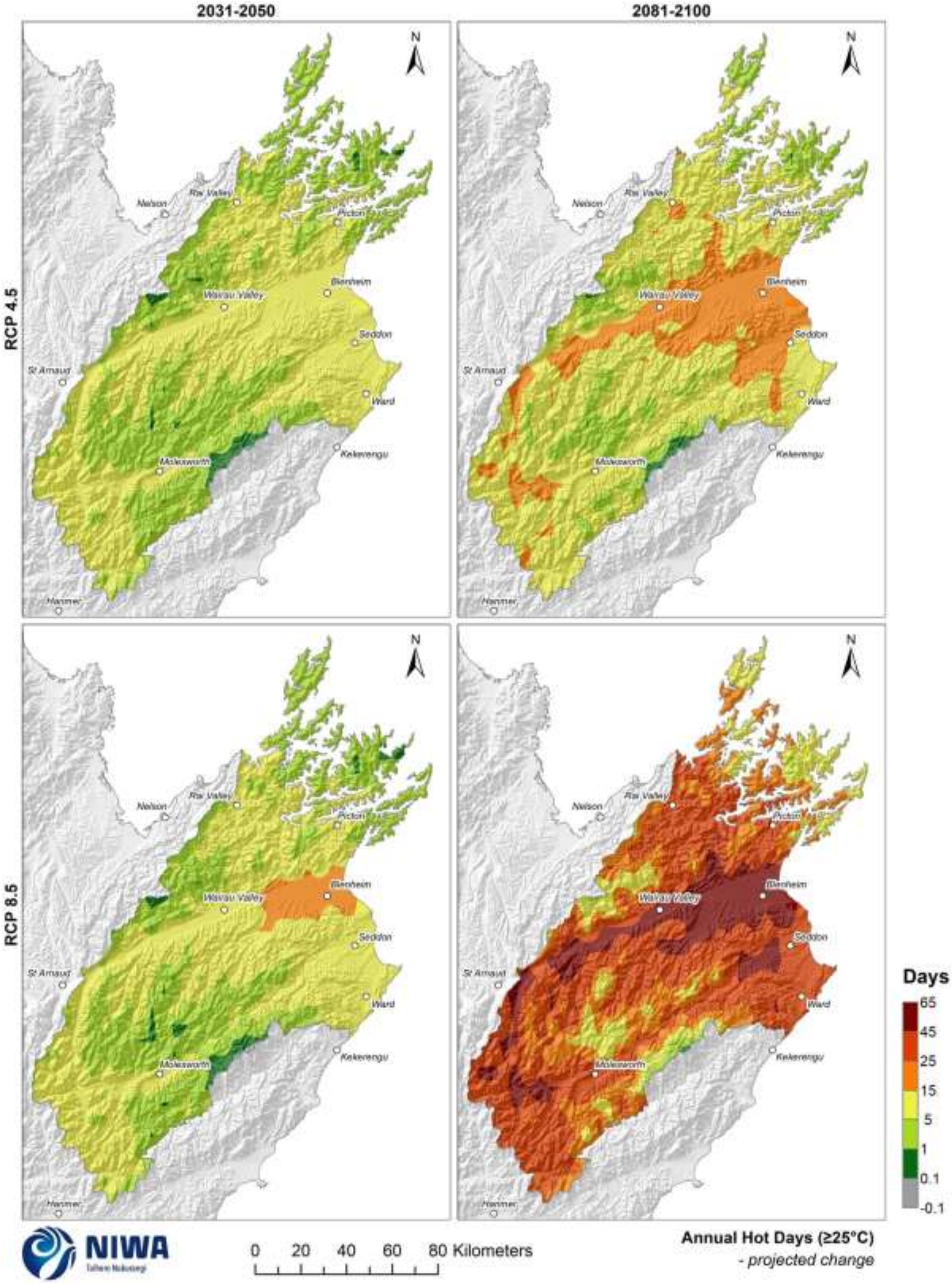


Figure 4-30: Projected annual hot day (days with maximum temperature ≥25°C) changes by 2040 and 2090, under RCP4.5 and RCP8.5. Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

4.7 Growing degree days

Projected growing degree day (base 10°C) changes

Annual:

Period	RCP4.5	RCP8.5
2040	Up to +200	Up to +300
2090	+50-400	+150-800

Growing degree-days (GDD) express the sum of daily temperatures above a selected base temperature (e.g. 10˚C) that represent a threshold for plant growth. The average amount of growing degree-days in a location may influence the choice of crops to grow, as different species have different temperature thresholds for survival. The daily GDD total is the amount the daily average temperature exceeds the threshold value (e.g. 10°C) per day. For example, a daily average temperature of 18°C would have a GDD base 10°C value of 8. The daily GDD values are accumulated over the period 1 July to 30 June to calculate an annual GDD value.

Historic (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for GDD are shown in this section. The historic maps show annual average GDD and the future projection maps show the change in GDD compared with the historic average. Note that the historic maps are on a different colour scale to the future projection maps.

The number of historic growing degree-days follows the same spatial pattern as mean temperature, with the highest number along the coastal and low elevation areas (1200-1400 GDD), and the lowest number of 100-400 GDD in Marlborough's higher elevation terrain (Figure 4-31). In the historic period, Blenheim experienced about 1200-1400 GDD per year with base 10°C.

Representative concentration pathway (RCP) 4.5

By 2040, increases to GDD are projected throughout Marlborough (Figure 4-32), with highest increases of 150-200 GDD projected for most coastal and lower elevations of the region.

By 2090, increases of 200-300 GDD are projected for most of the region. Largest increases of 300-400 GDD are projected about Blenheim (Figure 4-32).

Representative concentration pathway (RCP) 8.5

By 2040, the projected pattern of change under RCP8.5 is similar to that projected for the same time period under RCP4.5. The main difference is a higher projected increase of 200-300 GDD about Blenheim (Figure 4-32).

By 2090, considerable increases of 150-800 GDD are projected for Marlborough (Figure 4-32). The largest increases of 600-800 GDD are projected about Blenheim and Wairau Valley. The increase in GDD will likely influence the types of crops that can be grown at a location, and harvesting times for crops into the future – one would expect to see crops only suitable for warmer northern climates at present move further south as the climate warms, and harvesting times for crops presently grown in Marlborough may shift to an earlier time in the season.

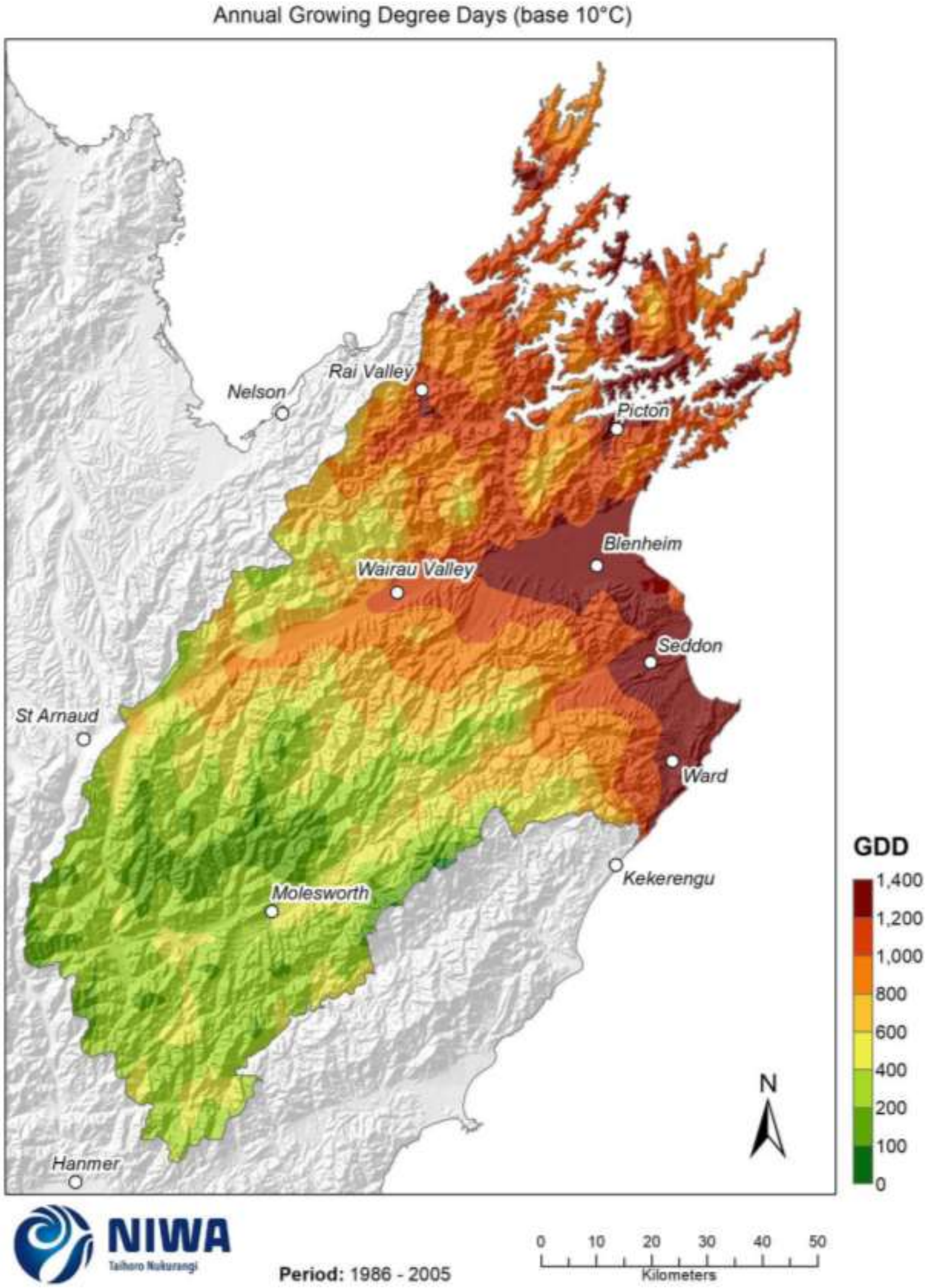


Figure 4-31: Median annual Growing Degree-Days (GDD) base 10°C. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

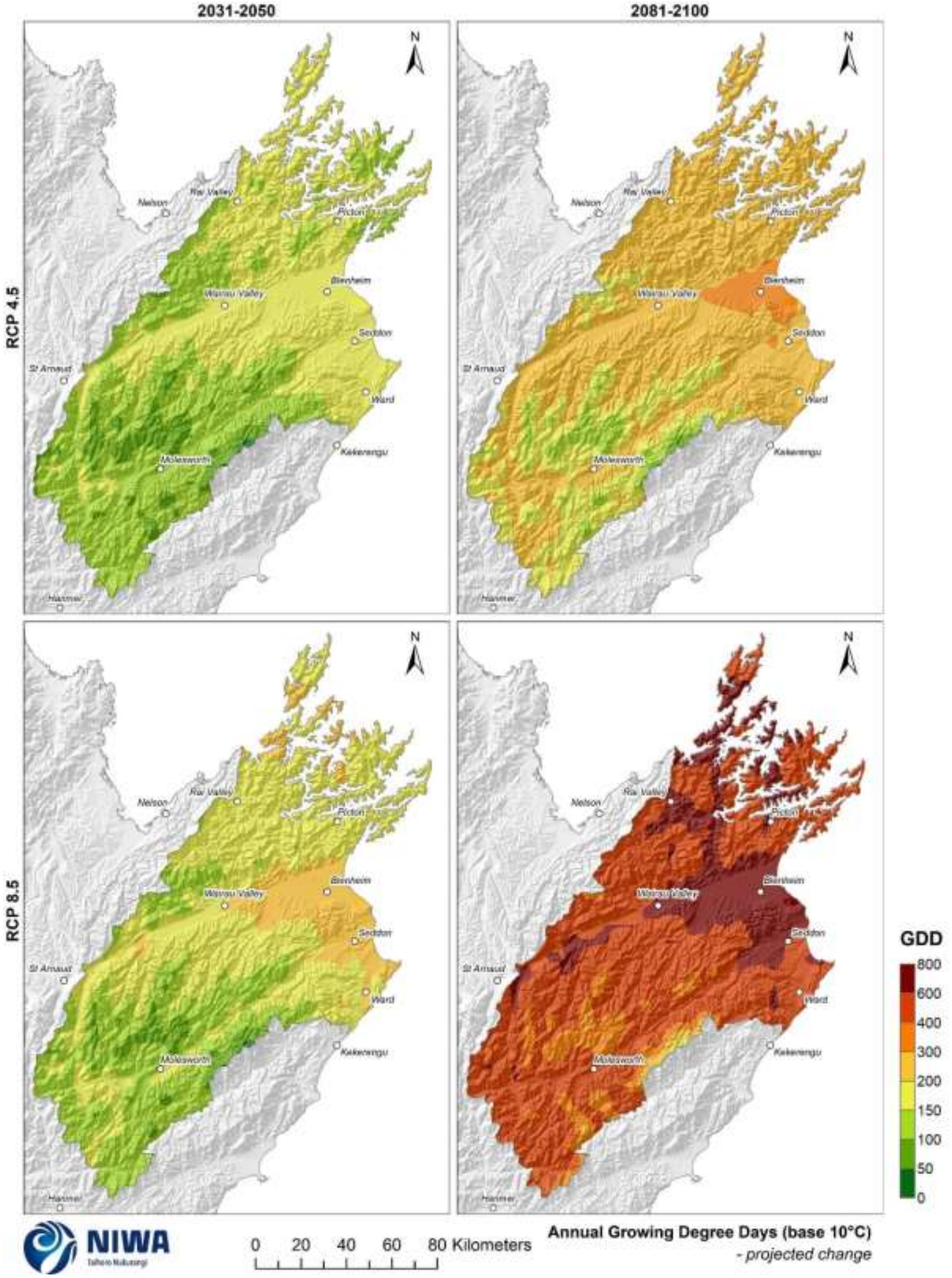


Figure 4-32: Projected increase in number of growing degree days per year (base 10°C) at 2040 (2031-2050) and 2090 (2081-2100) for RCP4.5 (left panels) and RCP8.5 (right panels). Projected change is relative to 1986-2005. Results are based on dynamically downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

5 Rainfall

5.1 Rainfall totals

Projected rainfall total changes (%)

Annual:

Period	RCP4.5	RCP8.5
2040	-5% to +15%	-5% to +10%
2090	-10% to +15%	-10% to +30%

Seasonal:

	RCP4.5		RCP8.5	
	2040	2090	2040	2090
Summer	-10% to +15%	-10% to +20%	± 10%	-20% to +30%
Autumn	-5% to +10%	± 10%	-5% to +10%	-10% to +30%
Winter	-5% to +20%	-20% to +30%	-10% to +20%	-20% to +40%
Spring	-5% to +10%	± 10%	-10% to +5%	± 10%

This section contains maps showing historic total rainfall and the future projected change in total rainfall. Historic 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 historic total. Note that the historic maps are on a different colour scale to the future projection maps.

For the modelled historic period, the highest annual rainfall totals are recorded in the high elevations and about the Marlborough Sounds (1500-2000 mm/year) (Figure 5-1). In the Richmond Range north of Wairau Valley, annual rainfall totals of 2000-3000 mm are recorded. The lowest annual rainfall totals are recorded in low elevation areas about Blenheim, Seddon and Ward, and heading southwest along the Awatere Valley towards Molesworth (500-750 mm). Rainfall is mostly evenly distributed throughout the year, where summer is typically the driest season (Figure 5-2).

Representative concentration pathway (RCP) 4.5

By 2040, projected change to annual rainfall ranges from -5% to +15% throughout the region (Figure 5-3). Greater changes are projected seasonally, with decreases of up to 10% projected for southwestern parts in summer, and increases of up to 20% projected for parts of Marlborough in winter (Figure 5-4). Smaller changes of -5% to +10% are projected in autumn and spring throughout the region.

By 2090, projected annual change is not dissimilar to that projected for the 2040 period, with most locations projected to experience small changes to rainfall of ±5% (Figure 5-3). Again, there are more noticeable changes projected at the seasonal scale (Figure 5-5). Changes of ±10% are projected for autumn and spring, whilst decreases of up to 20% are projected in winter. Increases in winter rainfall of 5-15% are projected for most of the northern half of Marlborough.

Representative concentration pathway (RCP) 8.5

By 2040, the projected pattern of change to annual rainfall is similar to that projected for RCP4.5, with changes ranging from -5% to +10% (Figure 5-3). Seasonal projected changes are also similar to RCP4.5, with the exception of winter and spring where a decrease of up to 10% is projected for parts of Marlborough.

By 2090, a stronger pattern of change is evident, especially seasonally. At the annual timeframe, projected rainfall changes range from a decrease of 10% to an increase of 30% (Figure 5-3). Seasonal changes project a summer reduction and winter increase for most of Marlborough. For much of the region, summer reductions of 5-20% are projected, with winter increases of 10-40% projected (Figure 5-7). Spring sees a projected decrease in rainfall of up to 10% for many parts.

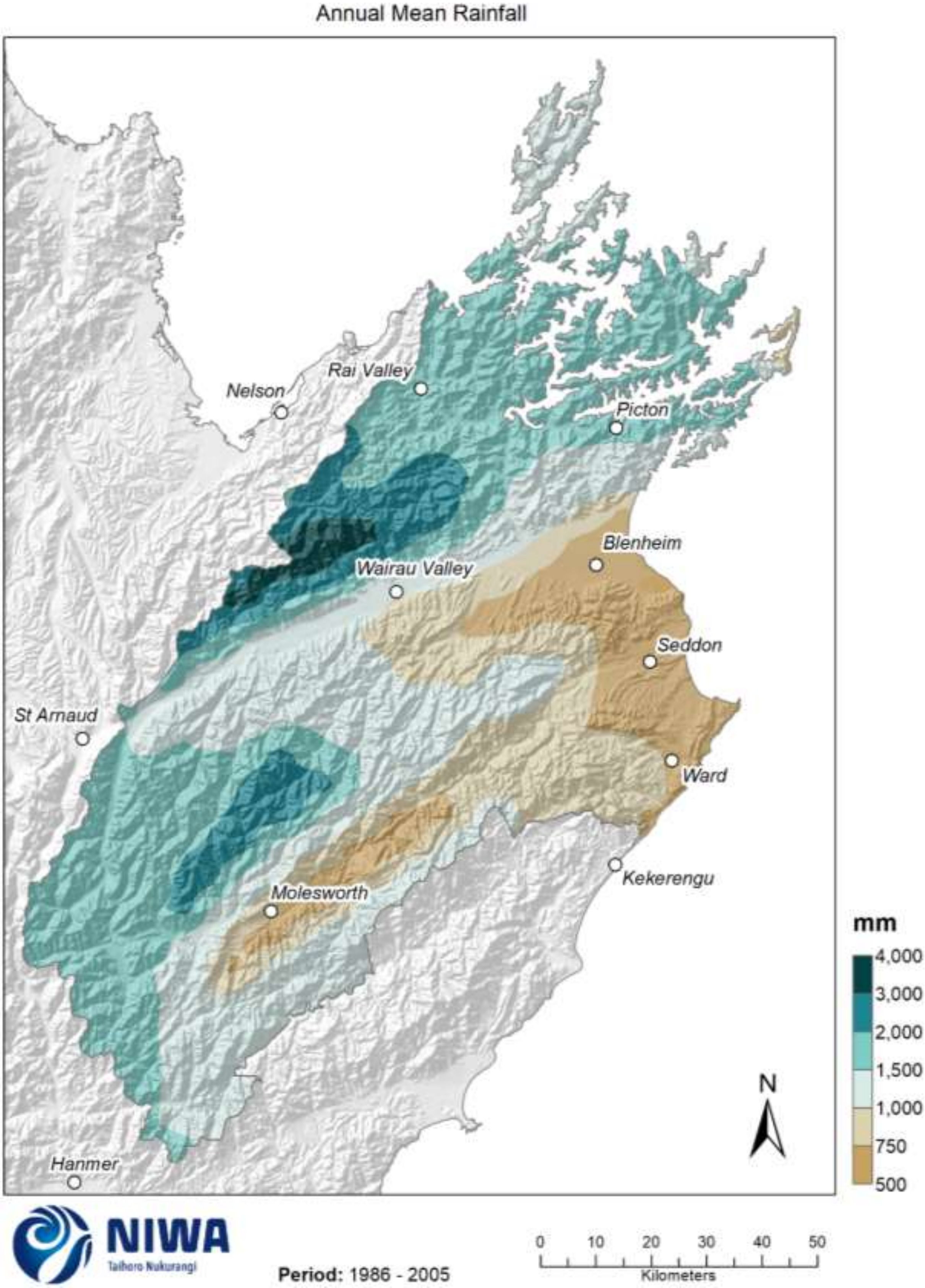


Figure 5-1: Modelled annual rainfall (mm), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

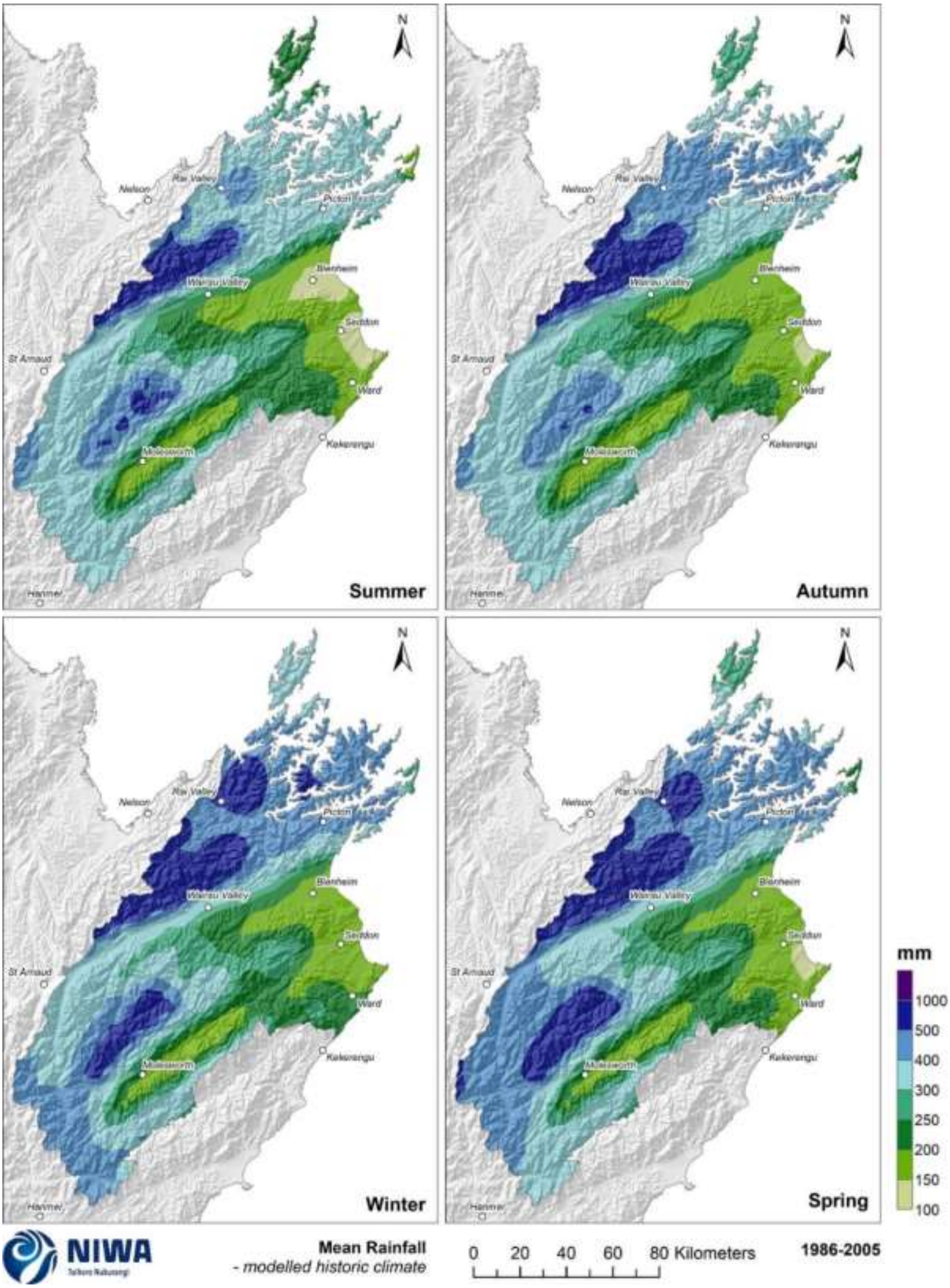


Figure 5-2: Modelled seasonal rainfall (mm), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

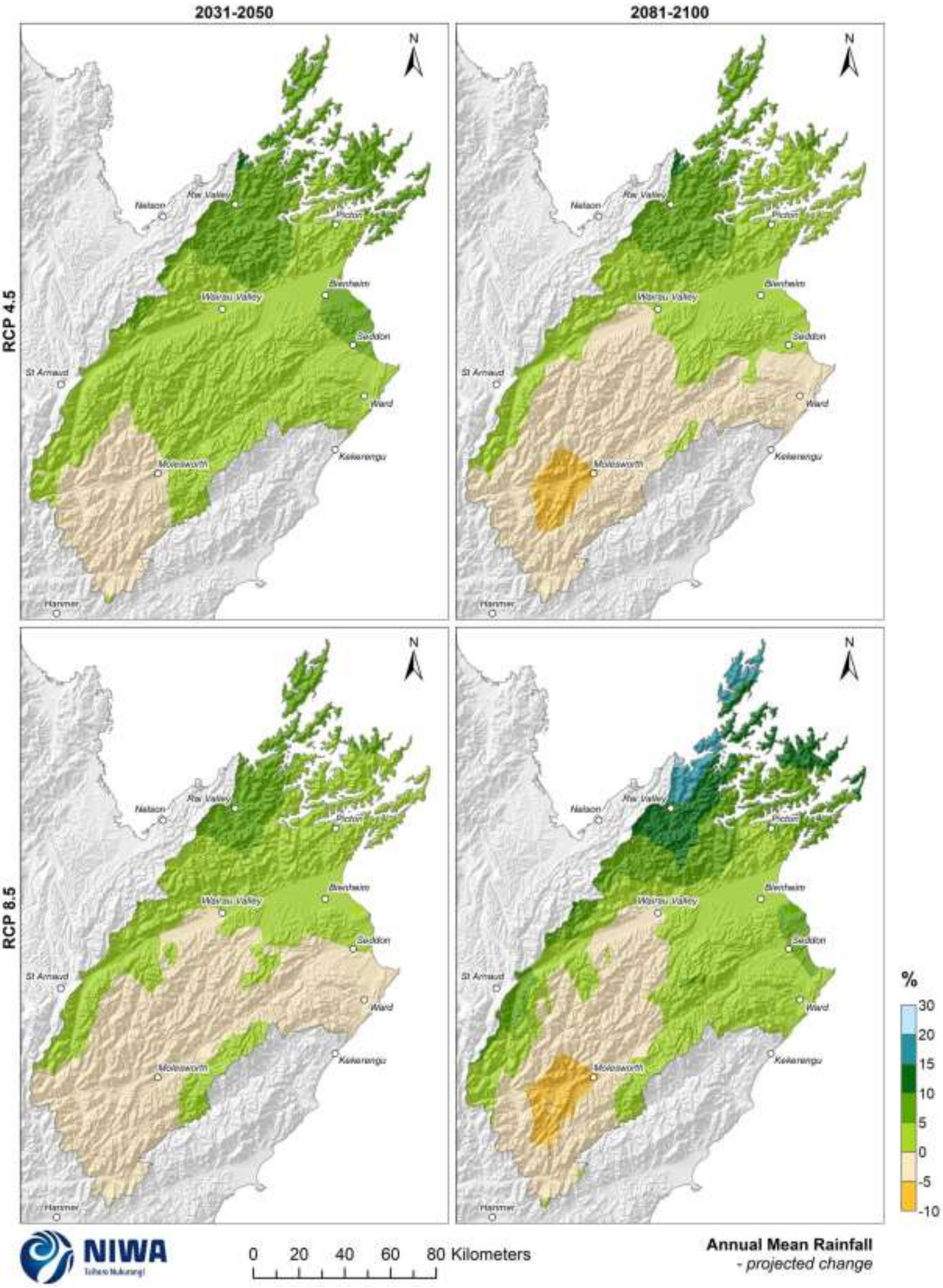


Figure 5-3: Projected annual rainfall changes (%). Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

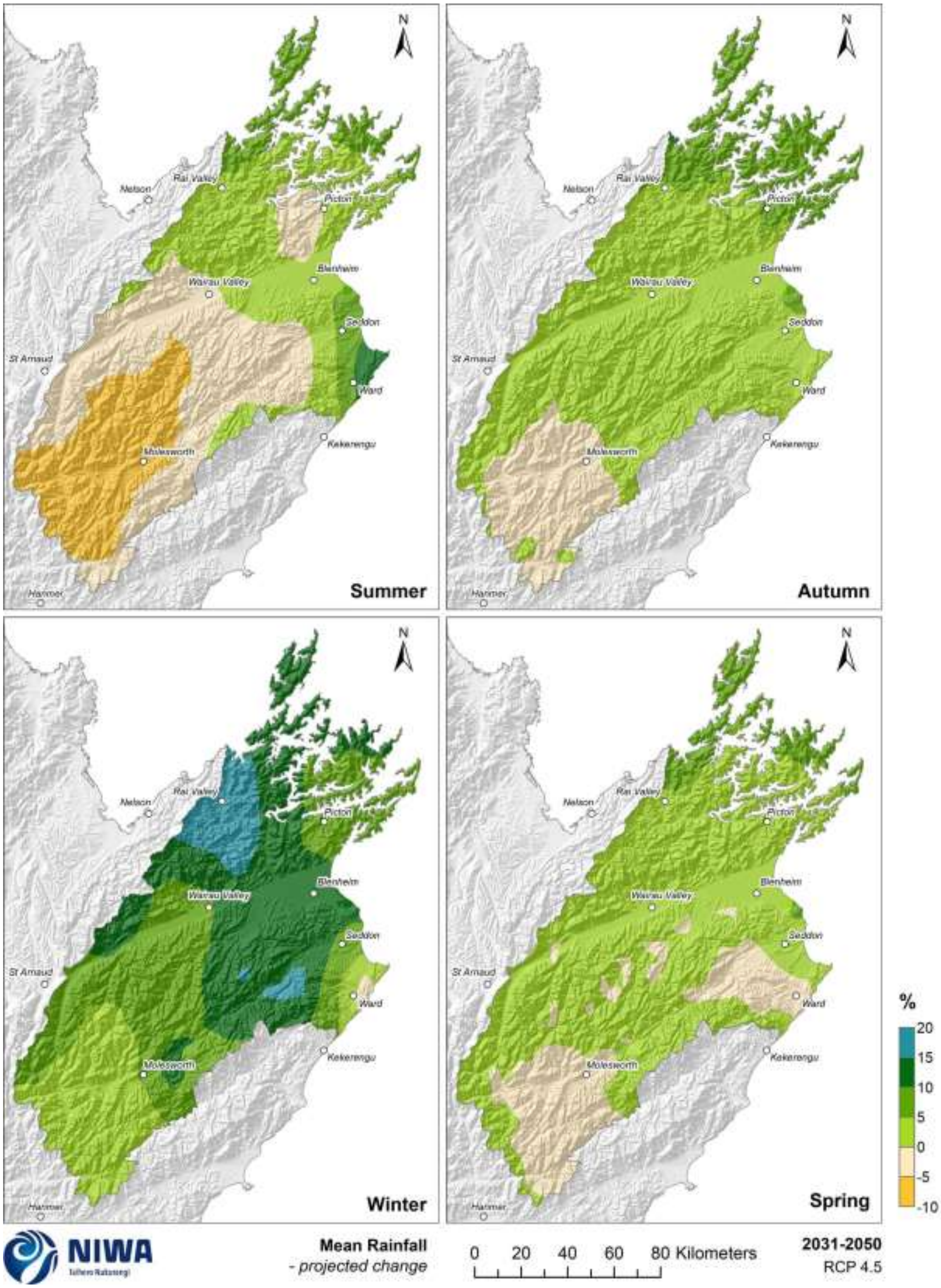


Figure 5-4: Projected seasonal rainfall changes (%) by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

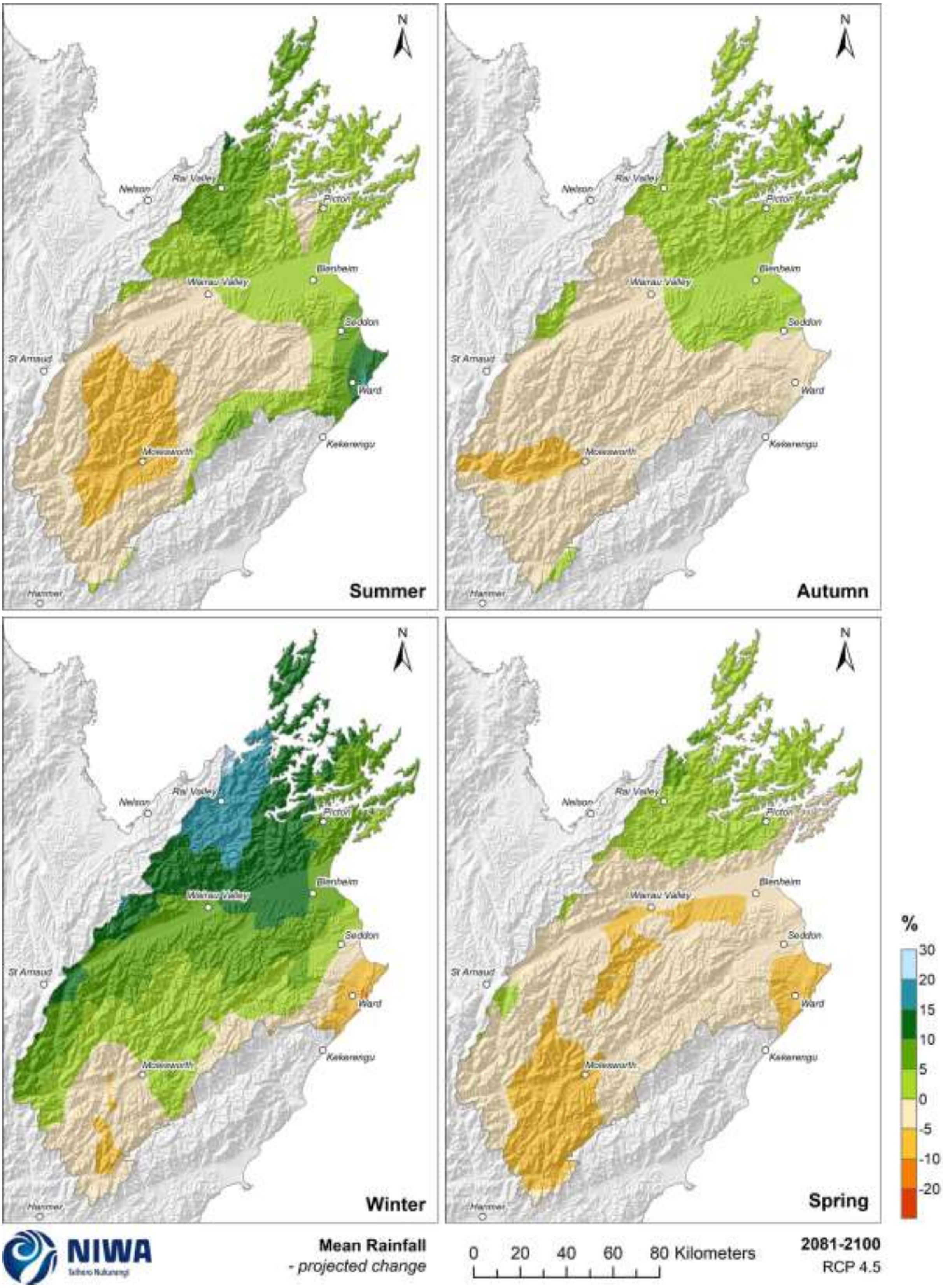


Figure 5-5: Projected seasonal rainfall changes (%) by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

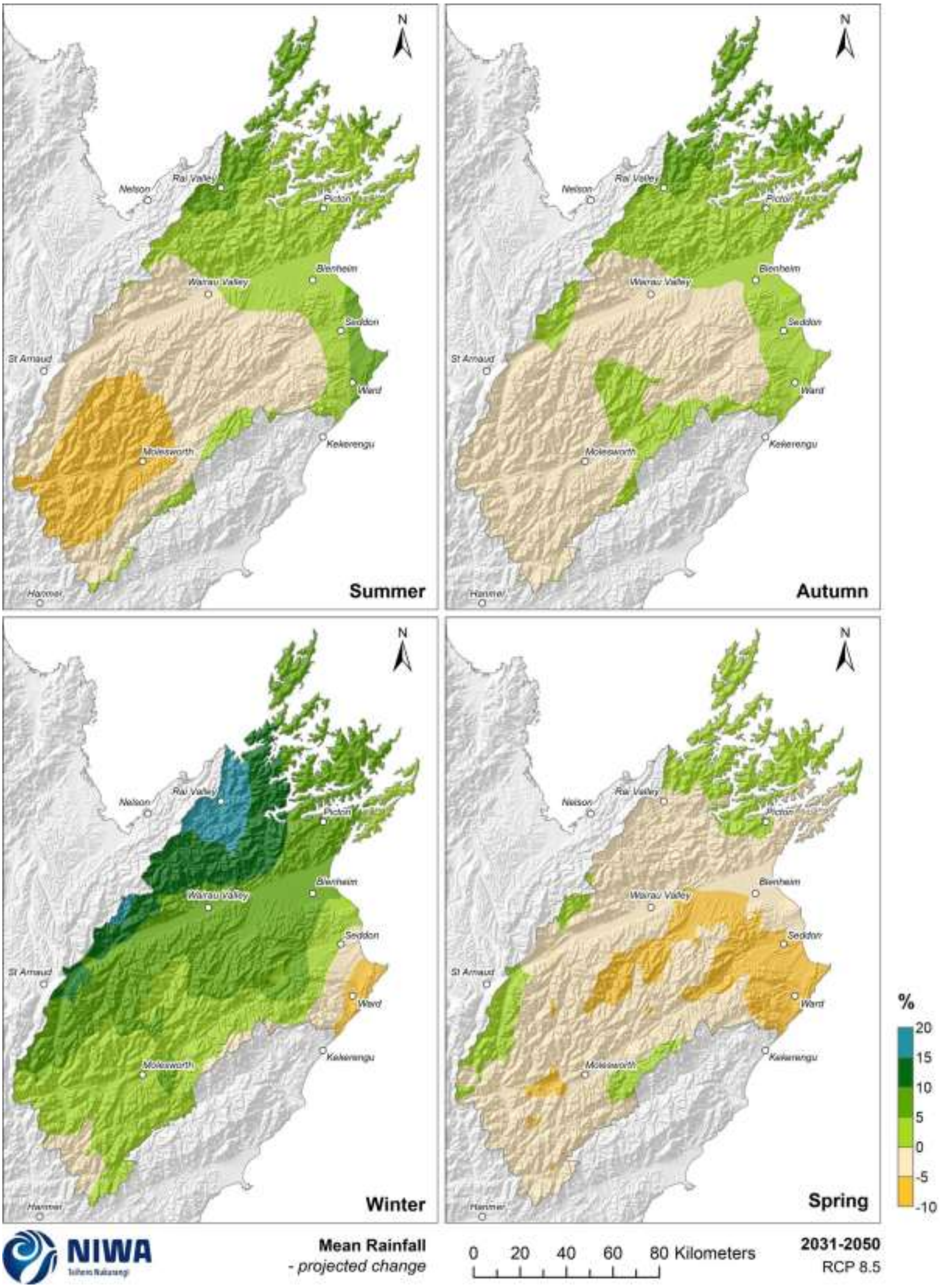


Figure 5-6: Projected seasonal rainfall changes (%) by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

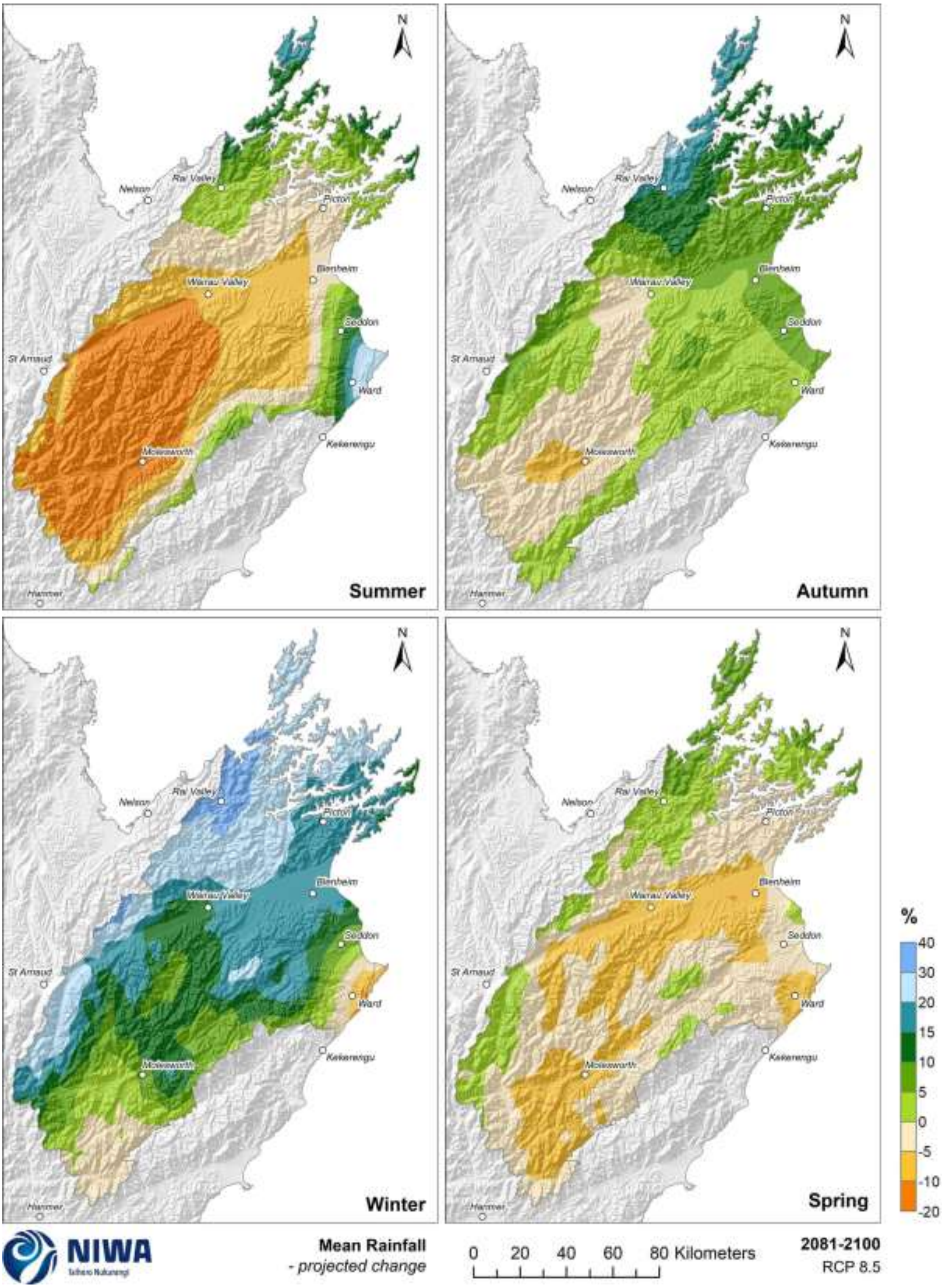


Figure 5-7: Projected seasonal rainfall changes (%) by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

5.2 Dry days

Projected dry day changes (days)

Annual:

Period	RCP4.5	RCP8.5
2040	-5 to +10	-1 to +15
2090	-1 to +15	-5 to +30

Seasonal:

	RCP4.5		RCP8.5	
	2040	2090	2040	2090
Summer	-1 to +5	± 5	-1 to +5	-5 to +10
Autumn	-1 to +5	-1 to +5	-1 to +5	-5 to +10
Winter	-± 5	± 5	± 5	-5 to +10
Spring	-1 to +5	-1 to +5	-1 to +5	-1 to +10

A dry day considered here is when less than 1 mm of rainfall is recorded over a 24-hour period. Historic (average over 1986-2005) and future (average over 2031-2050 and 2081-2100) maps for dry days are shown in this section. The historic 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 the historic period. Note that the historic maps are on a different colour scale to the future projection maps.

Historically, the largest annual number of dry days is experienced in eastern parts of Marlborough about Blenheim, Seddon and Ward (250-300 days per year; Figure 5-8). Many remaining areas of Marlborough average around 200-250 dry days per year. Southwestern areas of the region experience the fewest annual dry days for the region, averaging 150-200 dry days per year. The seasonal distribution of dry days in Marlborough is relatively even, although there tends to be fewer dry days in winter and spring compared to summer and autumn (Figure 5-9).

Representative concentration pathway (RCP) 4.5

By 2040, northeastern parts of Marlborough see relatively little change in dry days, with projections of ±1 day per year (Figure 5-10). For central and southern parts of the region, increases of 1-10 days per year are projected. Seasonal changes of ±5 days are projected in winter, with projected changes ranging from -1 to +5 days for remaining seasons.

By 2090, annual increases of 5-15 dry days are projected for the southwestern half of the region (Figure 5-10), with minimal change projected about Blenheim and Seddon (±1 day). Seasonal patterns of change are much the same as those projected by 2040, although an increase of 1-5 days in spring is projected for most of the region (Figure 5-12).

Representative concentration pathway (RCP) 8.5

By 2040, the projected pattern of annual change under RCP8.5 is similar to that projected for the same time period under RCP4.5 (Figure 5-10). This is also the case seasonally, with the main difference being a projected increase of 1-5 dry days in spring for a larger proportion of the region (Figure 5-13).

By 2090, increases of 10-30 dry days per year are projected for the southwestern half of Marlborough (Figure 5-10). Projected patterns of seasonal change are varied, but within the range of 5 fewer to 10 more dry days.

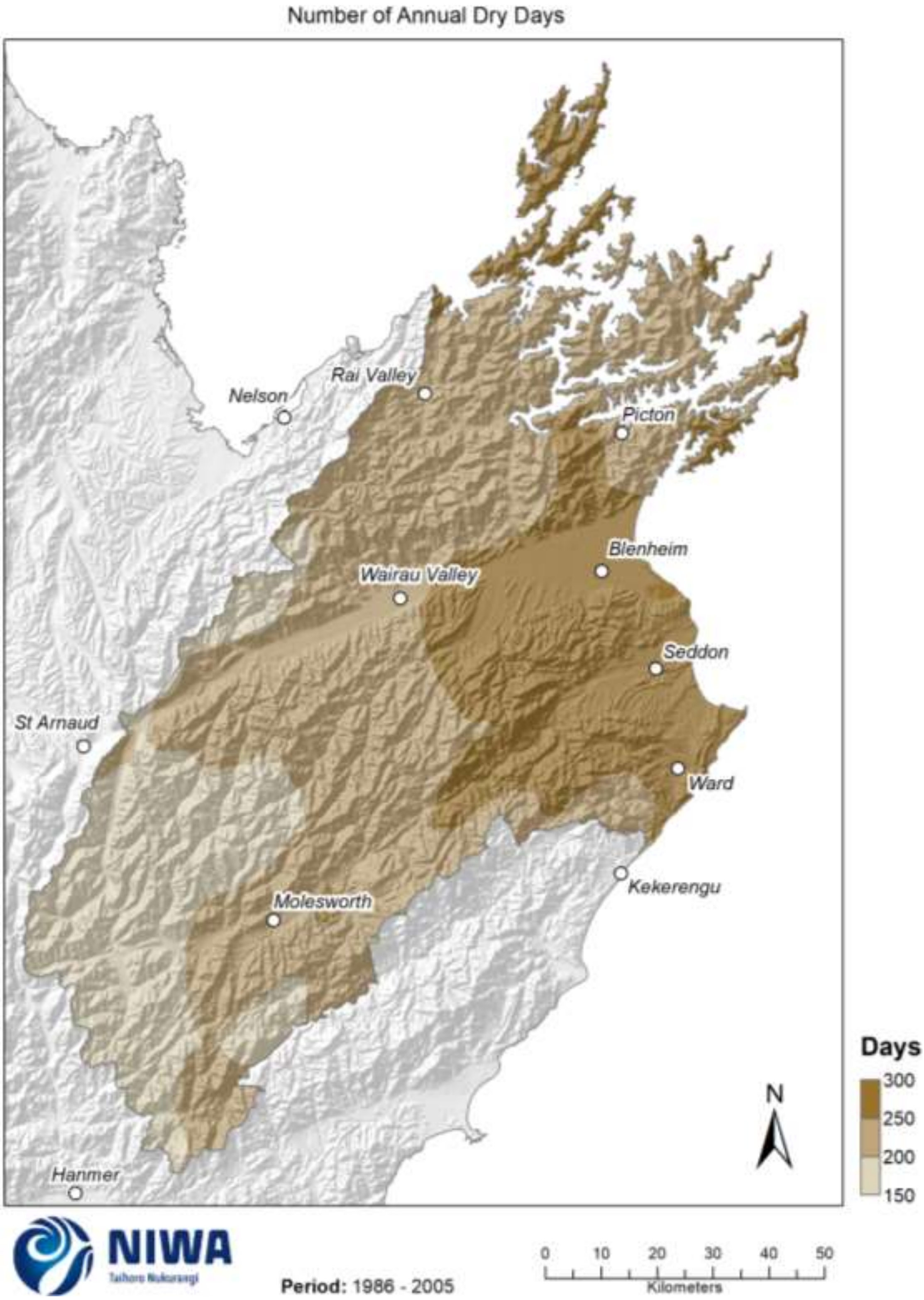


Figure 5-8: Modelled annual number of dry days (daily rainfall <1mm), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

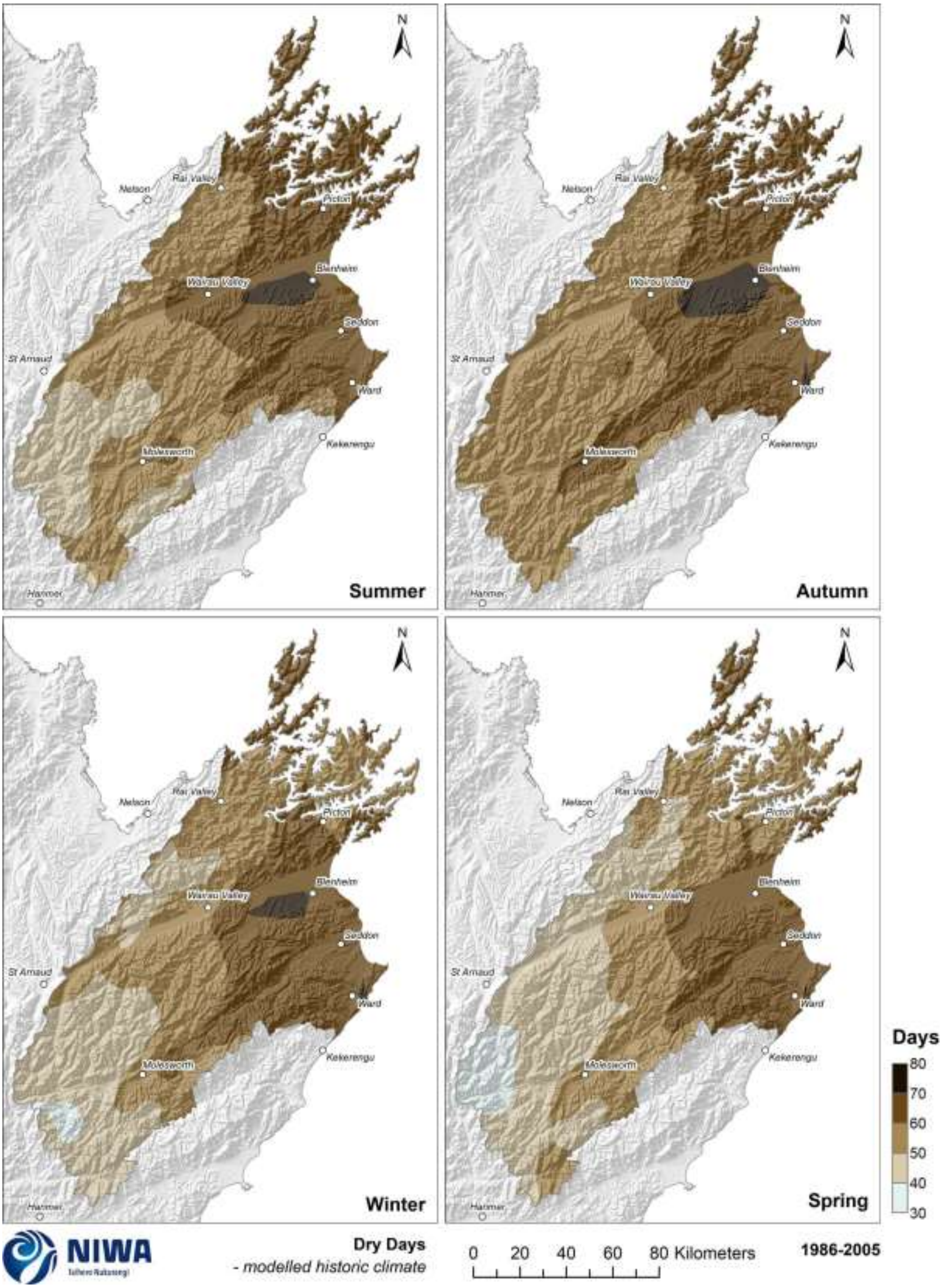


Figure 5-9: Modelled seasonal number of dry days (daily rainfall <1mm), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

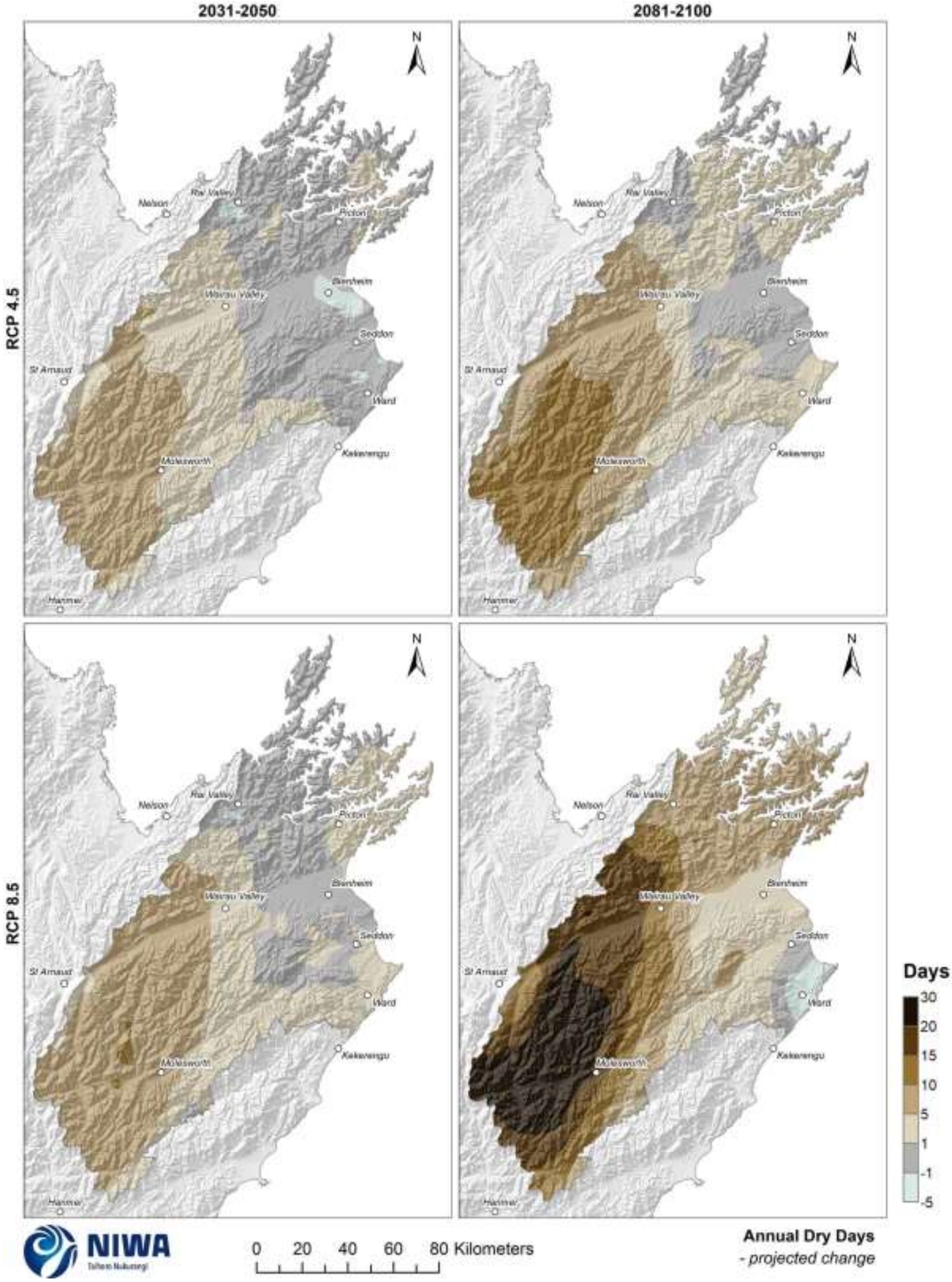


Figure 5-10: Projected annual number of dry day (daily rainfall <1mm) changes by 2040 and 2090, under RCP4.5 and RCP8.5. Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

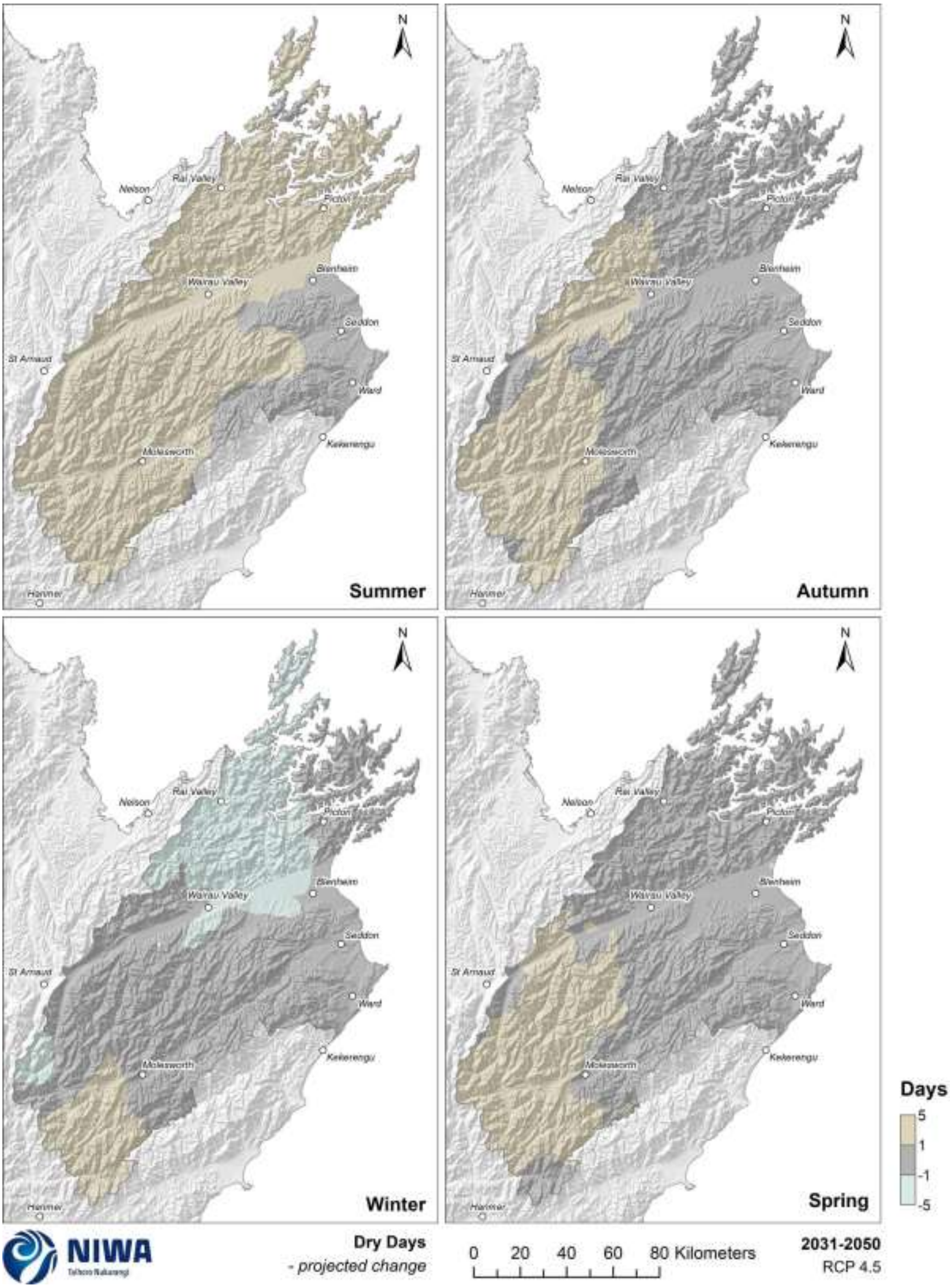


Figure 5-11: Projected seasonal number of dry day (daily rainfall <1mm) changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

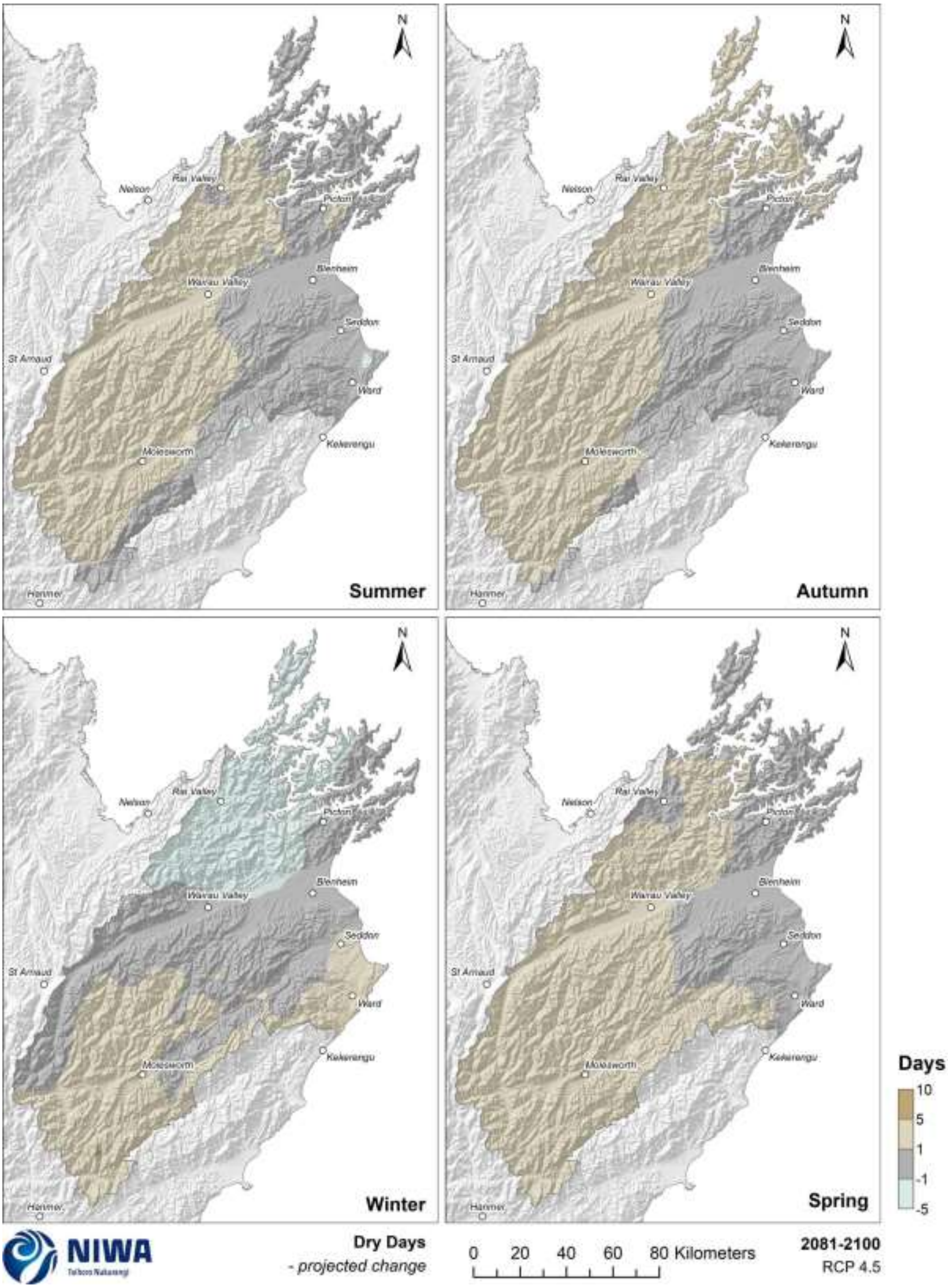


Figure 5-12: Projected seasonal number of dry day (daily rainfall <1mm) changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

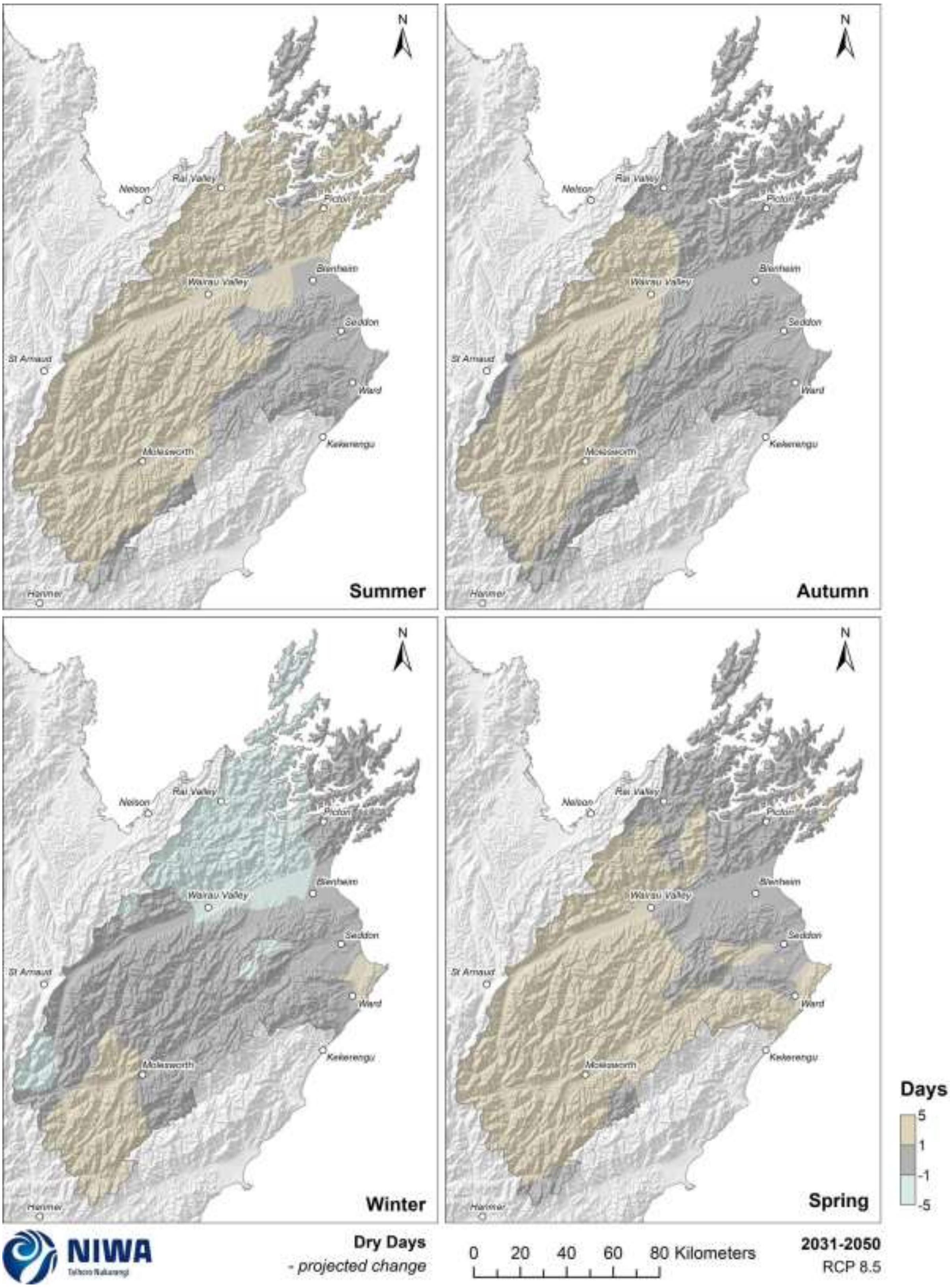


Figure 5-13: Projected seasonal number of dry day (daily rainfall <1mm) changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

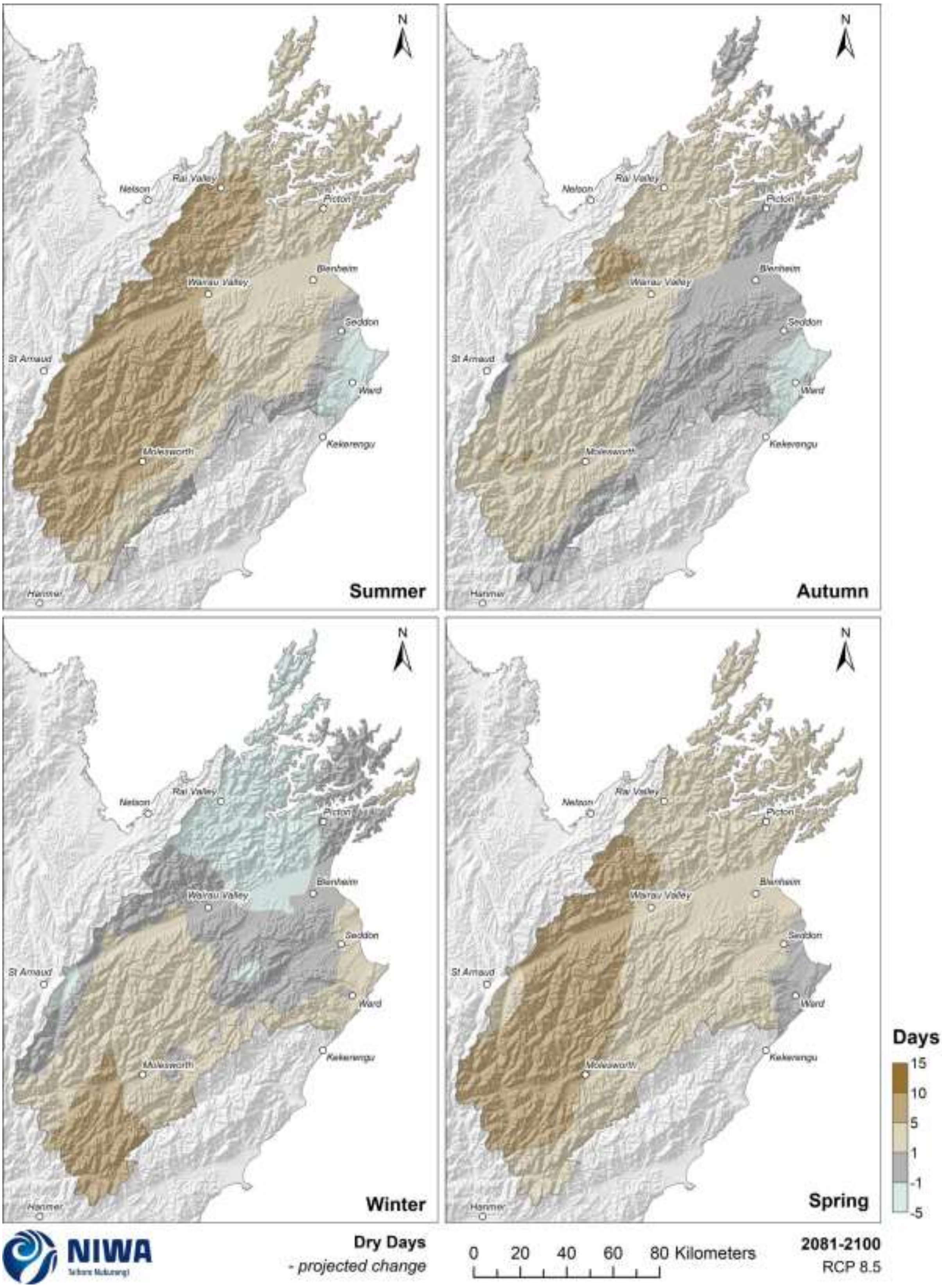


Figure 5-14: Projected seasonal number of dry day (daily rainfall <1mm) changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

5.3 Extreme, rare rainfall events

Projected extreme, rare rainfall event changes in Marlborough (average of the 4 selected sites)

50-year return period rainfalls:

	RCP4.5		RCP8.5	
Rainfall duration	2040	2090	2040	2090
1-hour	+10%	+16%	+12%	+35%
6-hours	+8%	+14%	+9%	+29%
12-hours	+7%	+12%	+8%	+25%
24-hours	+6%	+10%	+7%	+22%
48-hours	+6%	+9%	+6%	+19%

Extreme rainfall events are often considered in the context of return periods (e.g. 1-in-100-year rainfall events). A return period, is an estimate of the likelihood of an event. It is a statistical measure typically based on historical 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 (also known as the Average Recurrence Interval, ARI). For example, a 1-in-10-year rainfall event has a 1/10 = 0.1 ARI or 10% chance of being exceeded in any one year, and a 1-in-100-year rainfall event has a 1/100 = 0.01 ARI 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. With a changing climate, the return periods used below should be thought of only within the 20-year period in which they are defined. For instance, if extreme heavy rainfall events are becoming a lot more frequent under climate change then the 1-in-100-year rainfall event for 2040 as defined as the 2031-2050 period will be less than the 1-in-100-year rainfall event when defined under 2001-2080, because the latter is dominated by the more frequent heavy events during the 2070s. 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).

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 (5 days). 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. The future rainfall increases calculated by the HIRDS v4 tool are based on a percent change per degree of warming, which is averaged across New Zealand. The short duration, rare events have the largest relative increases of around 14% per degree of warming, while the longest duration events increase by about 5 to 6%. HIRDS v4 can be accessed at https://hirds.niwa.co.nz/, and more background information to the HIRDS methodology can be found at https://niwa.co.nz/information-services/hirds/help.

HIRDS rainfall projections for selected sites in the Marlborough region are presented in this section. For each site there are two tables; the first table presents data for 1-in-50-year rainfall events, and the second table presents data for 1-in-100-year rainfall events, with each of these tables listing the modelled historical and projected rainfall depths for one to 48-hour rain events. The results for Blenheim, Molesworth, Picton and Rai Valley are presented in Table 5-1 to Table 5-8.

For each of the selected locations, rainfall depths are projected to increase across all the future scenarios, and both return periods. For example, Table 5-1 shows that the projected rainfall depth for a 12-hour rainfall event at Blenheim (50-year ARI) is projected to increase under RCP4.5 from 90.1 mm (historical depth) to 96.7 mm by 2040, and 101 mm by 2090. Under RCP8.5 and for the same rainfall event duration, the projected amounts are 97.6 mm by 2040, and 113 mm by 2090, which indicate a 11 mm and 23 mm rise respectively compared with historical depth.

Table 5-1: Modelled historical and projected rainfall depths (mm) for Blenheim for different event durations with a 50-year return period (0.02 ARI) Source: HIRDS v4. Location selected: -41.514, 173.957 (WGS84).

Rainfall event duration	Historical depth (mm)	Projected depth (mm)			
		Mid-century average (2031-2050)		Late-century average (2081-2100)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
1-hour	27.4	30.2	30.6	31.9	37.0
6-hour	66.9	72.5	73.3	76.0	86.4
12-hour	90.1	96.7	97.6	101	113
24-hour	116	123	124	128	141
48-hour	140	148	149	153	167

Table 5-2: Modelled historical and projected rainfall depths (mm) for Blenheim for different event durations with a 100-year return period (0.01 ARI) Source: HIRDS v4. Location selected: -41.514, 173.957 (WGS84).

Rainfall event duration	Historical depth (mm)	Projected depth (mm)			
		Mid-century average (2031-2050)		Late-century average (2081-2100)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
1-hour	31.4	34.5	35.0	36.5	42.4
6-hour	75.9	82.4	83.4	86.5	98.5
12-hour	102	110	111	114	129
24-hour	131	139	140	144	160
48-hour	158	167	168	172	189

Table 5-3: Modelled historical and projected rainfall depths (mm) for Molesworth for different event durations with a 50-year return period (0.02 ARI) Source: HIRDS v4. Location selected: -42.080, 173.260 (WGS84).

Rainfall event duration	Historical depth (mm)	Projected depth (mm)			
		Mid-century average (2031-2050)		Late-century average (2081-2100)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
1-hour	25.5	28.0	28.4	29.7	34.4
6-hour	60.2	65.3	66.0	68.5	77.8
12-hour	80.7	86.6	87.5	90.3	101
24-hour	104	110	111	114	126
48-hour	126	133	134	137	150

Table 5-4: Modelled historical and projected rainfall depths (mm) for Molesworth for different event durations with a 100-year return period (0.01 ARI) Source: HIRDS v4. Location selected: -42.080, 173.260 (WGS84).

Rainfall event duration	Historical depth (mm)	Projected depth (mm)			
		Mid-century average (2031-2050)		Late-century average (2081-2100)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
1-hour	29.0	31.9	32.4	33.8	39.2
6-hour	68.2	74.0	74.9	77.7	88.5
12-hour	91.2	98.0	99.0	102	115
24-hour	117	124	125	129	143
48-hour	142	150	151	155	169

Table 5-5: Modelled historical and projected rainfall depths (mm) for Picton for different event durations with a 50-year return period (0.02 ARI) Source: HIRDS v4. Location selected: -41.291, 174.007 (WGS84).

Rainfall event duration	Historical depth (mm)	Projected depth (mm)			
		Mid-century average (2031-2050)		Late-century average (2081-2100)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
1-hour	40.1	44.2	44.8	46.7	54.1
6-hour	117	126	128	133	151
12-hour	168	180	182	188	210
24-hour	230	244	246	253	280
48-hour	297	313	316	324	354

Table 5-6: Modelled historical and projected rainfall depths (mm) for Picton for different event durations with a 100-year return period (0.01 ARI) Source: HIRDS v4. Location selected: -41.291, 174.007 (WGS84).

Rainfall event duration	Historical depth (mm)	Projected depth (mm)			
		Mid-century average (2031-2050)		Late-century average (2081-2100)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
1-hour	45.5	50.1	50.7	53.0	61.4
6-hour	132	143	144	150	171
12-hour	189	203	205	212	238
24-hour	259	275	278	286	316
48-hour	334	352	355	364	399

Table 5-7: Modelled historical and projected rainfall depths (mm) for Rai Valley for different event durations with a 50-year return period (0.02 ARI) Source: HIRDS v4. Location selected: -41.230, 173.580 (WGS84).

Rainfall event duration	Historical depth (mm)	Projected depth (mm)			
		Mid-century average (2031-2050)		Late-century average (2081-2100)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
1-hour	52.5	57.7	58.5	61.1	70.8
6-hour	151	163	165	171	194
12-hour	212	228	230	237	266
24-hour	282	300	302	311	343
48-hour	350	369	372	382	417

Table 5-8: Modelled historical and projected rainfall depths (mm) for Rai Valley for different event durations with a 100-year return period (0.01 ARI) Source: HIRDS v4. Location selected: -41.230, 173.580 (WGS84).

Rainfall event duration	Historical depth (mm)	Projected depth (mm)			
		Mid-century average (2031-2050)		Late-century average (2081-2100)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
1-hour	59.2	65.1	66.0	68.9	79.9
6-hour	170	184	186	193	220
12-hour	239	257	259	268	301
24-hour	318	338	341	351	388
48-hour	394	416	420	430	471

6 Drought

6.1 Potential evapotranspiration deficit

Projected potential evapotranspiration deficit accumulation changes (mm)

Annual:

Period	RCP4.5	RCP8.5
2040	+50-150	+50-150
2090	+50-200	+75-250

One measure of meteorological drought[2] that is used in this section is 'potential evapotranspiration deficit' (PED). Evapotranspiration is the process where water held in the soil is gradually released to the atmosphere through a combination of direct evaporation and transpiration from plants. As the growing season advances, the amount of water lost from the soil through evapotranspiration typically exceeds rainfall, giving rise to an increase in soil moisture deficit. As soil moisture decreases, pasture production becomes moisture-constrained and evapotranspiration can no longer meet atmospheric demand.

The difference between this demand (evapotranspiration) and the actual evapotranspiration is defined as the 'potential evapotranspiration deficit' (PED). In practice, PED represents the total amount of water required by irrigation, or that needs to be replenished by rainfall, to maintain plant growth at levels unconstrained by water shortage. As such, PED estimates provide a robust measure of drought intensity and duration. Days when water demand is not met, and pasture growth is reduced, are often referred to as days of potential evapotranspiration deficit.

PED is calculated as the difference between potential evapotranspiration (PET) and rainfall, for days of soil moisture under half of available water capacity (AWC), where an AWC of 150mm for silty-loamy soils is consistent with estimates in previous studies (e.g. Mullan *et al*., 2005). PED, in units of mm, can be thought of as the amount of missing rainfall needed in order to keep pastures growing at optimum levels. Higher PED totals indicate drier soils. An increase in PED of 30 mm or more corresponds to an extra week of reduced grass growth. Accumulations of PED greater than 300 mm indicate very dry conditions.

For the modelled historic period, the highest PED accumulation is experienced near Molesworth (500-600 mm). Low elevation eastern areas near Blenheim, Seddon and Ward generally experience 300-400 mm of PED per year. PED accumulation of 100-300 mm per year is typical for the remainder of Marlborough (Figure 6-1).

For all future scenarios, annual PED accumulation is projected to increase throughout the region (Figure 6-2). The greatest increase is projected by 2090 under RCP8.5, with an increase of 75-250 mm PED accumulation in Marlborough.

[2] Meteorological drought happens when dry weather patterns dominate an area and resulting rainfall is low. Hydrological drought occurs when low water supply becomes evident, especially in streams, reservoirs, and groundwater levels, usually after an extended period of meteorological drought.

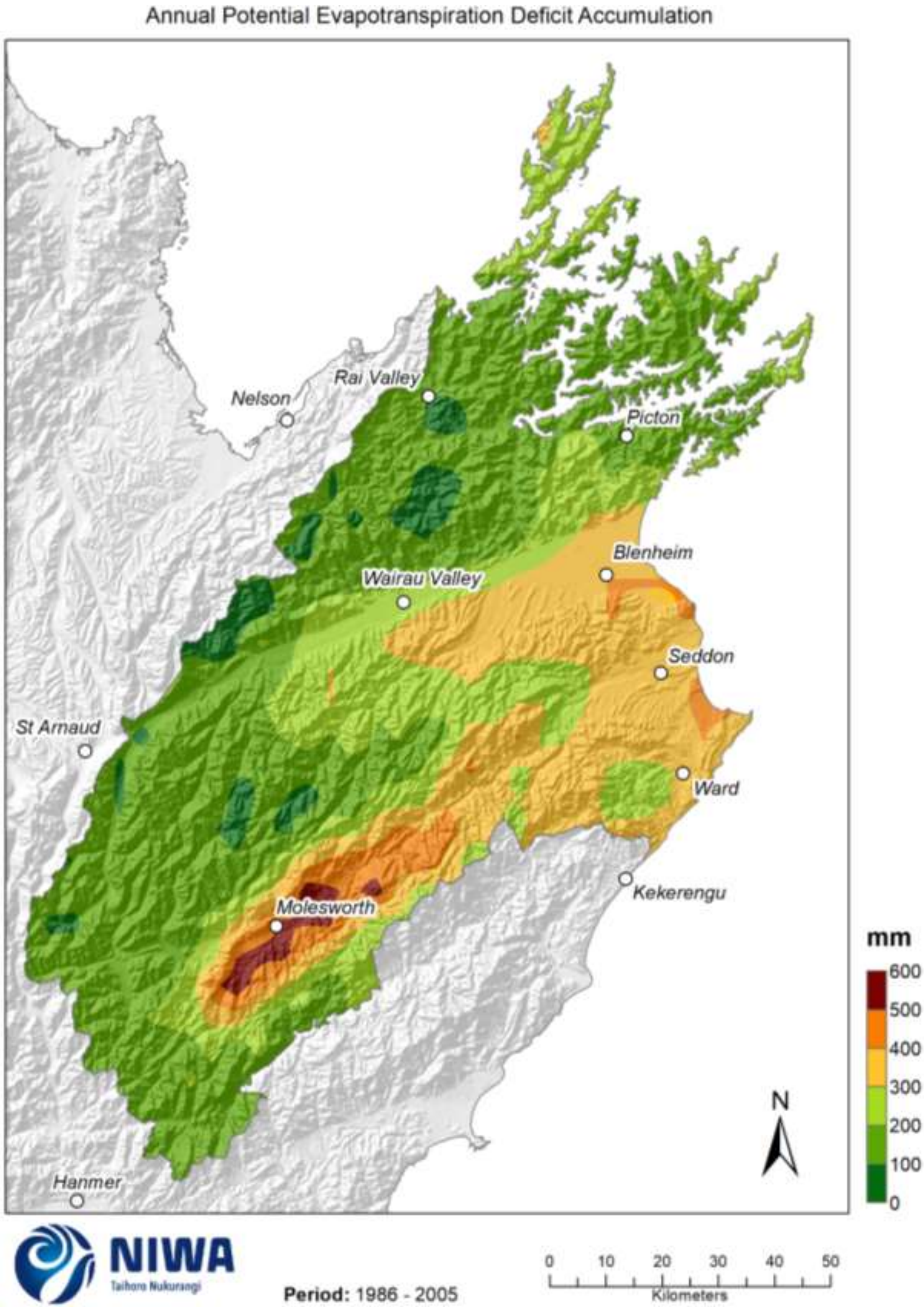


Figure 6-1: Modelled annual potential evapotranspiration deficit accumulation (mm), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

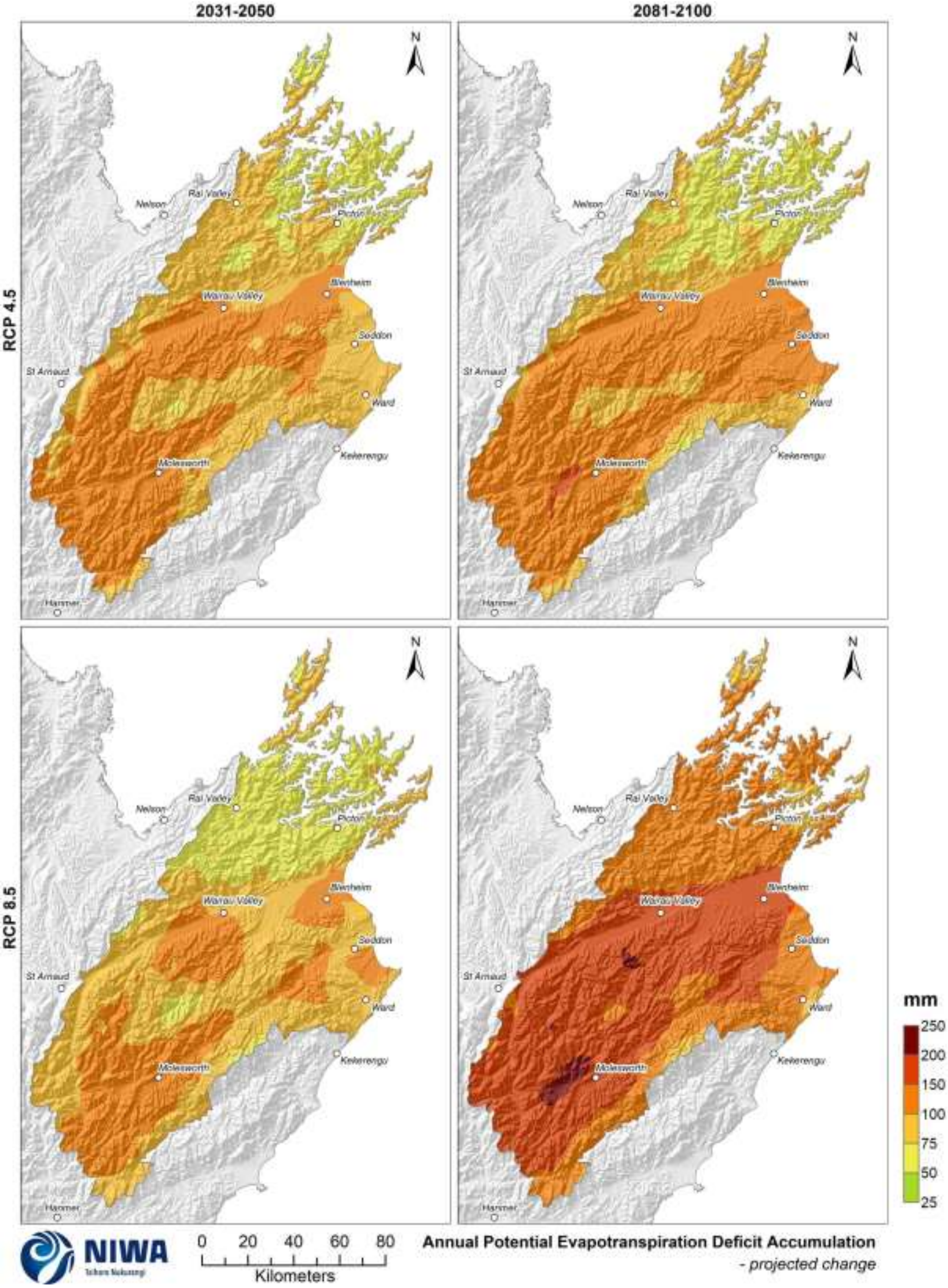


Figure 6-2: Projected annual potential evapotranspiration deficit accumulation (mm) changes by 2040 and 2090 under RCP4.5 and RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

7 Other climate variables

Modelled wind, surface solar radiation and relative humidity data have not had bias correction processes applied as has been carried out for temperature and rainfall, and do not validate well with observations. For this reason, only the future relative changes in these variables have been reported here using the modelled climate data.

7.1 Mean wind speed

Projected mean wind speed changes (%)

Annual:

Period	RCP4.5	RCP8.5
2040	± 5%	± 5%
2090	± 5%	-5% to +10%

Seasonal:

	RCP4.5		RCP8.5	
	2040	2090	2040	2090
Summer	± 5%	Up to +5%	± 5%	-5% to +10%
Autumn	± 5%	Up to +5%	± 5%	-5% to +10%
Winter	± 5%	-5% to +10%	± 5%	-15% to +20%
Spring	± 5%	± 5%	Up to +10%	Up to +15%

This section contains maps showing future projected change in mean wind speed. Future (average over 2031-2050 and 2081-2100) maps show the percentage change in annual and seasonal mean wind speed compared with the historic average. The change signal in mean wind speed is due to changes in atmospheric circulation and local variables (e.g. temperature).

Representative concentration pathway (RCP) 4.5

By 2040, projected change to annual mean wind speed is small, with changes of ±5% throughout the region (Figure 7-1). Similar changes of ±5% are projected seasonally (Figure 7-2). By 2090, projected change to annual mean wind speed remains small (±5%; Figure 7-1). Projected seasonal changes typically fall within ±5% for the region (Figure 7-3).

Representative concentration pathway (RCP) 8.5

By 2040, the projected pattern of change to annual mean wind speed is very similar to that projected for RCP4.5, with changes of ±5% (Figure 7-1). Seasonal projected changes are also similar to RCP4.5, with the exception of spring where an increase of 5-10% is projected about Molesworth. By 2090, a stronger pattern of change is evident, with annual projected changes in mean wind speed ranging from -5% to +10% (Figure 7-1). Seasonal changes project a winter and spring increase in mean wind speed of 5-10% for most of Marlborough, with projected increases of 10-20% in some areas about Blenheim and Molesworth (Figure 7-5).

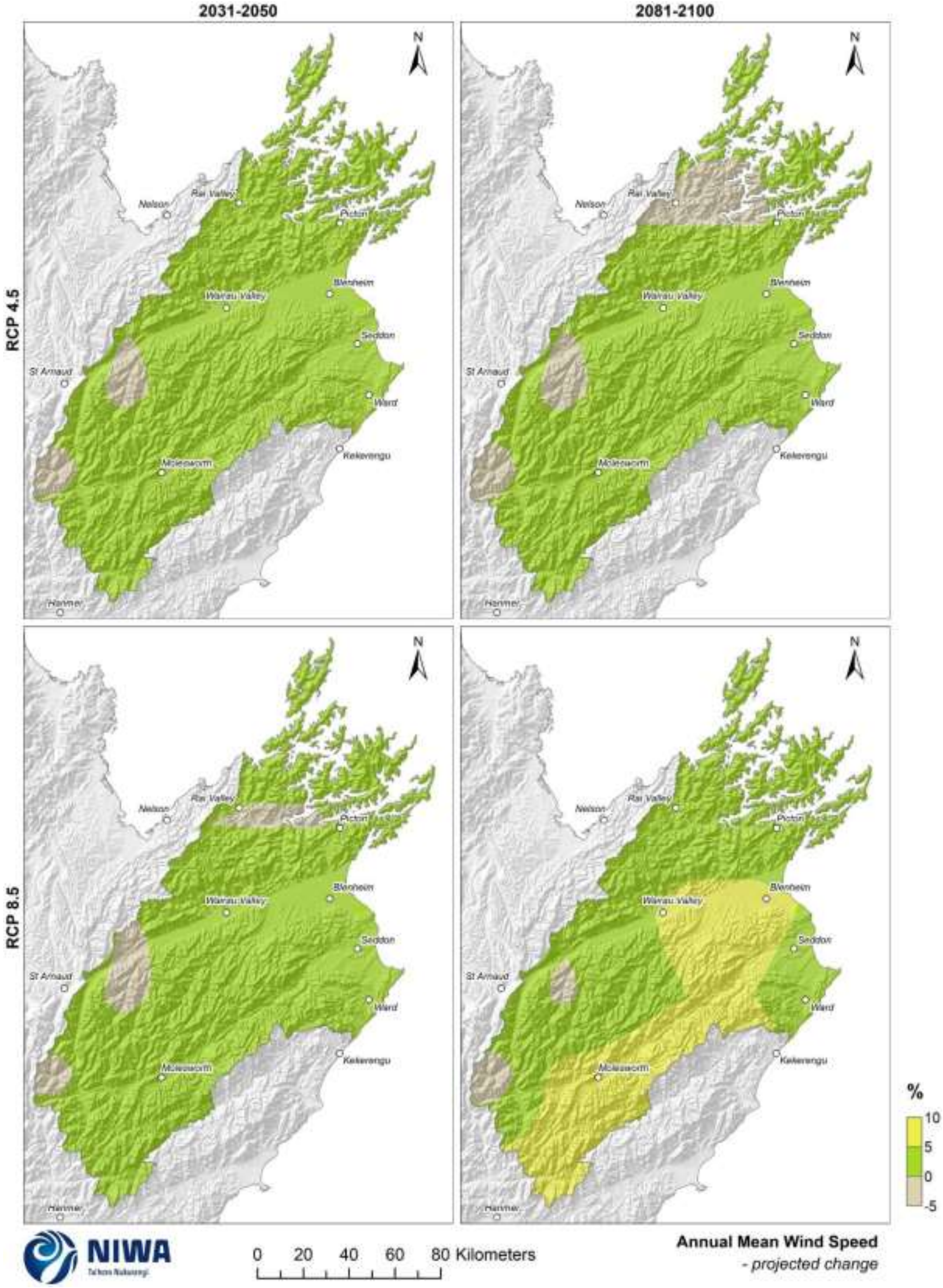


Figure 7-1: Projected annual mean wind speed changes by 2040 and 2090, under RCP4.5 and RCP8.5. Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

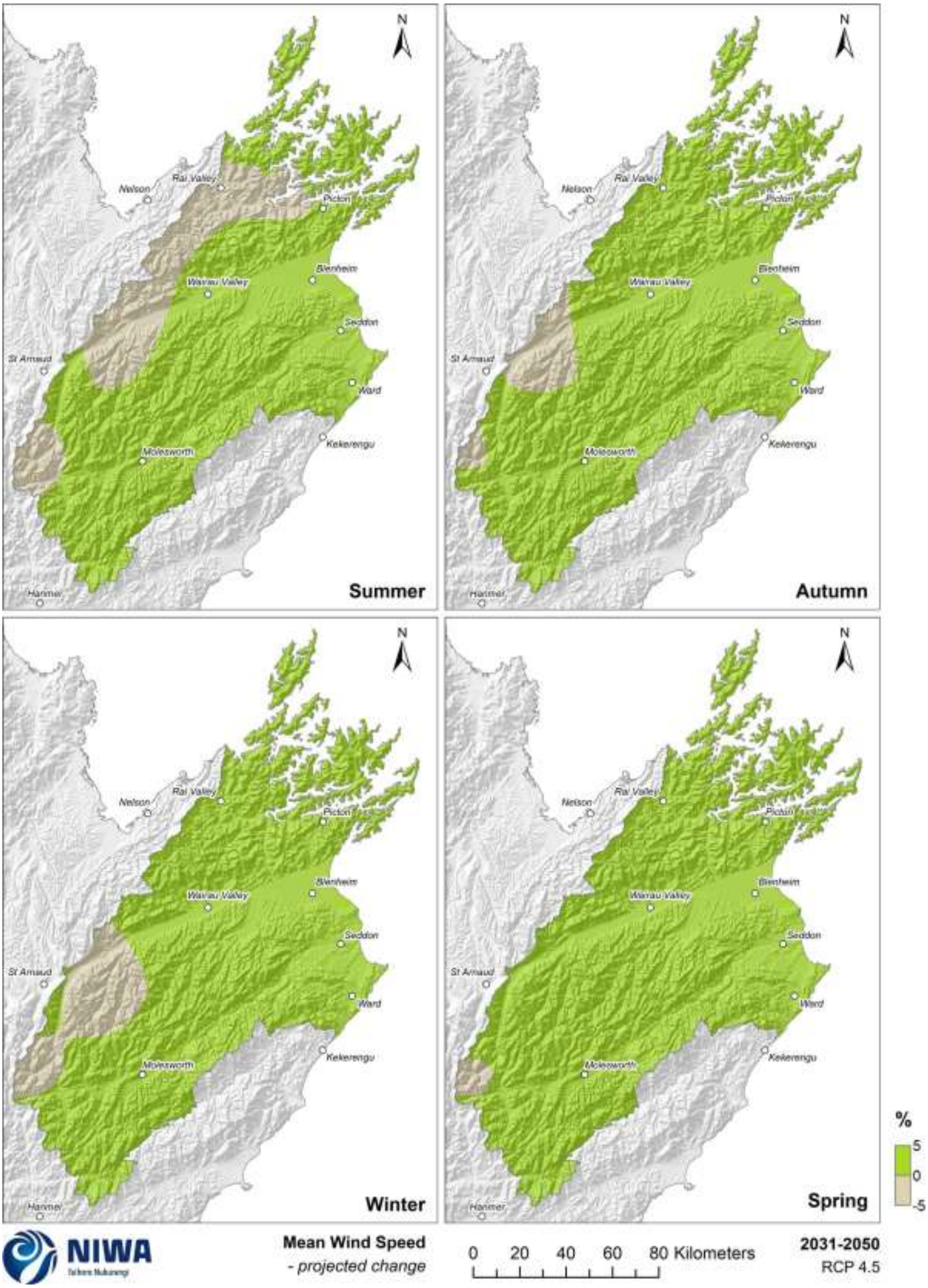


Figure 7-2: Projected seasonal mean wind speed changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

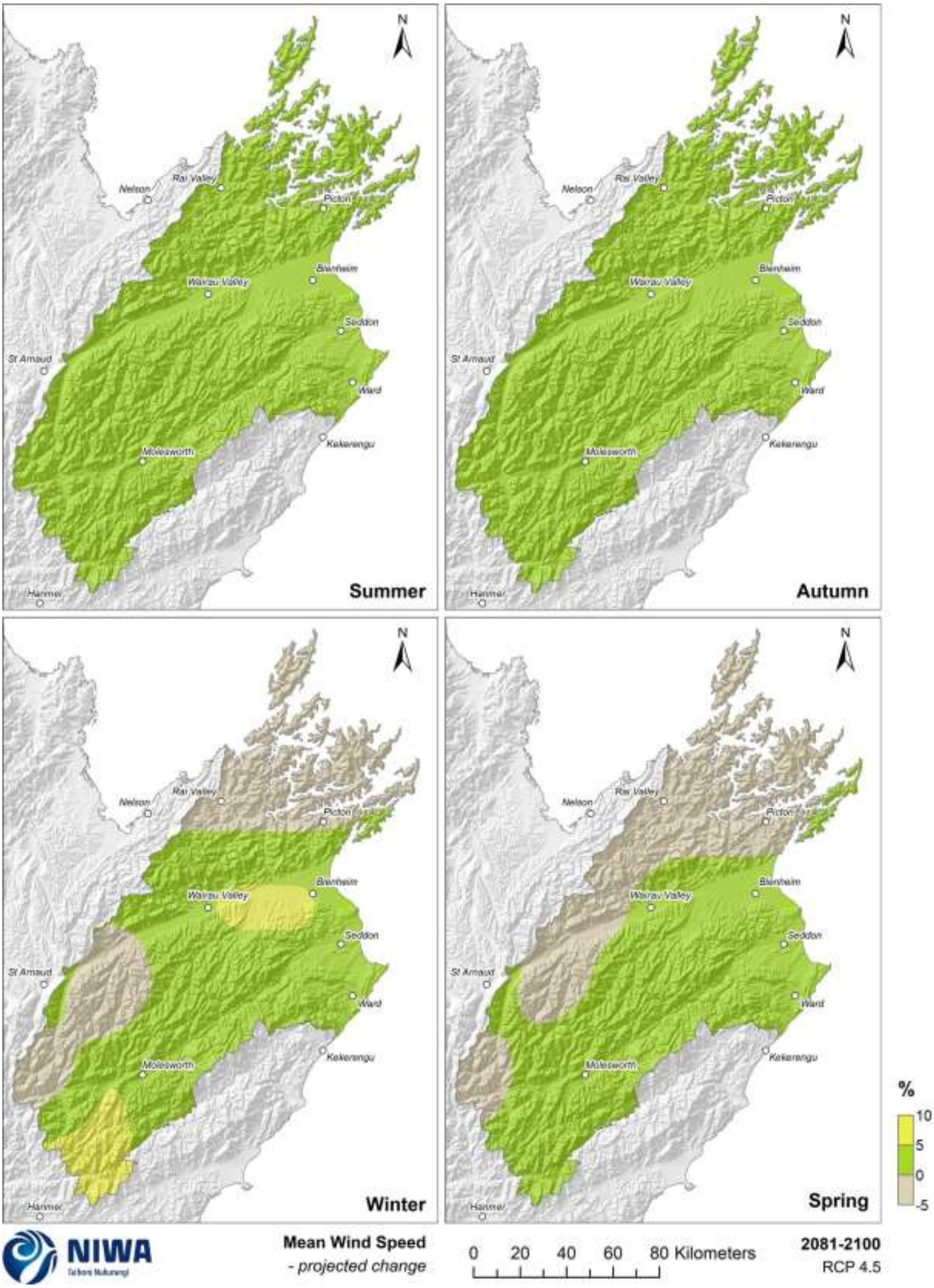


Figure 7-3: Projected seasonal mean wind speed changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

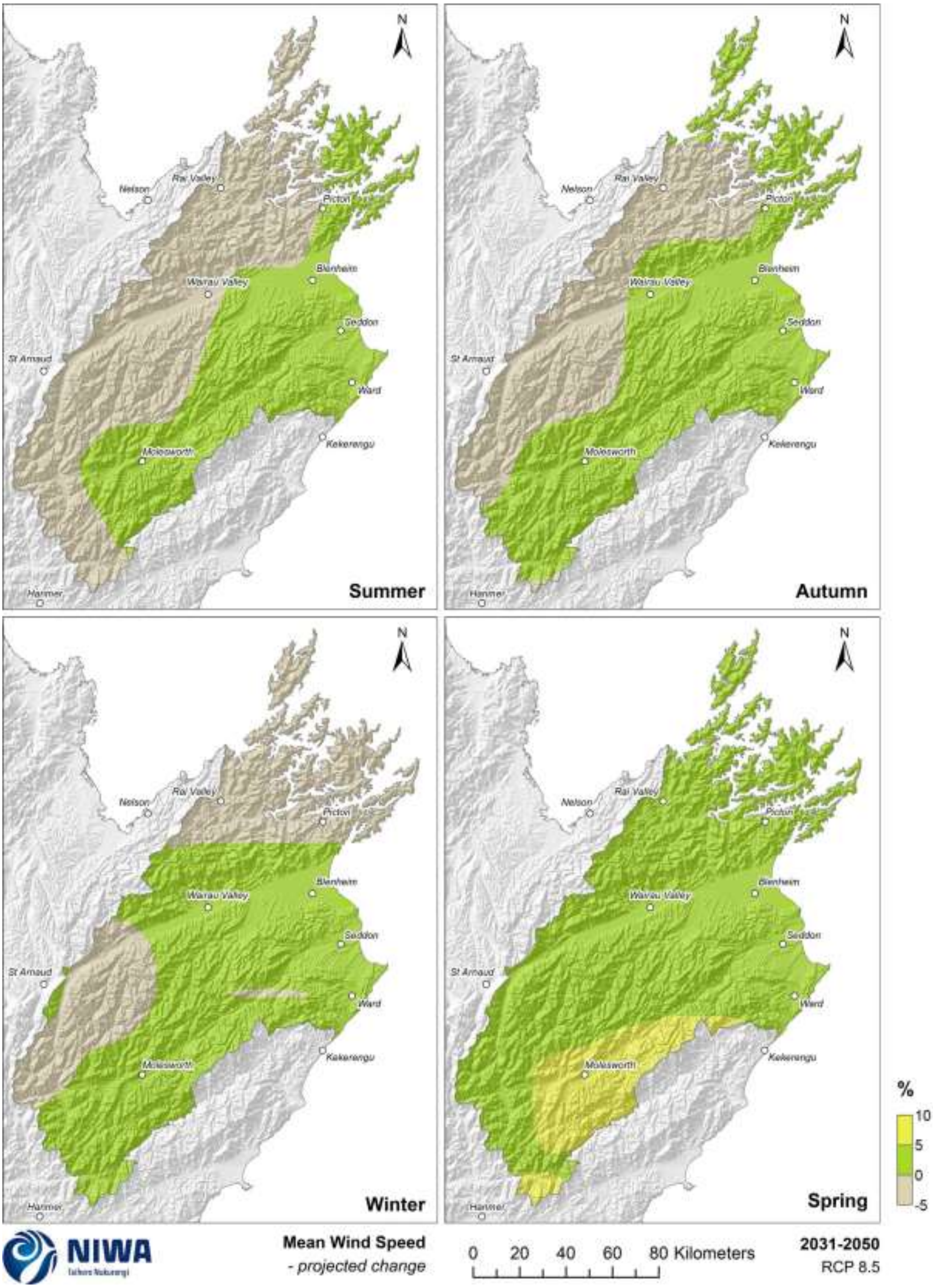


Figure 7-4: Projected seasonal mean wind speed changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

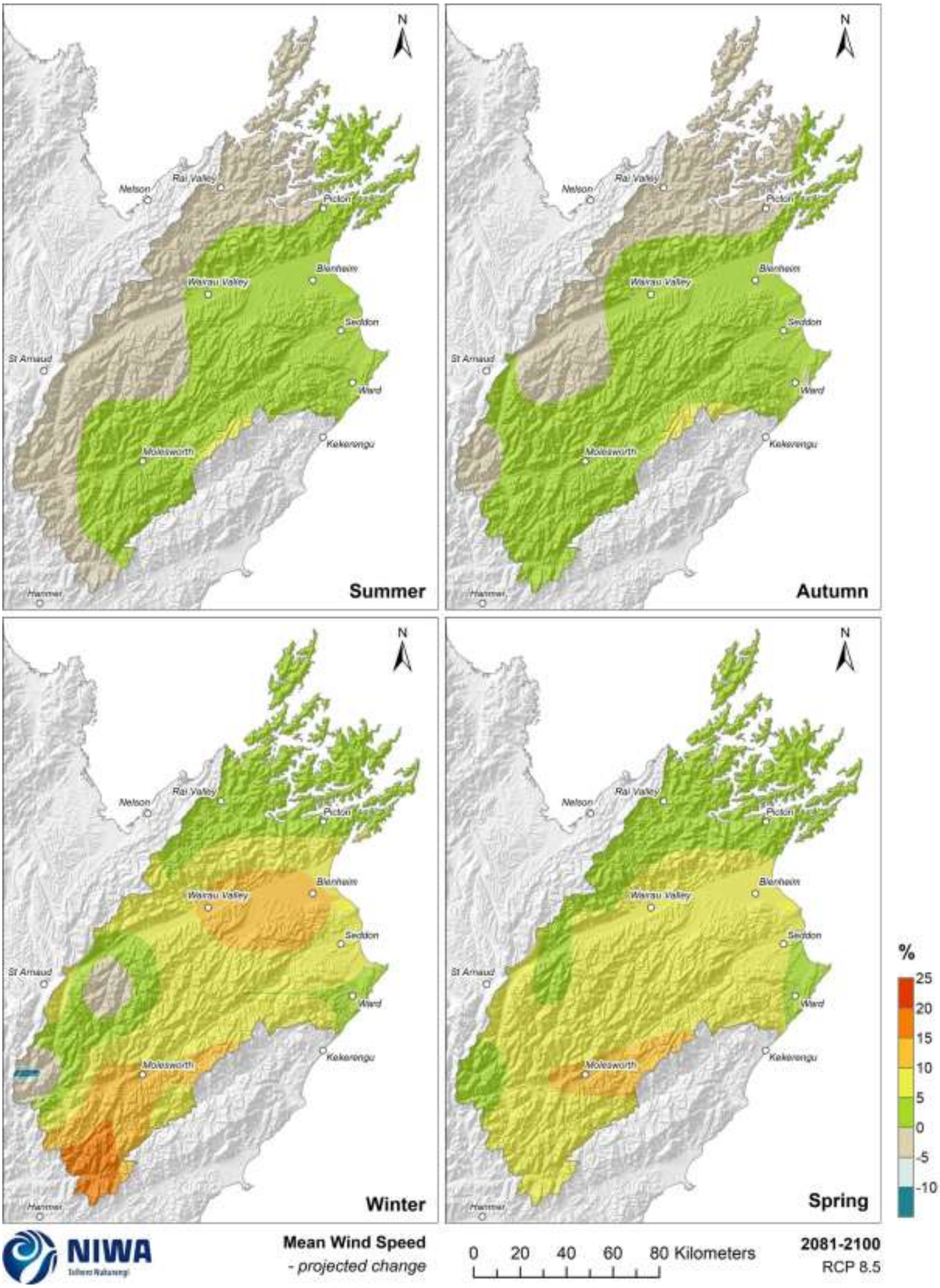


Figure 7-5: Projected seasonal mean wind speed changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

7.2 Surface solar radiation

Projected surface solar radiation changes (W/m^2)

Annual:

Period	RCP4.5	RCP8.5
2040	± 2.5	± 2.5
2090	± 2.5	-2.5 to +10

Seasonal:

	RCP4.5		RCP8.5	
	2040	**2090**	**2040**	**2090**
Summer	-5.0 to +10	± 10	-5.0 to +10	-15 to +20
Autumn	± 2.5	-2.5 to +5.0	± 2.5	± 5.0
Winter	Up to -5.0	-10 to +2.5	Up to -5.0	-10 to +5.0
Spring	± 2.5	-2.5 to +5.0	Up to +10	-2.5 to +15

This section contains maps showing future projected change in surface solar radiation (solar radiation received at the land surface). The solar radiation reaching the surface is not accurately modelled. The changes in surface solar radiation reflects modelled changes in clouds with a low degree of confidence. Since surface solar radiation is determined by cloud cover, it can also be thought of as a proxy for changes in sunshine. Future (average over 2031-2050 and 2081-2100) maps show the change in annual and seasonal surface solar radiation compared with the historic average, and the units are watts per square metre.

Representative concentration pathway (RCP) 4.5

By 2040, projected change to annual surface solar radiation is ±2.5 W/m^2 throughout the region (Figure 7-6). Similar changes are projected during autumn and spring, with decreases of up to 5 W/m^2 projected in winter (Figure 7-7).

By 2090, projected changes to annual and seasonal (Figure 7-8) surface solar radiation are similar to 2040.

Representative concentration pathway (RCP) 8.5

By 2040, the projected pattern of change to annual surface solar radiation is very similar to that projected for RCP4.5, with changes of ±2.5 W/m^2 throughout the region (Figure 7-6). Seasonal projected changes are also similar to RCP4.5, with the exception of spring where an increase of up to 10 W/m^2 is projected for some parts of the region (Figure 7-9).

By 2090, a stronger pattern of change is evident, with annual projected changes in surface solar radiation ranging from a decrease of 2.5 W/m^2 to an increase of 10 W/m^2 (Figure 7-6). Seasonal changes project a summer change in surface solar radiation ranging from a decrease of 15 W/m^2 to an increase of 20 W/m^2 for Marlborough (Figure 7-10). Winter decreases of up to 10 W/m^2 are projected for the southwest of the region.

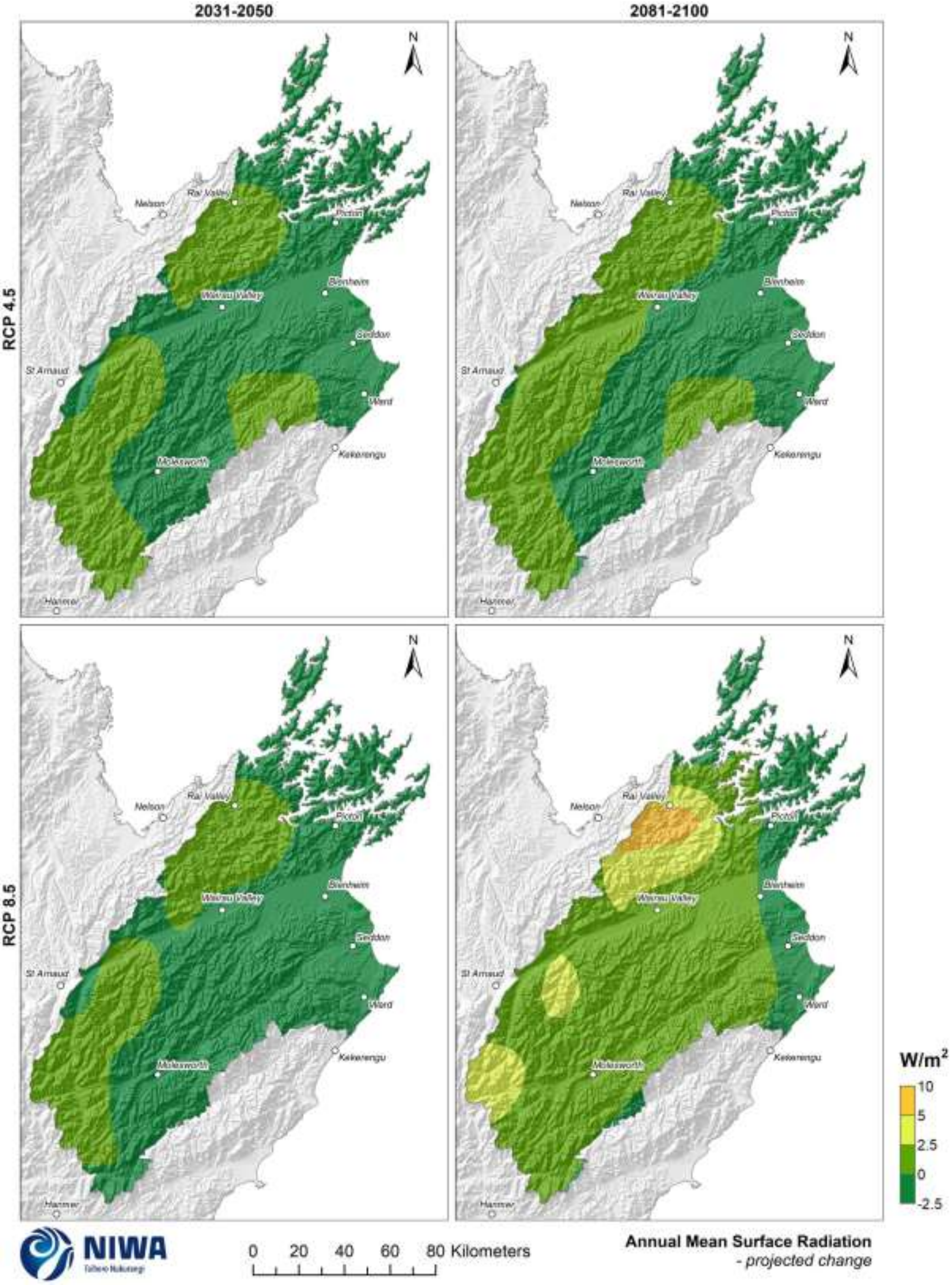


Figure 7-6: Projected annual mean surface solar radiation changes by 2040 and 2090, under RCP4.5 and RCP8.5. Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

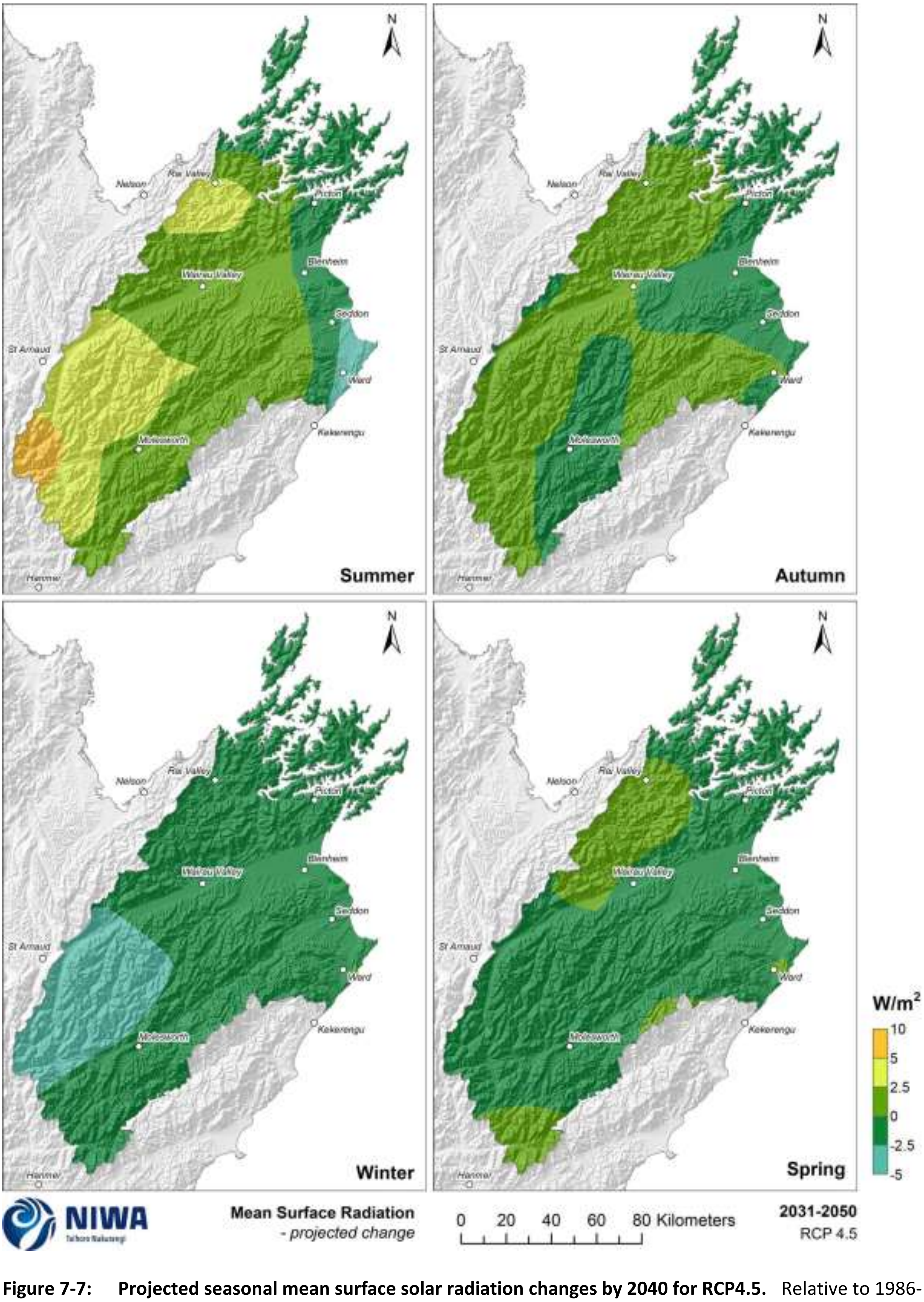


Figure 7-7: Projected seasonal mean surface solar radiation changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

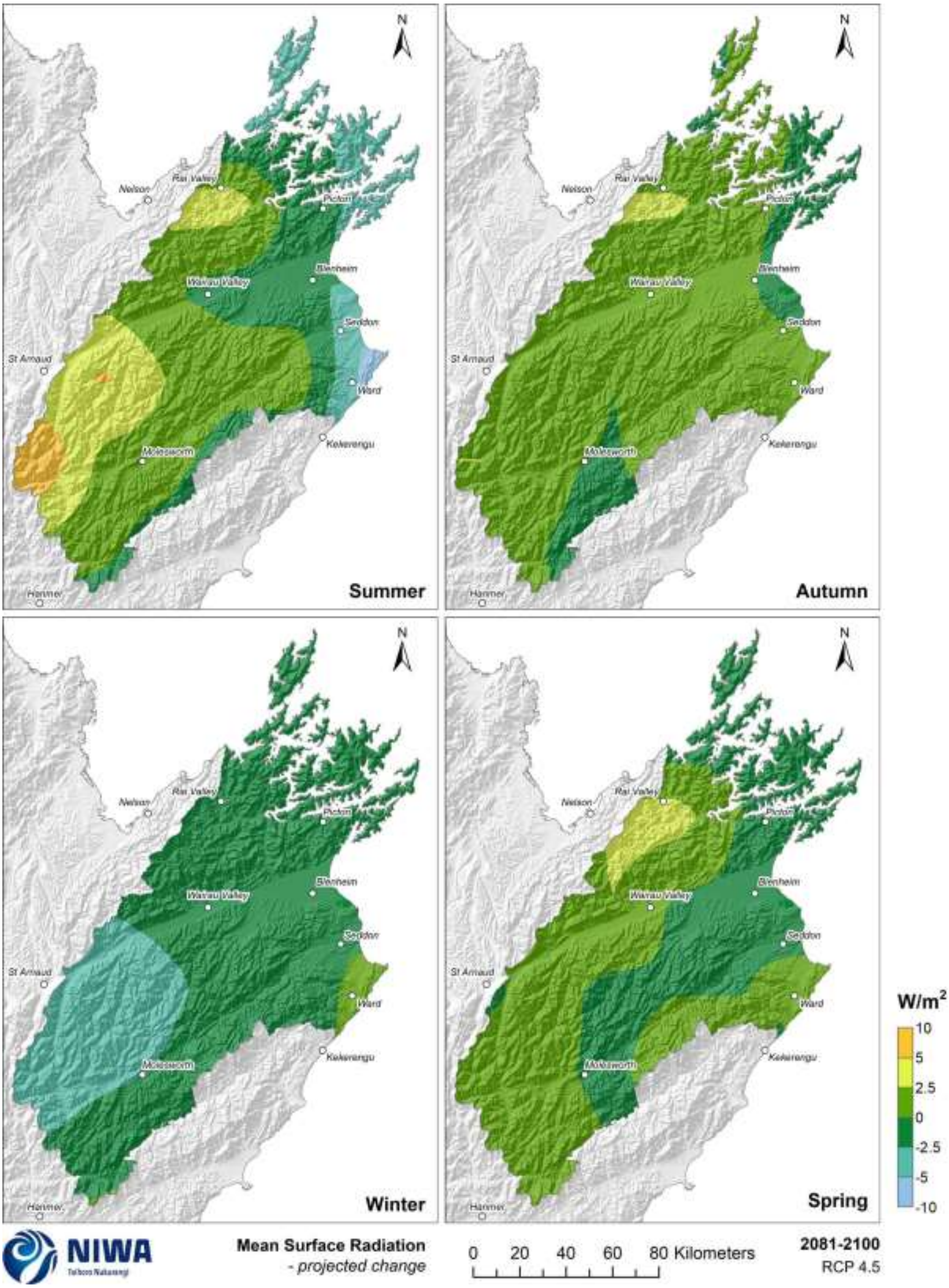


Figure 7-8: Projected seasonal mean surface solar radiation changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

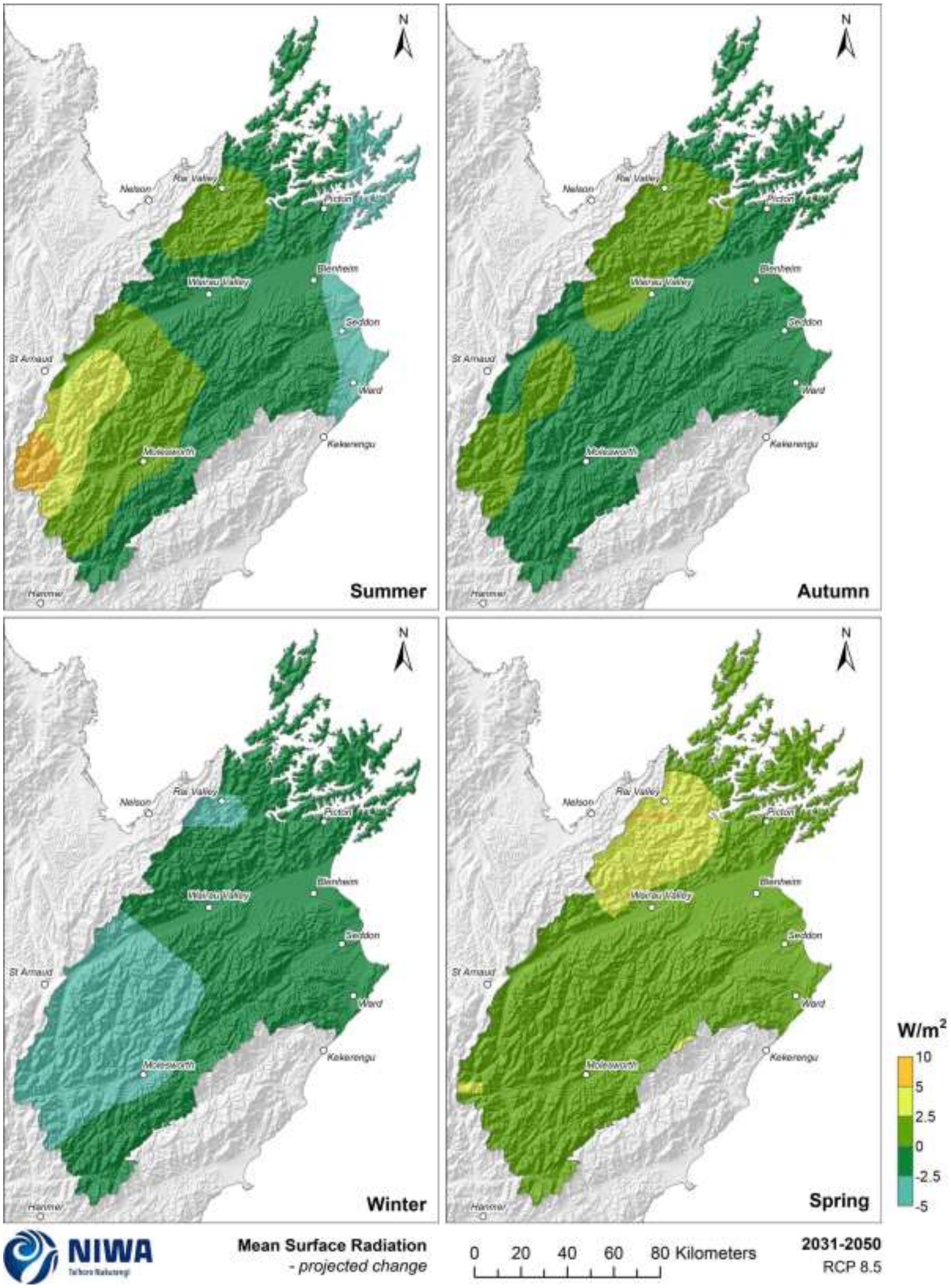


Figure 7-9: Projected seasonal mean surface solar radiation changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

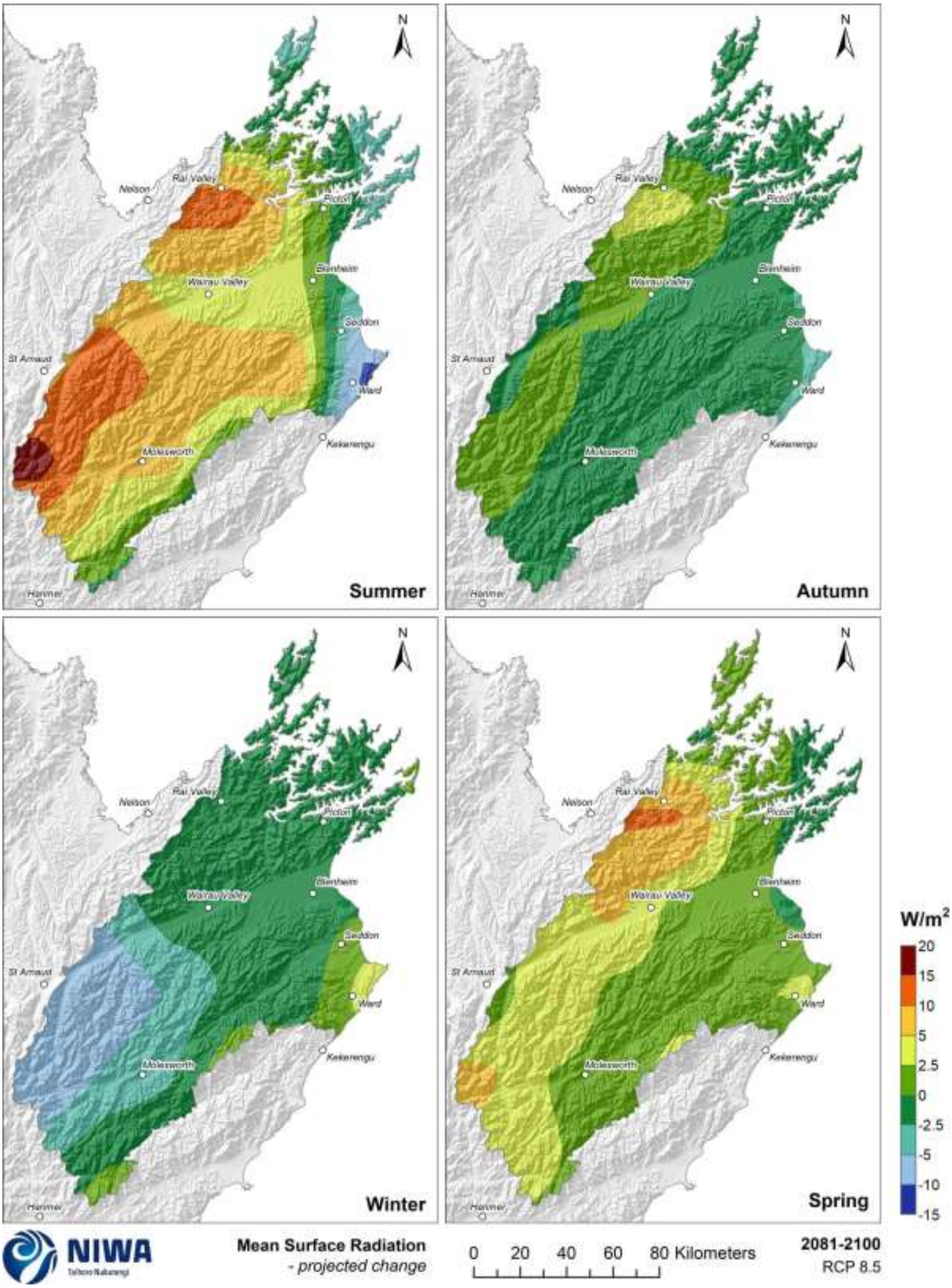


Figure 7-10: Projected seasonal mean surface solar radiation changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

7.3 Relative humidity

Projected relative humidity changes (%)

Annual:

Period	RCP4.5	RCP8.5
2040	-2 to +1	-3 to +1
2090	-3 to +1	-10 to +1

Seasonal:

	RCP4.5		RCP8.5	
	2040	2090	2040	2090
Summer	-3 to +1	-3 to +1	-3 to +1	-10 to +2
Autumn	-2 to +1	-3 to +1	-3 to +1	-10 to +2
Winter	-2 to +1	-3 to +1	-2 to +1	-10 to +1
Spring	-5 to +1	-5 to +1	Up to -5	-10 to +1

This section contains maps showing future projected change in relative humidity. Future (average over 2031-2050 and 2081-2100) maps show the percentage change in annual and seasonal mean relative humidity compared with the historic average. **A note about relative humidity compared to specific humidity:** Projected decreases in relative humidity are a consequence of the higher temperatures. The absolute water content of the air, as measured by specific humidity, increases with time, but the temperature effect is larger; the rate of decrease in relative humidity over New Zealand is mostly 1–2% per degree increase in mean temperature. This is in line with evidence in the recent observations (Simmons *et al*., 2010) in reanalysis and station data over low and mid latitudes.

Representative concentration pathway (RCP) 4.5

By 2040, projected change to annual mean relative humidity is small, with decreases of up to 2% for most the region (Figure 7-11). Similar changes are projected seasonally, except for summer and spring where decreases of 2-5% are projected west of Molesworth (Figure 7-12).

By 2090, projected change to annual mean relative humidity remains relatively small, ranging from a decrease of up to 3% to an increase of up to 1% (Figure 7-11). Projected seasonal decreases of up to 3% occur in each season, with 3-5% decreases projected in the far southwest of Marlborough in spring (Figure 7-13).

Representative concentration pathway (RCP) 8.5

By 2040, annual mean relative humidity is projected to decrease by up to 3% in some parts of the region (Figure 7-11). Seasonal projected changes are similar to RCP4.5, with the exception of spring where a decrease of 2-3% is projected for a much larger portion of the southern half of the region (Figure 7-14).

By 2090, annual projected decreases in mean relative of 3-10% are common throughout Marlborough (Figure 7-11). Seasonal changes are relatively pronounced, with projected decreases of 3-10% common for most of Marlborough (Figure 7-15).

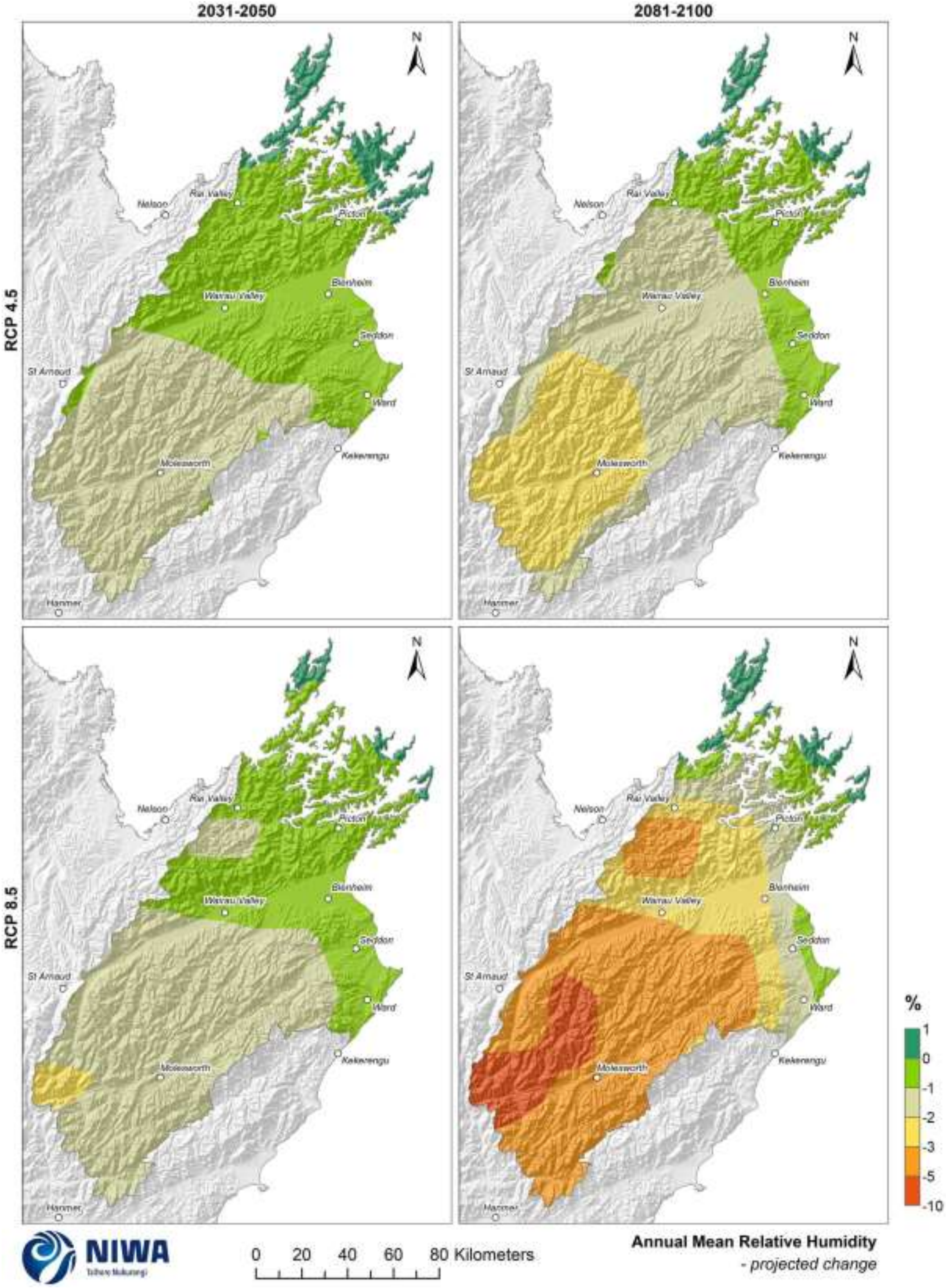


Figure 7-11: Projected annual mean relative humidity changes by 2040 and 2090, under RCP4.5 and RCP8.5. Changes relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

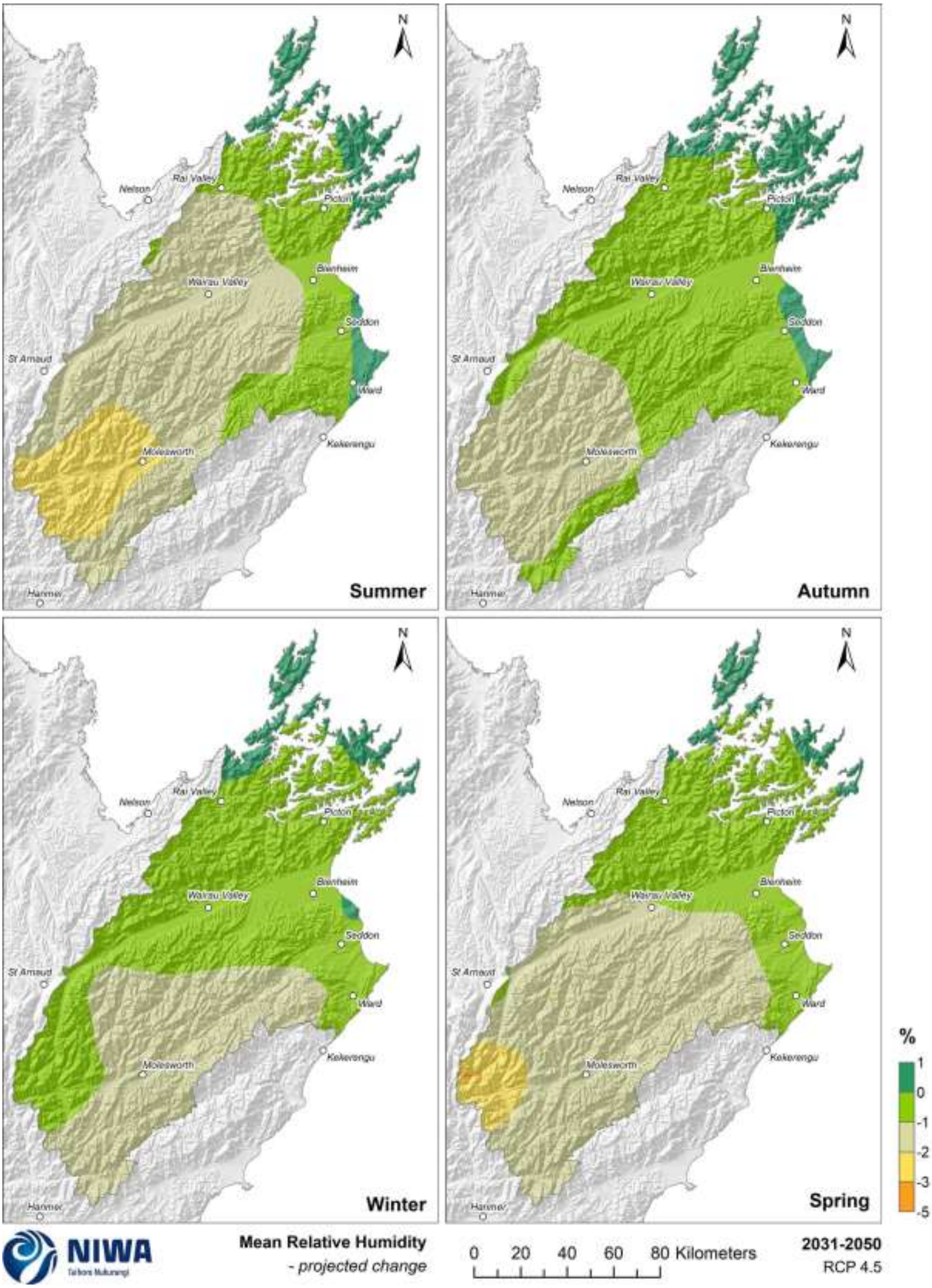


Figure 7-12: Projected seasonal mean relative humidity changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

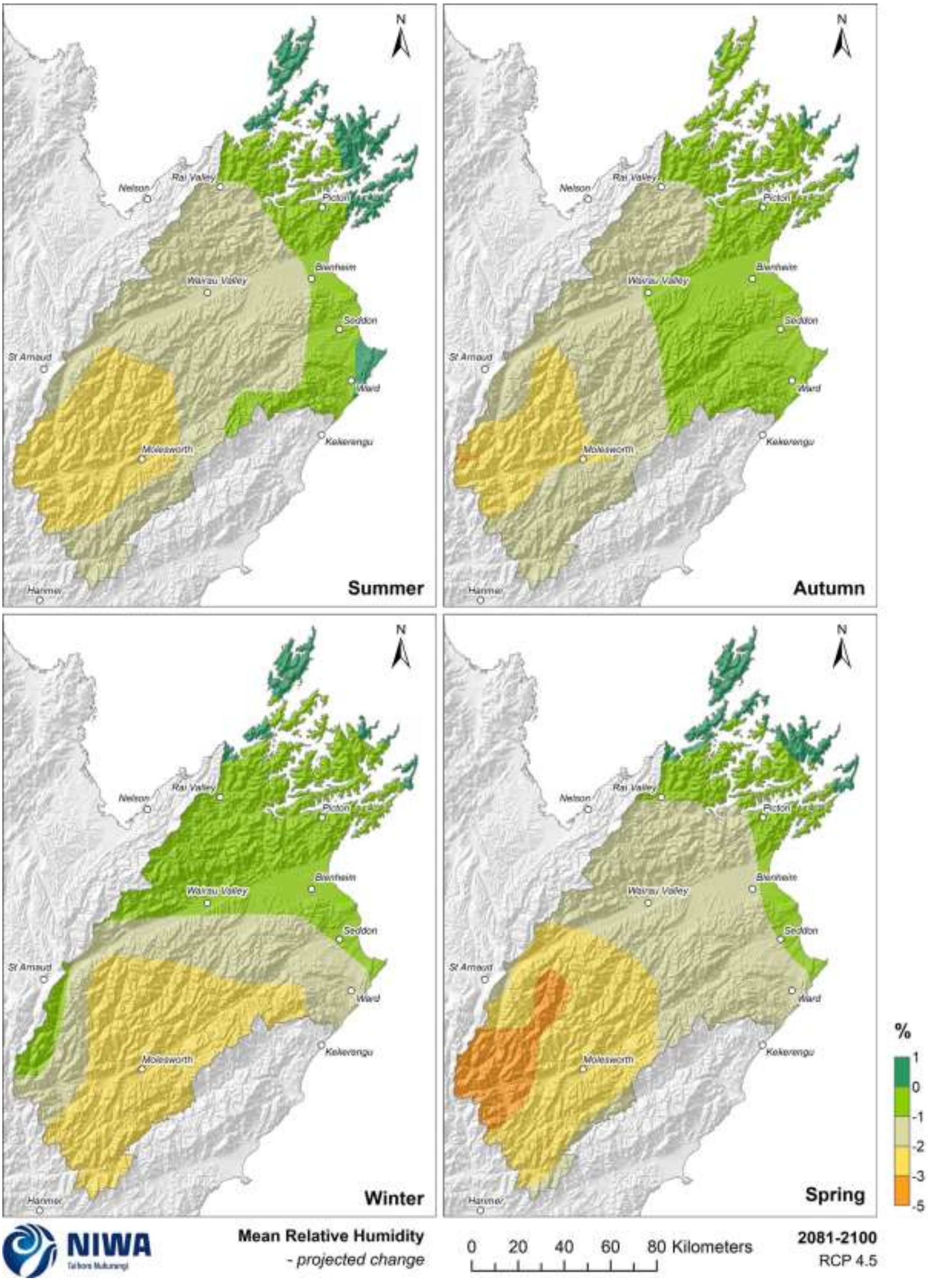


Figure 7-13: Projected seasonal mean relative humidity changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

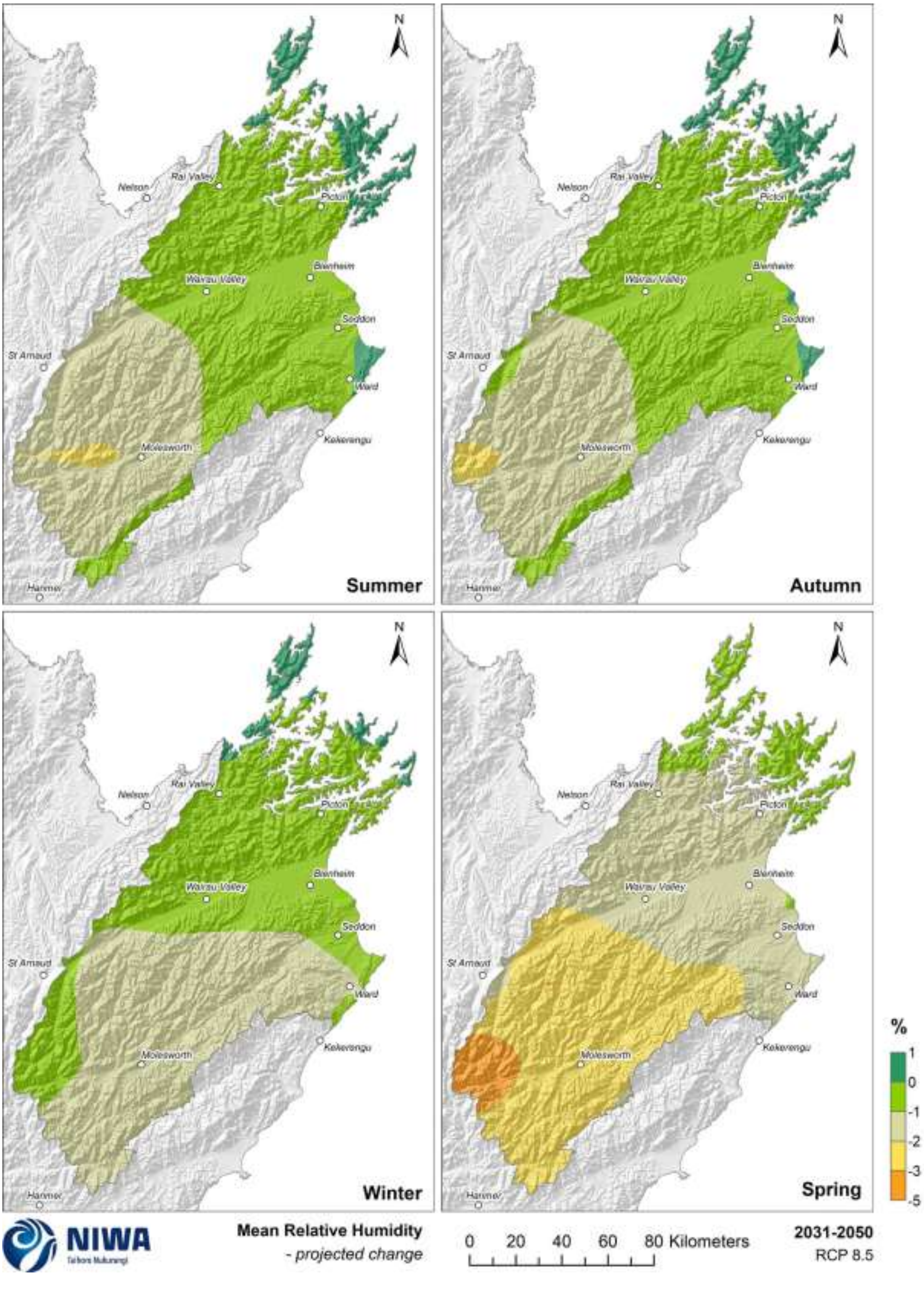


Figure 7-14: Projected seasonal mean relative humidity changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

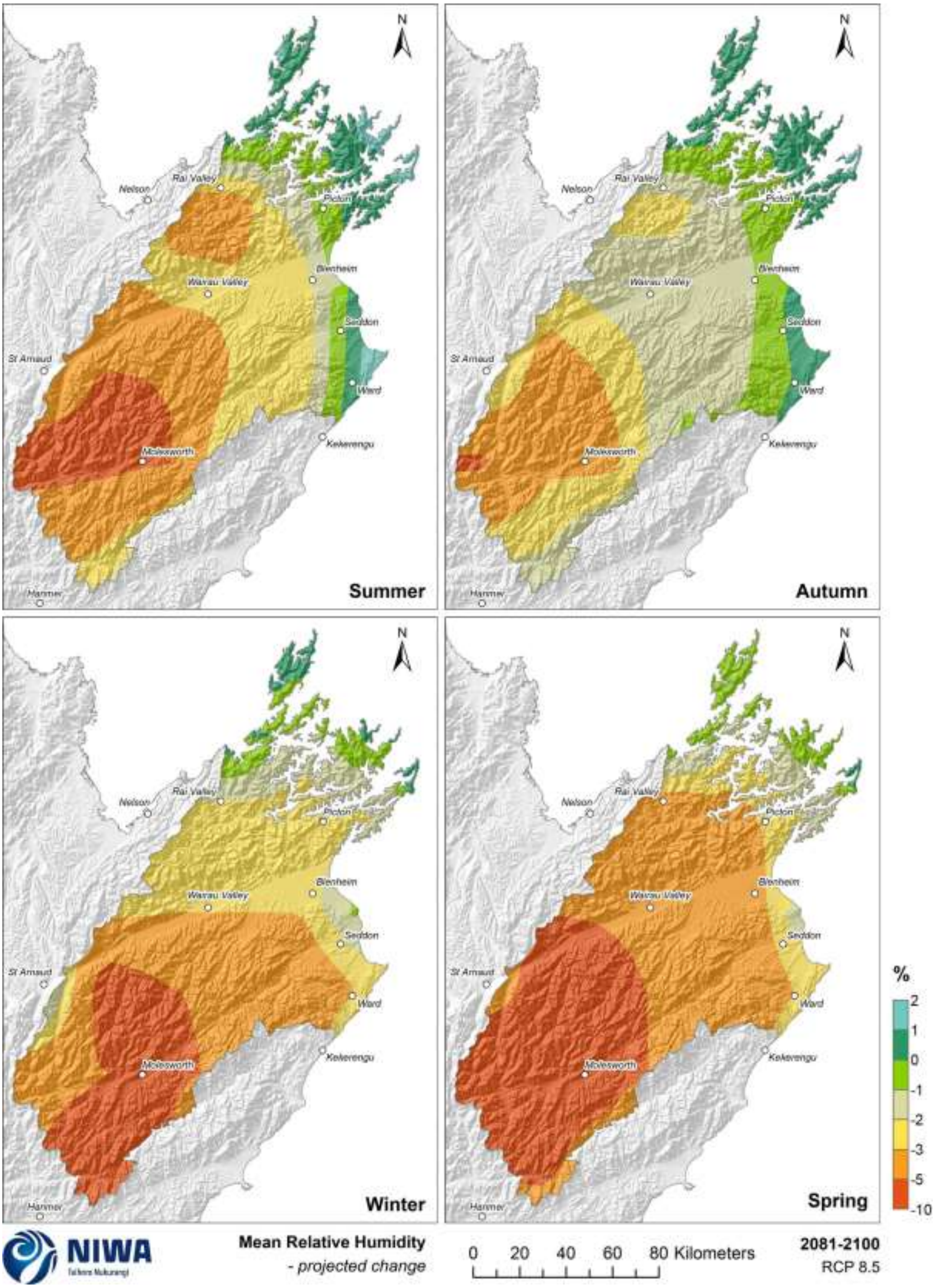


Figure 7-15: Projected seasonal mean relative humidity changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

7.4 Air pressure

Key messages

- Mean sea level pressure (MSLP) is projected to increase in summer, causing more north easterly airflow and more anticyclonic patterns (high pressure systems).
- MSLP tends to decrease in model simulations during winter, especially over and south of the South Island, resulting in stronger westerly winds over central New Zealand.

Mean sea level pressure (MSLP) varies over New Zealand from day to day as different weather systems pass over the country. Figure 7-16 shows average seasonal MSLP over the Southwest Pacific, including New Zealand. Westerly or south westerly wind flows dominate over most of the South Island throughout the year. However, east to northeasterly winds are common in coastal areas of Marlborough, particularly during summer when daytime heating establishes a sea-breeze.

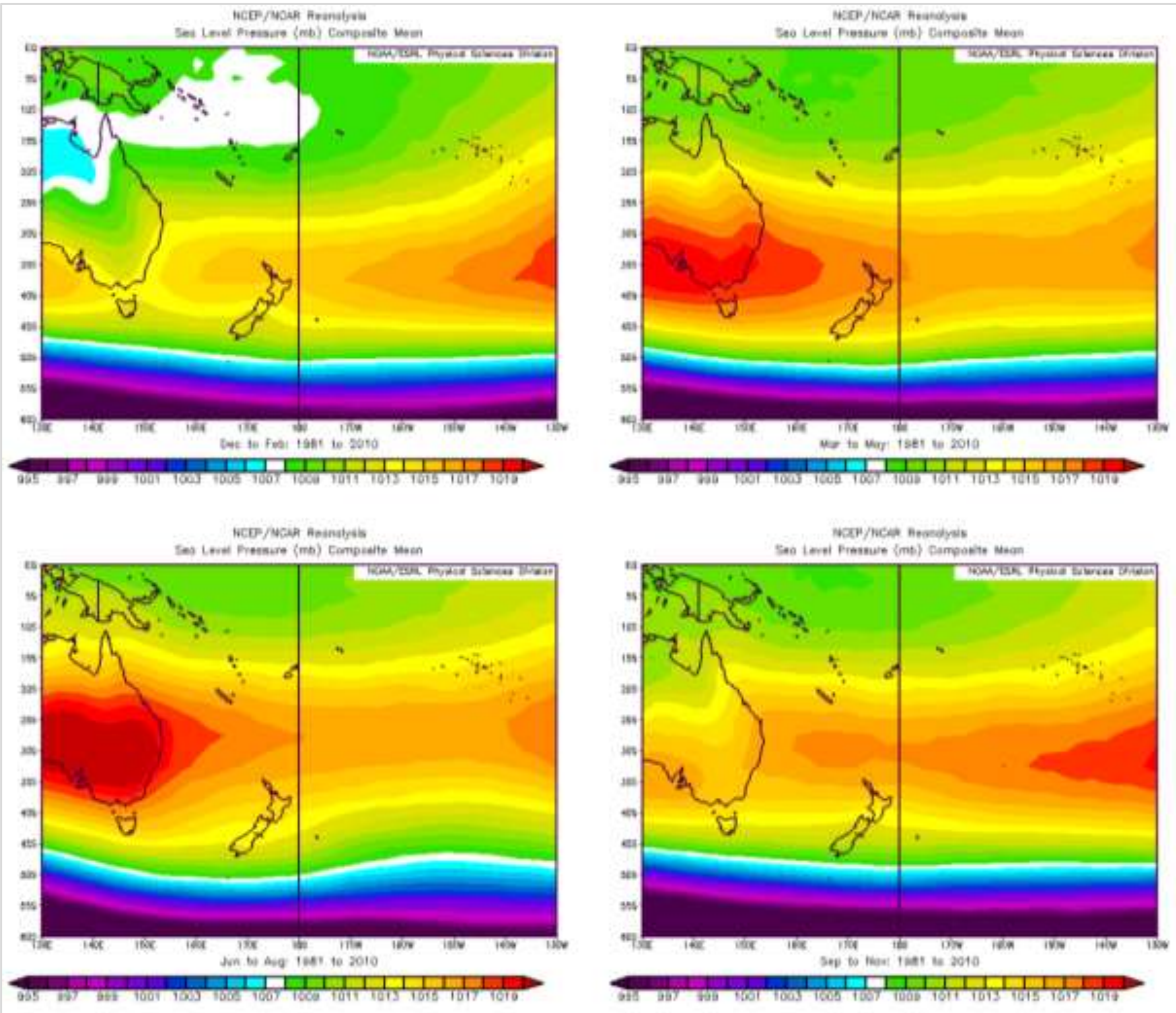


Figure 7-16: Average seasonal mean sea level pressure over the Southwest Pacific, 1981-2010. Top left: summer, top right: autumn, bottom left: winter, bottom right: spring. Sourced from: https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl.

Future mean sea-level pressure projections have been derived from the Regional Climate Model (RCM) simulations. The key projected changes in mean sea-level pressure (MSLP) and mean winds are as follows (for more detail see Mullan et al., 2016; MFE, 2018):

- MSLP tends to increase in summer (December–February), especially to the south-east of New Zealand. In other words, the airflow becomes more north easterly, and at the same time more anticyclonic (high pressure systems).
- MSLP tends to decrease in winter (June–August), especially over and south of the South Island, resulting in stronger westerlies over central New Zealand.
- In the other seasons (autumn and spring), the pattern of MSLP change is less consistent with increasing time and increasing emissions. There is, however, still general agreement for autumn changes to be like those of summer (i.e., more anticyclonic), and for spring changes to be like those of winter (lower pressures south of the South Island, and stronger mean westerly winds over southern parts of the country).

8 Sea-level rise and coastal impacts

8.1 Impacts of sea level rise

One of the major and most certain (and so foreseeable) consequences of increasing concentrations of greenhouse gases and associated warming, is the rising sea level (Parliamentary Commissioner for the Environment, 2015). IPCC (2013) found that warming of the climate system is unequivocal, and many of the changes observed since the 1950s are unprecedented over timescales of decades to millennia. The atmosphere and ocean have warmed, and the amounts of snow and ice globally have diminished, causing sea level to rise.

Rising sea level in past decades is already affecting human activities and infrastructure in coastal areas of New Zealand, with a higher base mean sea level contributing to increased vulnerability to storms and tsunami. Key impacts of an ongoing rise in sea level are:

- gradual inundation of low-lying marsh and adjoining dry land on spring high tides;
- escalation in the frequency of nuisance and damaging coastal flooding events (which has been evident in several low-lying coastal margins of New Zealand);
- exacerbated erosion of sand/gravel shorelines and unconsolidated cliffs (unless sediment supply increases);
- increased incursion of saltwater in lowland rivers and nearby groundwater aquifers, raising water tables in tidally-influenced groundwater systems.

These impacts will have increasing implications for existing development in coastal areas, along with environmental, societal and cultural effects. Infrastructure and its levels of service or performance will also be increasingly affected, such as wastewater treatment plants, potable water supplies, and particularly capacity and performance issues with stormwater and overland drainage systems (particularly gravity-driven networks). Transport infrastructure (roads, ports, airports) in the coastal margin will also be affected, both by increased nuisance shallow flooding of saltwater (e.g., vehicle corrosion) and more disruptive flooding and damage from elevated storm-tides and wave overtopping.

There are three types of sea-level rise (SLR) in relation to observations and projections:

- absolute (or eustatic) rise in ocean levels, measured relative to the centre of the Earth, and usually expressed as a global mean (which is used in most sea-level projections e.g., IPCC);
- offsets (or departures) from the global mean absolute SLR for a regional sea, e.g., the sea around New Zealand, which will experience slightly higher rises (5–10%) than the global average rate. There can be significant variation in the response to warming and wind patterns between different regional seas around the Earth;
- relative sea-level rise (RSLR), which is the net rise in sea level experienced on coastal margins from absolute, regional-sea offsets and local vertical land movement (measured relative to the local landmass). Local or regional adaptation to SLR needs to focus on RSLR, particularly if the coastal margin is subsiding.

The first two types of SLR are measured directly by satellites, using radar altimeters, or by coalescing many tide-gauge records globally (after adjusting for local vertical land movement and ongoing re-adjustments in the Earth's crust following ice loading during the last Ice Age[3]).

RSLR is measured directly by tide gauges. One advantage of knowing the RSLR from gauge measurements is that this directly tracks the SLR that needs to be adapted to locally, or over the wider region represented by the gauge. If, for instance, the local landmass is subsiding, then the RSLR will be larger than the absolute rise in the adjacent ocean level acting alone.

8.2 Datums and mean sea-level

The primary Local Vertical Datum (LVD) used within the Marlborough region is Nelson Vertical Datum 1955 (NVD-55), which is 0.677 m above Chart Datum (CD). The New Zealand Vertical Datum 2016 (NZVD-2016) is now the official vertical datum for New Zealand and its offshore islands, and its relationship to the LVD is shown in Table 8-1 and Figure 8-1. Mean sea level (MSL), shown in Table 8-1, was calculated by LINZ using the 2005–2019 Port of Marlborough sea-level record using 6 years of data (2005–2008, 2017–2019), (*pers. comm.* Glen Rowe, LINZ).

Table 8-1: Mean sea-level and datum offsets at Picton.

Sea-level gauge location	Local vertical datum	Chart Datum (or gauge zero)	NZVD-2016	Mean sea level	Averaging period
Picton	NVD-55	-0.677 (NVD-55)	+0.319 (NVD-55)	+0.173 m (NVD-55) - 0.146 m (NZVD-2016)	2005–2019

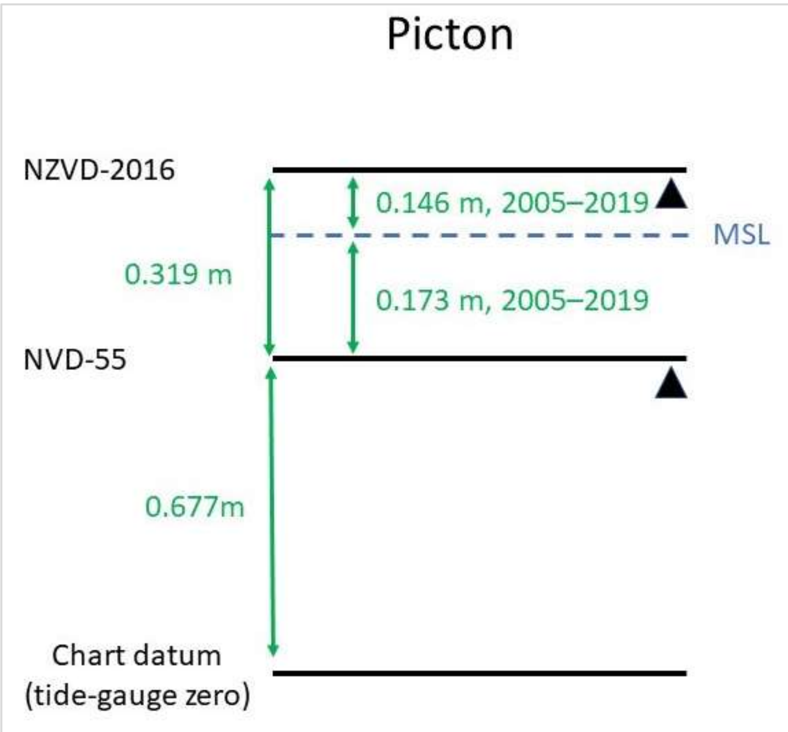


Figure 8-1: Mean sea-level and datum offsets at Picton.

[3] Scientific term is glacial isostatic adjustment (GIA)

8.3 Historic trend in sea-level rise

Hannah and Bell (2012) analysed SLR trends at 10 gauge sites around New Zealand, to extend the picture of local trends at a wider range of locations than just the four main port sites (Auckland, Wellington, Lyttelton, Dunedin), where records exist from 1900 onwards. While the additional 6 sites (Whangarei, Moturiki, New Plymouth, Nelson, Timaru, and Bluff) comprised shorter records, longer term SLR could be inferred by connecting the modern digital records with historic tide measurements (from LINZ archives) used to establish the local vertical datums around New Zealand.

Records from all four main New Zealand port tide gauges (> 110-year records) indicates a doubling in the rate of sea-level rise around the New Zealand coastline over the last five to six decades, from an average of approximately 1 mm/year earlier last century to nearly 2 mm/year from 1961 to 2015 (MfE, 2017). A summary of historic rates of relative SLR across 10 sites in New Zealand is provided in Figure 8-2, with the New Zealand wide average of nearly 1.8 mm/year up to 2015.

Global coverage (between 66°N and 66°S) of satellite altimeters, which measure the ocean surface, commenced in 1993. The global-average rate for absolute SLR from satellite altimetry in the period 1993 to 1 June 2018 is running at ~ 3.2 mm/year, which is about twice the long-term global rate since 1900. In the ocean waters around New Zealand, the trend since 1993 to present has been higher than the global average, with absolute SLR in the Marlborough region trending at around 4 mm/year (Figure 8-3). The NZ-wide average was 4.4 mm/year up to the end of 2015 (see Figure D3, Appendices; MfE, 2017). Some of this increase in the rate of rise is due to the Interdecadal Pacific Oscillation (IPO), a 20–30-year climate cycle, which is in its negative phase at present, leading to increased sea-surface temperature and therefore sea-surface height in the Western Pacific (see darker colours in Figure 8-3), but also is influenced by a warming atmosphere.

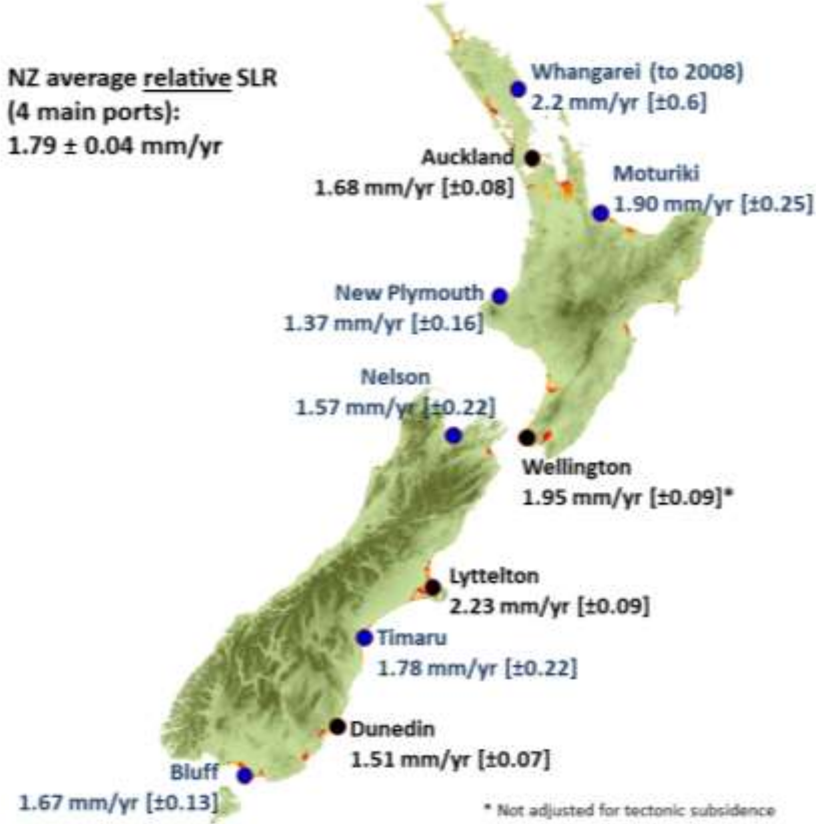


Figure 8-2: Relative SLR rates up to and including 2019 (excluding Whangarei), determined from longer sea-level gauge records at the four main ports (Auckland, Wellington, Lyttelton, Dunedin) and shorter records from the remaining sites. Determined from > 100-year gauge records at the four main ports (black circles) and inferred rates from gauge station records, used in the first half of the 1900s to set the local vertical datums, spliced with modern records (blue circles). Standard deviations of the trend are listed in the brackets. Source: Figure 19; MfE (2017).

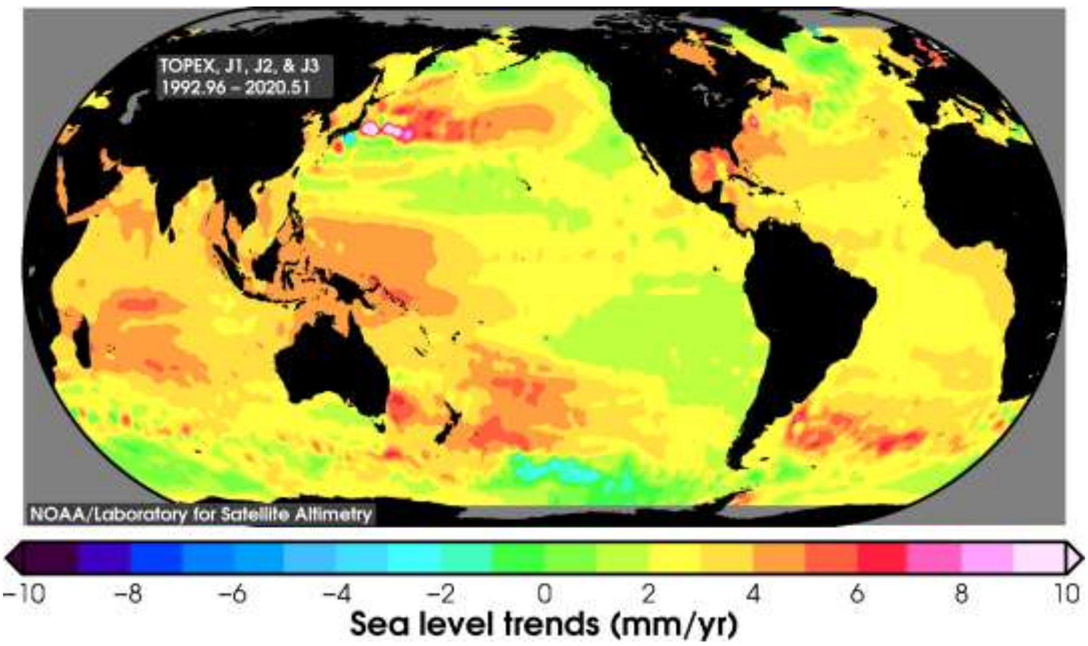


Figure 8-3: Map of regional trend in SLR from 1993 to 1 September 2020 based on satellite altimetry missions. Source: NOAA/NESDIS Center for Satellite Applications and Research.

Relative SLR along the Marlborough coast also incorporates a component due to vertical land movement (VLM). The Marlborough region is located within an extremely active tectonic zone, along a continental plate boundary, and is subject to frequent land movements. In particular, the 2016 Kaikoura Earthquakes contributed to significant land movement within the north eastern portion of the South Island (see https://www.linz.govt.nz/land/surveying/earthquakes/kaikoura-earthquakes). It should be noted that benchmarks used for the work pertaining to sea-level within this chapter have all been surveyed post Kaikoura earthquake. Continuous GPS stations have been operated near the coast in the region by GeoNet and LINZ since the early 2000s. Up to 2011, the vertical land movement was predominantly small uplift[4] (Figure 8-4; Beavan and Litchfield, 2012). Estimated uplift rates for locations about Marlborough include sites OKOH (0.7 mm/yr), TORY (1.3 mm/yr; Tory Channel), WITH (0.2 mm/yr; Wither Hills) and CMBL (0.9 mm/yr; Cape Campbell). Further updated analysis on vertical land movement around New Zealand, and the implications for long-term sea-level rise, is a component of an Endeavour Fund research project NZSeaRise, coordinated by Victoria University of Wellington. Recent research by Denys *et al.* (2020) included the effects of vertical land movement on observed sea level in New Zealand, and calculated an absolute sea level of +1.45 mm/year ± 0.28 mm/year (1891-2013).

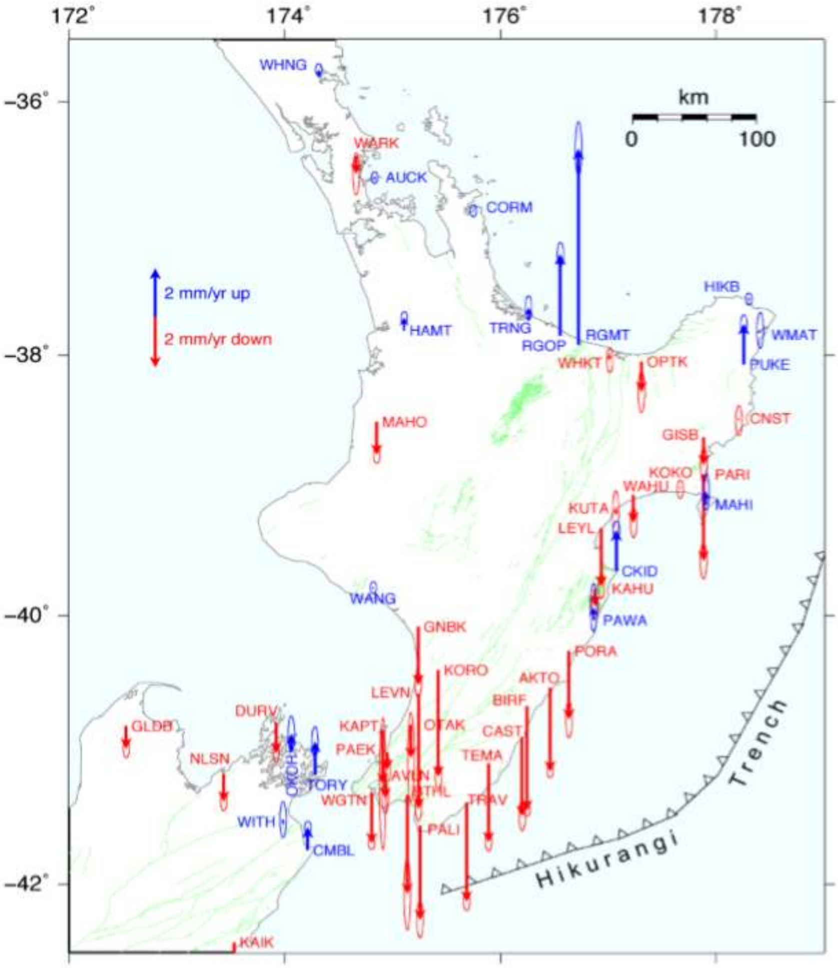


Figure 8-4: Average vertical land movement for near-coastal continuous GPS Sites across the North Island and upper South Island, New Zealand. Blue arrows show average uplift and red arrows average subsidence over around a 10-year period up to 2011. Source: Beavan and Litchfield (2012).

[4] Uplift means the relative SLR is smaller than the absolute rise in the ocean surface (subsidence means it is larger)

8.4 Projections for New Zealand sea-level rise

A synthesis of the historic and future projections of SLR, both globally and for New Zealand, is available in the Ministry for the Environment (MfE) guidance for local government: *Coastal Hazards and Climate Change* (MfE 2017) and an accompanying Summary[5] and set of Fact Sheets.[6]

Chapter 5 of the Coastal Guidance provides four specific New-Zealand based SLR scenarios to use when assessing and planning adaptation to coastal climate change in New Zealand (Figure 8-5). The SLR scenarios in the Coastal Guidance largely follow the synthesis of the IPCC Fifth Assessment Report (IPCC, 2013; Church *et al*., 2013), but are extended from 2100 to 2150, utilising the longer-range probabilistic projections of Kopp *et al*. (2014). Further, an adjustment has been made for ocean waters around New Zealand, where climate-ocean models have shown that SLR in our Pacific region will be somewhat higher than the global average rise – with IPCC projections couched in terms of the global average. The adjustment built into the New Zealand scenarios, for the regional ocean around New Zealand, is up to 0.05 m by 2100 for the higher RCP scenarios. A lesser pro-rata increment applies for the lower concentration RCPs.

The Coastal Guidance also listed a table of the time periods for which particular increments of SLR (relative to the 1986-2005 baseline) could be reached for the four different scenarios (Table 8-2). This information on time brackets can be applied to low-lying coastal areas, once the adaptation threshold SLR is known and agreed on from hazard and risk assessments, beyond which outcomes are not tolerable. All the details on developing firstly, hazard and risk assessments, then adaptation plans using the SLR scenarios, are available in the Coastal Guidance and Appendices (MfE 2017).

Table E-1, Appendices of MfE (2017) lists local values of sea level to use around New Zealand for the baseline (generally the 1986-2005 average MSL), to which the SLR projections are added - being 0.015 m NVD-55 for the Marlborough region when adding future SLR projections from Table 8-2 or Figure 8-5.

Figure 8-5 shows the projected SLR for the four scenarios (MfE, 2017). Due to the closeness of trajectories between the high and low projections in the near term, it is not possible to distinguish which path New Zealand SLR measurements will follow and may require another 1–2 decades of monitoring to conclusively determine which RCP trajectory applies. But, SLR trajectories (relative to the RCP scenarios) may change again in the future if polar ice-sheet instabilities emerge later this century and/or global emissions continue to track high or indeed global emissions may be substantially reduced if the 2015 Paris Agreement is adhered to. This future uncertainty is the reason why the Coastal Guidance (MfE 2017) recommends the use of all four SLR scenarios to plan for and test adaptation options in an adaptive planning framework.

[5] http://www.mfe.govt.nz/publications/climate-change/preparing-coastal-change-summary-of-coastal-hazards-and-climate-change
[6] http://www.mfe.govt.nz/publications/climate-change/preparing-coastal-change-fact-sheet-series

Table 8-2: Approximate years, from possible earliest to latest, when specific sea-level rise increments (metres above 1986–2005 baseline) could be reached for various projection scenarios of SLR for the wider New Zealand region. The earliest year listed is based on the RCP8.5 (83rd percentile) or H^+ projection and the next three columns are based on the New Zealand median scenarios, with the latest possible year assumed to be from a scenario following RCP2.6 (median), which approximates the fully globally-implemented Paris Agreement. Source: Table 11 in MfE (2017). Note: year for achieving the SLR is listed to the nearest five-year value.

	Approximate year for the relevant New Zealand-wide SLR percentile scenario to reach increments of SLR (relative to baseline of 1986–2005)			
SLR (m)	Year achieved for RCP8.5 H^+ (83%ile)	Year achieved for RCP8.5 (median)	Year achieved for RCP4.5 (median)	Year achieved for RCP2.6 (median)
0.3	2045	2050	2060	2070
0.4	2055	2065	2075	2090
0.5	2060	2075	2090	2110
0.6	2070	2085	2110	2130
0.7	2075	2090	2125	2155
0.8	2085	2100	2140	2175
0.9	2090	2110	2155	2200
1.0	2100	2115	2170	>2200
1.2	2110	2130	2200	>2200
1.5	2130	2160	>2200	>2200
1.8	2145	2180	>2200	>2200
1.9	2150	2195	>2200	>2200

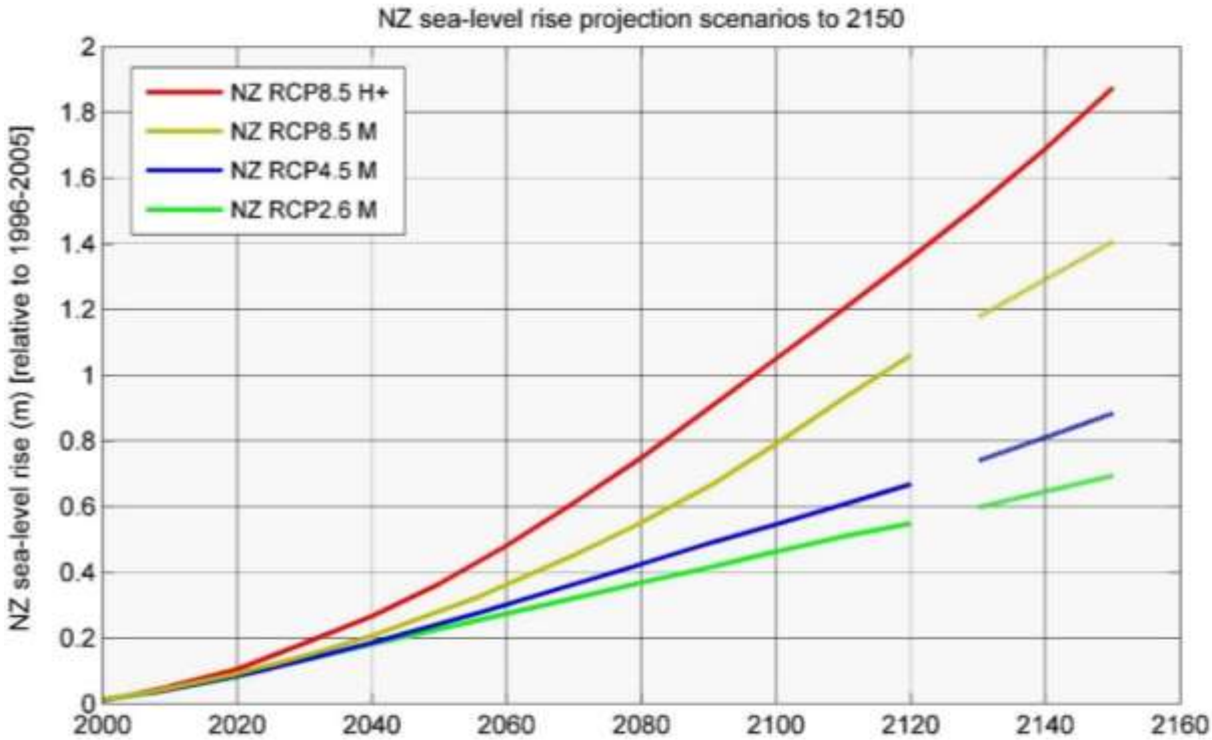


Figure 8-5: Four scenarios of New Zealand-wide regional SLR projections, with extensions to 2150. Based on Kopp *et al.* (2014)-K14. New Zealand scenario trajectories are out to 2120 (covering a minimum planning timeframe of at least 100 years), and the NZ H+ scenario trajectory is out to 2150 from K14. No further extrapolation of the IPCC-based scenarios beyond 2120 was possible, hence the rate of rise for K14 median projections for RCP2.6, RCP4.5 and RCP8.5 are shown as dashed lines from 2130, to provide an indication of the extension of projections to 2150. Note: All scenarios include a small SLR offset from the global mean SLR for the regional sea around New Zealand. Source: Figure 27, MfE (2017).

8.5 Tides and the effect of rising sea-level

8.5.1 Mean Spring tide levels

The present-day high tide marks are updated regularly by LINZ on their web site[7]. The Mean High Water Spring (MHWS) marks are shown in Table 8-3, after converting from CD (LINZ) to LVD using Table 8-1. The tide marks are based on averages of all spring tides in the 19-year forward period (1 January 2000 - 31 December 2018) using a set of tidal harmonic constituents extracted from the Picton data record.

Table 8-3: Tidal levels at Picton. Metres relative to chart datum. Source: https://www.linz.govt.nz/sea/tides/tide-predictions/standard-port-tidal-levels. MHWS = Mean High Water Spring, MHWN = Mean High Water Neap, MLWN = Mean Low Water Neap, MLWS = Mean Low Water Spring.

Standard Port	MHWS	MHWN	MLWN	MLWS	Mean spring range	Mean Sea Level
Picton	1.60	1.08	0.57	0.12	1.48	0.85

[7] https://www.linz.govt.nz/sea/tides/tide-predictions/standard-port-tidal-levels

At the Port of Marlborough (Picton), NIWA calculated that the Mean High Water Perigean Spring (MHWPS) mark is 1.59 m CD = 0.91 m NVD-55. The MHWPS value is the sum of the M2+S2+N2 tidal constituents generated with the U-tide solver (Codiga, 2011) from the 2-year Picton sea-level record (1 January 2019 - 1 December 2020). The values we calculated differ slightly from the LINZ website referenced above due to the variation in the time period used for the prediction of both the tidal prediction, the associated tidal constituents, and the manner in which the MHWPS value is derived (Bell & Lewis, 2006).

8.5.2 High-tide exceedances and effect of SLR

The full range of possible high tides (excluding weather, climate and SLR influences) was predicted over 100 years, covering all possible tidal combinations, based on tidal harmonic constituents fitted to a 2-year-long sea-level record (1 January 2019 - 1 December 2020) using a set of tidal harmonic constituents extracted from the Picton sea-level record. This was undertaken using the U-Tide Matlab package which undertakes tidal harmonic analysis (Codiga, 2011). Highest Astronomical Tide (HAT)[8], Lowest Neap High Tide (LNHT) and High Tide Range are shown in Table 8-4 and Table 8-5. The tide marks (HAT and LNHT) are based on values extracted from all spring tides generated from the predicted 100-year period. The values we calculated differ slightly from the LINZ website referenced in Table 8-3 above, due to the variation in the time period used for the prediction of both the tidal amplitudes and the associated tidal constituents. The resulting high-tide distribution curve is shown in Figure 8-6 (lower curve), in the form of a cumulative frequency of occurrence of high waters (also known as a high-tide exceedance nomograph) and with levels relative to LVD.

Table 8-4: High-tide values from 100-year tidal predictions for Picton. Values are obtained from the tidal harmonic analysis and include no datum offset, i.e. relative to MSL = 0.

Standard Port	Highest Astronomical Tide	Lowest Neap High Tide	High Tide Range
Picton	0.895 m (RMSL)	0.0879 m (RMSL)	0.81 m

Table 8-5: High-tide values from 100-year tidal predictions for Picton. Datum offsets from Table 8-1 have been added to the predicted tidal heights.

Standard Port	Highest Astronomical Tide	Lowest Neap High Tide	High Tide Range
Picton	1.068 m (NVD-55) 0.749 m (NZVD-2016) 1.745 m (CD)	0.261 m (NVD-55) -0.0581 (NZVD-2016) 0.938 m (CD)	0.81 m

Several high-tide definitions are shown in Figure 8-6 (relative to LVD), including the Mean High Water Perigean Spring (MHWPS)[9] and the Mean High Water Spring 10 (MHWS-10). Measuring 0.71 m (RMSL), the MHWS-10 is the high tide level above which only 10% of all predicted high tides exceed it for the present-day situation. MHWS-10, which can be consistently defined around the New Zealand coast, was used in the recent national coastal risk exposure study for the Parliamentary Commissioner for the Environment (PCE) in 2015 (Bell *et al*., 2015; PCE, 2015).

Putting aside storm events, SLR will continually lift the base MSL, on which the tide rides, which will result in an increasing percentage of normal high tides which exceed a given present-day elevation

[8] Sometimes called the Maximum High Water (Max HW)

[9] Perigean spring tides, also called "king" tides, occur around full or new moon, when the moon is closest in its monthly orbit around Earth (at its perigree). Small to moderate storm surge or waves can combine with these higher perigean spring tides to cause coastal flooding.

e.g., street level, berm or stopbank crest or present MHWS-10. Figure 8-6 shows the effect of changing high-tide inundation using two example SLR values of 0.65 m and 1.0 m SLR (Table 8-2 indicates that 0.65 m SLR would arise between 2070-2155, while the latter between 2100 to >2200). Based on the example of the present-day MHWS-10 level, which is exceeded by only 10% of all high tides (tide-only), a 0.65 m SLR will mean that same ground or tidal elevation would be exceeded by every high tide. In addition, the present-day HAT would be exceeded by approximately 93% of all high tides under the 0.65 m SLR scenario. These results exclude the influence of weather and storm surges on water level and assume the tidal characteristics for Picton do not change substantially – rather they focus just on normal upper tidal inundation levels as seas rise.

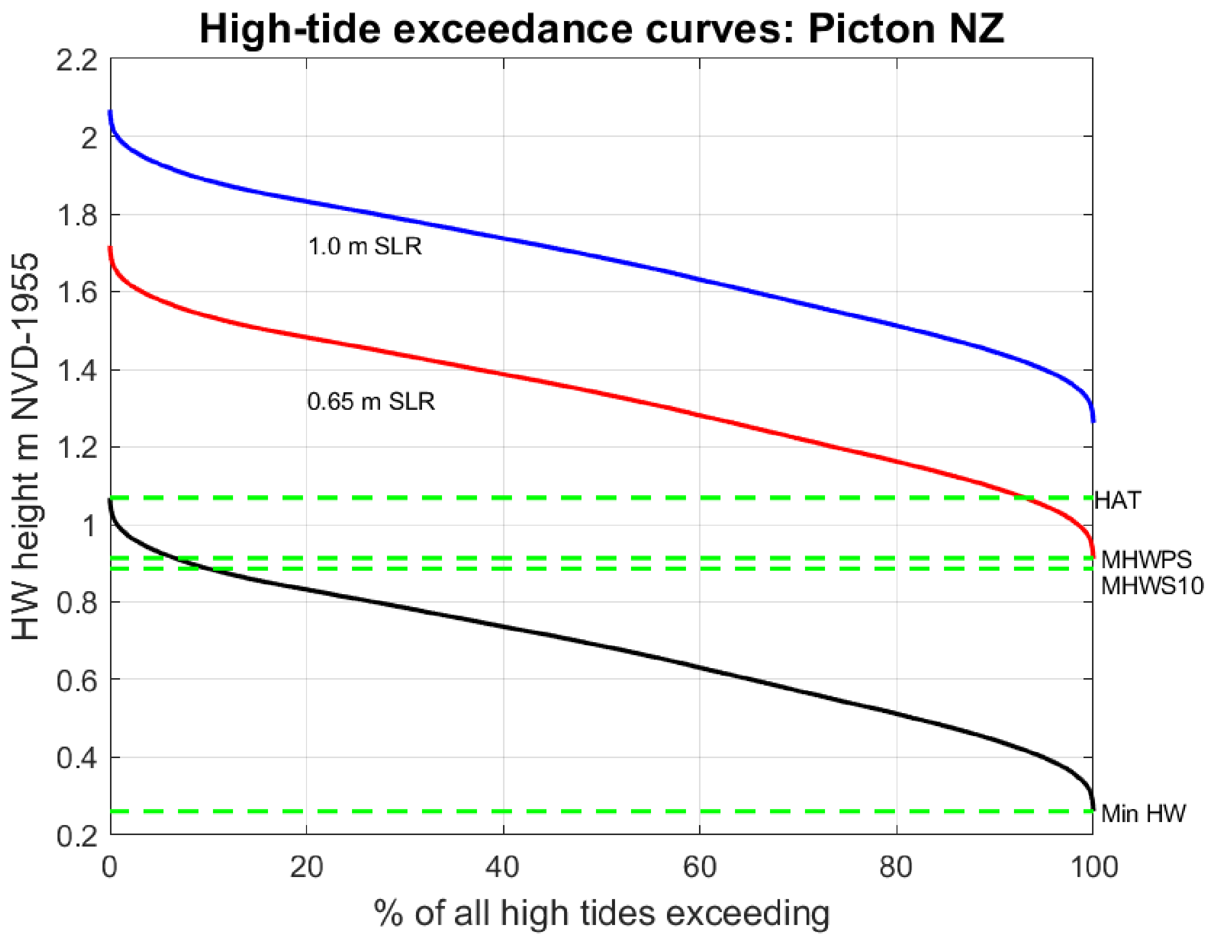


Figure 8-6: High-tide exceedance curve for all predicted high tides at Picton (excluding effects of weather, climate and SLR). Tidal exceedance levels are based on the on tidal constituents extracted from the Picton gauge dataset provided by LINZ (2017-2020), relative to NVD-1955 including 0.173 MSL offset, and processed by NIWA to predict all high tides over a 100-year period (excluding SLR for the heavy black line). Red and blue lines show high-tide exceedance curves for a sea-level rise of 0.65 and 1.0 m, respectively.

9 Impacts and implications from climate change in Marlborough

9.1 River flows

Key messages

- Mean annual discharge generally remains stable or slightly increases by mid-century across northern Marlborough. By late century, a similar spatial pattern of increase in mean discharge is identified in northern Marlborough, however there is a decrease in mean discharge within the headwaters of the Acheron River.
- Mean annual low flow is expected to decrease across the region by mid-century. This pattern is confirmed by late century, with decreases exceeding 50% for most of the river systems in the region.

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 hydrological 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 hydrological modelling analyses presented here were extracted from a national scale assessment (Collins & Zammit, 2016; Collins *et al*., 2018). The statistics included in this report are:

- Mean annual discharge;
- Mean annual low flow;

Projected changes to high flows, river flood levels and associated inundation maps for all New Zealand is the subject of a new 5-year research project. Interested readers of this report are asked to contact NIWA for more information.

9.1.1 Mean annual discharge

The projected future differences in the mean annual discharge for RCP4.5 and RCP8.5 at two future time periods are presented in Figure 9-1 for Marlborough. At the annual scale, mean discharge across the Marlborough region remains relatively stable by mid-century across both RCPs with a slight increase in mean annual discharge close to the northeastern coast under RCP4.5. The end of the century is characterised by a similar spatial pattern of mean annual discharge changes. The headwaters of the Acheron and Awatere rivers are likely to experience a decrease in mean discharge (up to 20% reduction) across both RCPs.

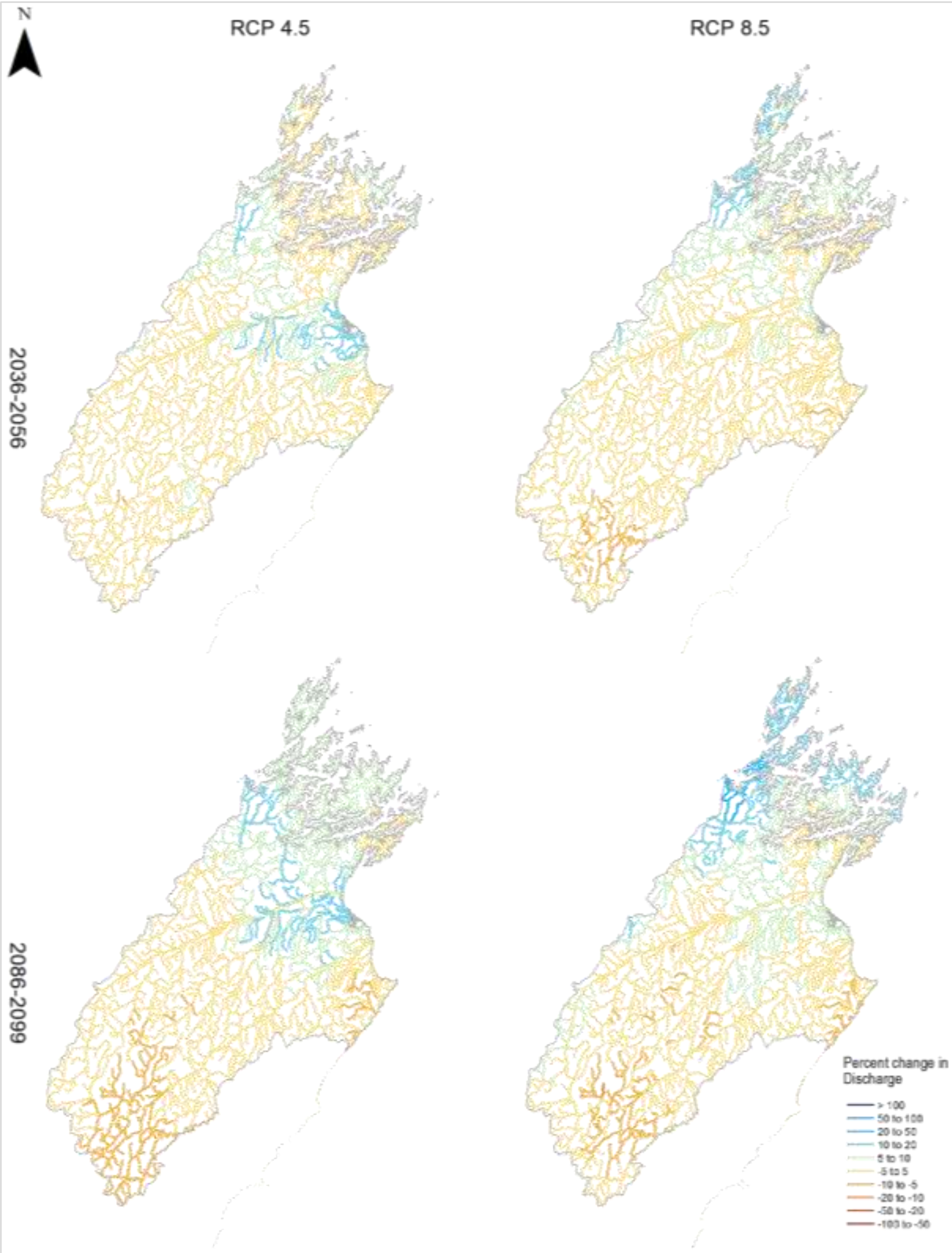


Figure 9-1: Percent changes in multi-model median of the mean discharge across Marlborough for mid (top) and late-century (bottom). Climate change scenarios: RCP4.5 (left panels) and RCP8.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

9.1.2 Mean annual low flow

Mean annual low flow (MALF) is defined as the mean of the lowest 7-day average flows in each year of a projection period. Median projected changes in the MALF are presented for RCP4.5 and RCP8.5 for two time periods in Figure 9-2 for Marlborough. At the annual scale, MALF decreases across both RCPs by mid-century across the Marlborough region with the area north of the Wairau River projected to experience large changes. Changes to Wairau River flows may impact adversely on the Wairau Aquifer, as the aquifer relies on river flows for recharge (Marlborough District Council, 2021). By the end of the century, the projected decrease in MALF is accentuated, with the decreases exceeding 50% for nearly all the Marlborough region, particularly under RCP8.5.

Seasonal winter snowfall comprises an important component of summer discharge in some Marlborough catchments. As described in Section 2.3, water storage in the snowpack is accounted for in this assessment. However, the cryospheric model parametrisation is carried out at the national scale and does not take account of specific cryospheric interactions at the regional or sub-regional scale. The national scale parametrisation (described in Hendrikx *et al.,* 2012) might not be representative of the Marlborough region.

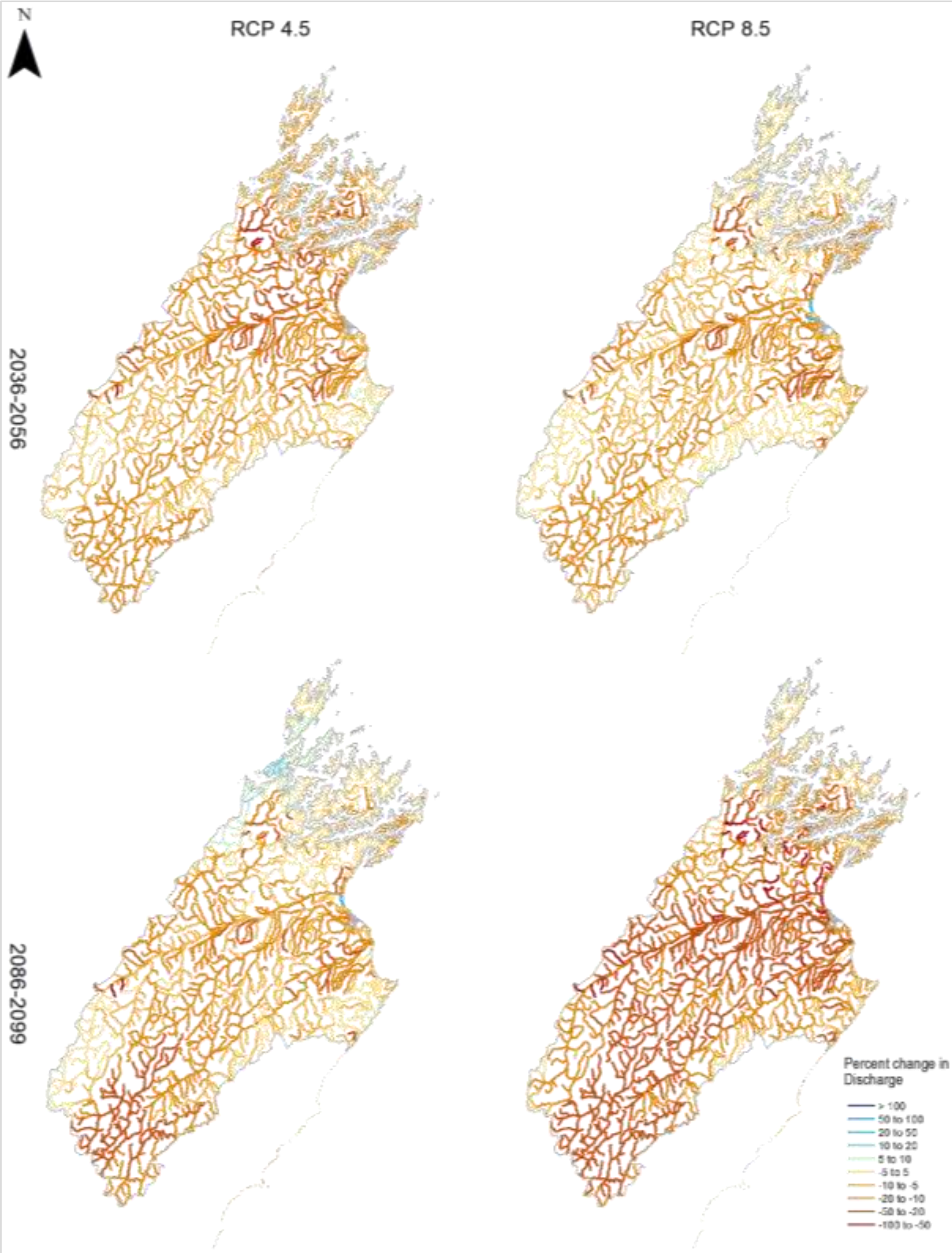


Figure 9-2: Percent changes in multi-model median of the mean annual low flow (MALF) across Marlborough for mid (top) and late-century (bottom). Climate change scenarios: RCP4.5 (left panels) and RCP8.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

9.2 Impacts of drought and future pasture growth

It is likely that much of Marlborough will experience more frequent and severe drought conditions in the future than at present, with larger potential evapotranspiration deficit accumulations and more days of soil moisture deficit (discussed in Section 6). Drought can have significant impacts on primary industries in Marlborough.

For primary production, rainfall is one of the most important climate drivers, as there are limits (both too much and not enough water) where plants cease to grow or experience harm. When other climatic factors are not limiting, precipitation levels within these limits can have a direct and proportional relationship to productivity (Clark *et al*., 2012). Changes in rainfall patterns are important when considering future yield variability of crops and pasture grass. This is because crops respond to both amounts and timing of water supply in relation to demand.

Low rainfall (and therefore drought) can limit crop and grass growth in different ways. When water supply is less than demand, crop and grass yield is mainly reduced by limited canopy expansion and increased leaf aging, thereby decreasing sunlight interception, and reduced photosynthesis rates due to stomatal closure (Clark *et al*., 2012). In pasture grasses, legumes, and maize, reductions in plant growth are manifested by reduced leaf appearance and extension rates, as well as increased tiller (shoot) and plant mortality. The extent of reduction in growth depends on factors such as the severity and duration of the water deficit as well as the plant species, as some species are more sensitive to water deficits than others.

A plant's demand for water and its sensitivity to water stress varies throughout the plant's annual cycle. Therefore, timing of drought is critical: drought in late summer when plants have largely completed growth does not have the devastating impact of late winter/early spring drought that prevents achievement of full productive potential (McGlone *et al*., 2010).

For fruit, rainfall can have positive or negative effects. Girona *et al*. (2006) found that for grapes, the best fruit-quality parameters were obtained when plants were well watered for the first part of the growing seasons, but then deficit irrigated until harvest to avoid excess vegetative growth. While rainfall in spring and early summer provides needed water and reduces irrigation costs, rainfall later in the season can reduce fruit (and therefore wine) quality. In other fruit crops, similar principles apply. Miller *et al*. (1998) found that the main effect of early-season water stress on kiwifruit was to reduce vine yields, so rainfall early in the season has demonstrable benefits. Deficit irrigation late in the season had little impact on yield, but did improve fruit quality.

Primary industries may turn towards increased irrigation as a method for dealing with increased incidence of drought (Clark *et al*., 2012). However, this approach may not be suitable depending on the future changes to rainfall and availability of water for irrigation.

The effect of increased carbon dioxide levels on plants under limited water supply may help with the effects of drought. Under limited water supply conditions, the effect of carbon dioxide fertilisation is more evident. Higher carbon dioxide concentrations reduce the loss of water vapour through leaf transpiration and, therefore, improve the water use of crops (Leakey *et al*., 2009, Clark *et al*., 2012). The faster growth of plants due to carbon dioxide fertilisation may enable plants to avoid exposure to late-season droughts. However, extreme heat and severe drought (deficits of around two to three weeks in duration) override the effect of carbon dioxide fertilisation in pastures and crops (Clark *et al*., 2012).

Temperature will also influence the seasonality of pasture growth in Marlborough. Warmer winter and spring periods will allow for increased seasonal growth rates, however growth during summer may be suppressed due to temperatures being too hot and water availability being limited (Clark *et al*., 2012).

9.3 Forestry

Climate change-induced hazards, such as changes in the temperature, rainfall and carbon dioxide concentration, could impact natural and modified forests substantially (Kirilenko and Sedjo, 2007, FAO, 2018). The possible impacts of climate change on forests include, but are not limited to, shorter or longer growing seasons, modifications in the forest's biodiversity including its macro and microbiota, changes in the pests and disease factors and their spread pattern, and increase of bushfire frequency (FAO, 2018; Kirilenko and Sedjo, 2007; Whitehead *et al*., 1992).

New Zealand's forestry, as the nation's third-largest export sector, has been impacted by global and local hazards induced by a changing climate, and the impacts are expected to continue or accelerate under the future scenarios of climate change (MPI, 2018; Watt *et al*., 2019; Whitehead *et al*., 1992). Research indicates there are potential impacts of climate change on New Zealand's natural and plantation forests such as: alteration in the forest productivity due to an increase in the growth rate, more wind-related damage, amplified bush fire risk (very high to extreme), and a possible surge in the pest and weed population (Watt *et al*., 2019). Forestry is an important sector for Marlborough and was seen as a suitable land use for large tracts of unproductive land, to promote soil stabilisation and generate funding from logging (Marlborough District Council, 2020).

Increases to temperature and changing rainfall patterns could negatively influence *P. radiata* productivity. However, the effect of increased carbon dioxide fertilisation is modelled to outweigh these negative impacts, significantly increasing *P. radiata* productivity across New Zealand by 2040 and 2090 some 19% and 37%, respectively (Watt *et al*., 2019). Note, the extra growth caused by carbon dioxide fertilisation may make trees more susceptible to wind damage.

Extreme rainfall intensity, as discussed earlier in this report, is likely to increase in Marlborough. This may have implications for the forestry sector through exacerbating erosion, landslides, movement of slash, and impacts on access to forests for trucks and machinery. Such impacts may be more prominent in recently harvested forestry sites, as harvesting practices can cause soil compaction (Ares *et al.*, 2005), which in turn decreases the water infiltration capacity of the soil (Viglione *et al.*, 2016). In contrast, severe droughts are likely to become more frequent for the region, which may have implications for forestry through reducing water availability for trees and increasing fire risk.

Fire risk is projected to increase in the future in New Zealand, due to the following conditions (Pearce *et al*., 2011):

- Warmer temperatures, stronger winds, lower rainfall and more drought for some areas will exacerbate fire risk. Note that projected changes to mean wind speed for Marlborough are generally small at the annual scale, with greater change projected at the seasonal scale (e.g. larger increases to mean wind speed during winter and spring). Further work is needed to evaluate changes to wind at the regional scale;
- The fire season will probably be longer - starting earlier and finishing later;
- Potentially more thunderstorms and lightning may increase ignitions;

- Fuel will be easier to ignite (because of increased drying due to increased evapotranspiration/less rainfall); and
- Drier conditions (and possibly windier periods) may result in faster fire spread and greater areas burned.

The following projections for fire risk are based on the IPCC Fourth Assessment Report emission scenarios (Pearce *et al*., 2011). For Seasonal Severity Rating (SSR)[10], the 17-model average projection shows minimal change for Nelson Aero (a representative climate station for the Wellington – Nelson/Marlborough Fire Climate Region) by the 2050s (2040-2059) compared to the 1980-1999 historical period. Similar patterns were observed for the 2080s (2070-2089). The average SSR over fire season months (October-April) for Nelson Aero is projected to increase from 2.05 over the historical period to 2.40 in the 2050s and 2080s.

The number of days of Very High and Extreme (VH+E) forest fire danger is projected to increase for Nelson Aero by the 2050s and the 2080s compared to 1980-1999. The historical number of VH+E forest fire danger days for Nelson Aero is 8.9 days, and this is projected to increase to 12.3 days in the 2050s and 12.5 days in the 2080s. Note that some individual models project a higher increase in Very High and Extreme forest fire danger days, as noted by Reisinger *et al*. (2014). The reader is directed to Pearce *et al*. (2011) for more information on the projections of Seasonal Severity Rating and Very High and Extreme forest fire danger days in New Zealand.

Pest species are likely to shift to new habitat areas due to climate change. Increasing average temperatures and changing rainfall patterns across the country may make conditions more suitable for climate-limited tree pathogens such as pitch canker (currently present in northern coastal areas). Insect pests may become more of an issue for forestry plantations with climate change, as the major limiting factor for most insect pests is cold stress. Therefore, subtropical insect pests may be able to establish in a warmer New Zealand in the future, and existing insect pests may increase their distribution within New Zealand. Climate change may also affect the severity of damage from existing insect pests because warmer temperatures can be expected to accelerate insect development and therefore lead to an increase in population levels, especially in species that can complete more than one generation per year (e.g. the Monterey pine aphid *Essigella californica*).

Increasing competition with weeds is also a concern for the forestry industry. New Zealand's future climate may become more suitable for some weeds which are already established in some parts of New Zealand but have not spread, so-called "sleeper weeds" (Kean *et al*., 2015). An example of this is *Melaleuca quinquenervia,* an exotic tree that is currently established in Auckland and Northland. If the species' thermal requirement for reproduction is reached with a warming climate, this could become quite invasive and difficult to control. Also, woody tree species that are native to Australia (e.g. *Acacia spp.*) have very high growth rates and vigorously compete with *P. radiata* seedlings. As tree species, they can compete further into the plantation rotation than other weed species which are predominantly shrubs. Wilding conifers have become a significant threat to New Zealand's ecosystems, covering more than 1.8 million hectares and spreading at a rate of 5% annually (Greene *et al.*, 2020). The climate change impacts on the distribution of wilding pines in NZ has not yet been

[10] Seasonal Severity Rating (SSR) is a seasonal average of the Daily Severity Rating (DSR), which captures the effects of both wind and fuel dryness on potential fire intensity, and therefore control difficulty and the amount of work required to suppress a fire. It allows for comparison of the severity of fire weather from one year to another. Source: http://www.nrfa.org.nz/OperationalFireManagment/ResourceLibraries/AlertsAndNotices/Documents/Seasonal%20Fire%20Danger%20Outlook_North%20Island.pdf

thoroughly researched. However, without large scale funding and control it is estimated 20% of New Zealand will be covered by wilding conifers within 20 years (DOC, 2021). Given the rapid spread of wilding conifers, modern technology such as remote sensing (e.g. Greene *et al.*, 2020) may become a critical tool to identify wilding conifer distributions.

Overall, there are several potential impacts on the forestry sector from climate change. Tree growth may be more vigorous due to increasing concentrations of carbon dioxide in the atmosphere and warmer temperatures, but this may be counteracted by reduced water availability and risk of fire. Forestry operations may be negatively affected by increasing rainfall intensity causing more erosion, flooding, and site access issues, as well as more frequent and prolonged droughts as well as fire risk which may affect safety of workers.

9.4 Horticulture

The horticulture industry is likely to be subject to increasing impacts of climate change over time (MPI, 2012). The production of horticultural crops (including grapes) is projected to be influenced by changes in precipitation patterns, temperature variability, and greenhouse gas concentrations (MPI, 2012). For example, temperature rise, either annual or seasonal, alters the evaporation rate, hydrological cycles of the catchment, and water availability; therefore, influencing the quality and quantity of horticultural products (Rehman *et al*., 2015). Table 9-1 shows a snapshot of the potential impacts of climate change on some horticultural products.

Table 9-1: Overall impacts of climate change on the main horticultural crops in NZ. Source: Clothier *et al.* (2012).

	Apples	Grapes	Kiwifruit
Temperature			
Temperature means ↑	Yield ↑ Quality ↑ Disease risk ↑ Sunburn ↑	Yield ↑ Quality ↑ Disease risk ↑	Yield ↓ Quality ↑ (and ↓) Disease risk ↑
Temperature extremes Frost ↓ Heatwaves ↑	Frost damage ↓	Frost damage ↓	Frost damage ↓
CO_2 ↑	Biomass ↑	Biomass ↑	Biomass ↑
Rainfall variability ↑↓	Irrigation ↑	Irrigation ↑ Drought risk ↑	Irrigation ↑
Water quality	Leachate load ↓	Leachate load ↓	Leachate load ↓
Extreme events Hail ~ Wind ~	Damage to fruit ~ Damage to trees ~	Damage to fruit ~ Damage to vines ~	Damage to fruit ~ Damage to vines ~
Combined impacts ~	↑ unless pest & disease impacts override	↑ unless pest & disease impacts override	↑↓

In Marlborough, the top horticultural crop by area is wine grapes. Several statistics below highlight the significant contribution the region makes to New Zealand's wine industry:

- As at 2020, the area of Marlborough planted with wine grapes was 27,808 hectares, representing approximately 70% of the total area of planted wine grapes in New Zealand (New Zealand Winegrowers, 2020).

- Marlborough produced 295,301 tonnes of Sauvignon Blanc in 2020 (Wine Marlborough, 2020), which was 91% of the total for that variety in New Zealand. Furthermore, this represents 65% of New Zealand's total for all grape varieties (Wine Marlborough, 2020; New Zealand Winegrowers, 2020).

Increasing temperatures will impact all types of crops, as plant phenological development may occur at a faster rate. Different stages of plant growth (e.g. bud burst, flowering, and fruit development) may happen at different times, which may affect the harvested crop. For example, the hottest summer on record for New Zealand in 2017/18 saw wine grapes in multiple New Zealand regions ripen faster than usual, including very early Sauvignon Blanc wine-grape maturation in Marlborough (Salinger *et al*., 2019). In Central Otago, this resulted in the earliest start to harvest of Pinot Noir grapes on record (almost a month earlier than usual). In Wairarapa, the period from flowering to harvest for wine grapes was about 10 days shorter than usual[11]. Although the end date for frosts are projected to occur earlier in the year on average (Section 4.5.1), frosts will likely remain a risk to crop development.

Extreme heat affects the rate of evapotranspiration, or the uptake of water by plants. Therefore, increases to extreme heat may affect water availability, as under hot conditions, plants use more water. Extreme heat may also result in current varieties of crops and pasture becoming unsustainable if they are not suited to growing in hot conditions. Extreme heat may also affect fruit quality, such as sunburn on apples and kiwifruit, and 'shrivelling' of grapes (Clothier *et al*., 2012). The projected increase in diurnal temperature range may have implications for crops in Marlborough. In the case of grapes, warmer daytime temperatures foster sugar development, while cool nights help to preserve aromas, freshness and acidity (Douglas, 2019). As a result, changes to Marlborough's diurnal temperature range may alter the characteristics of the grapes grown in the region.

Reductions in cold conditions may have positive impacts for diversification of new crop varieties that are not able to currently be grown in Marlborough. For example, certain crops (e.g. kiwifruit) are currently grown in warmer parts of New Zealand such as Bay of Plenty, and other crop species are currently not grown in New Zealand at all. In the future, with a warmer climate, there may be opportunities for growers in Marlborough to take advantage of the overall warmer climate to diversify their crops. However, future warmer temperatures may create issues for horticulture in the region. The increasing risk from pests (plants and animals) and diseases is a concern. Currently, many pests are limited by cold conditions, so that they cannot survive low winter temperatures, and therefore their spread is limited (Kean *et al*., 2015). Under a warmer climate, these pests may not be limited by cold conditions and therefore cause a larger problem for farmers and growers in Marlborough.

Increased prevalence of drought and longer dry spells in Marlborough will likely have impacts on water availability for irrigation and other horticultural uses. The amount of irrigation may need to increase to maintain productivity, however this may be limited by future water availability. Should water availability become increasingly problematic, increased investment in storage options may be required. More frequent and severe droughts may negatively affect horticultural productivity, particularly for crops that require larger quantities of water. Soils may be more exposed to wind erosion with increasing drought severity. With ongoing risk of wildfire, smoke taint may be an issue for crops such as wine grapes (Mira de Orduña, 2010).

[11] https://michaelcooper.co.nz/2018-regional-vintage-overview-report/

Increases in extreme rainfall event magnitude and frequency may impact horticulture in several different ways. Slips on hill country land may become more prevalent during these events (Basher *et al*., 2012), and soils may become waterlogged more often. This has impacts on the quality of soil for horticulture, the area of land available for production, and other impacts such as sedimentation of waterways (which can impact flooding and water quality). Slips may also impact transport infrastructure (e.g. roads, farm tracks) which may, in turn, affect the connectivity of farms and orchards to markets. Heavy rain at harvest times for fruit may cause a decline in fruit quality, with skins splitting and increased prevalence of diseases.

Overall, climate change impacts on horticulture in Marlborough are likely. Increasing temperatures may provide opportunities for new crop types to be grown in the area but this may also cause issues for some existing crop types and encourage the spread of new pests. Droughts are likely to cause significant issues for the sector in terms of water availability for irrigation and resulting productivity. However, increasing rainfall intensity is likely to have impacts on soil erosion, sedimentation, and saturation of soils.

9.5 Ecosystem health

The impact of climate change on terrestrial, aquatic and marine ecosystems has been the subject of much research in the past couple of decades (Brodie and Pearson, 2016, Rapport *et al*., 1998, Wang and Cao, 2011, Malhi *et al*., 2020). Climate change is expected to be a stressor on terrestrial, freshwater, coastal and marine ecosystems, particularly under high-warming scenarios. For example, wetlands are highly sensitive areas and are amongst the most threatened ecosystems in New Zealand. In the future, wetlands will be threatened by changes to rainfall patterns, drought and surface and groundwater hydrology. Wetlands close to the coast will also be at risk from sea-level rise (inundation and erosion) and changes to the salinity of groundwater which may impact the distribution and assemblage of species. Although many of New Zealand’s ecosystems are being degraded due to climate change-oriented hazards, some of them, such as alpine, freshwater and coastal ecosystems, are more vulnerable than others (DOC, 2020). For example, rising sea level, coastal inundation and flooding may lead to the loss of habitat for coastal and estuary species, which could cause an interruption in the food chain for a wider range of biodiversity (DOC, 2020).

Climate change hazards could impact the ecosystem’s health from two different, but interrelated aspects including: biodiversity and habitat loss, and pests and biosecurity issues.

9.5.1 Native biodiversity (terrestrial, aquatic and marine biodiversity)

Climate change is continuously impacting all aspects of biodiversity on the planet, from terrestrial to marine ecosystems and biodiversity. Anthropogenic climate change is already impacting 19% of threatened species recorded in the IUCN Red List, and pushing them toward extinction (IUCN, 2019). Climate change-induced hazards, such as temperature rise, have significant impacts on native biodiversity, including their abundance, behaviour and genetic properties (IUCN, 2019). Changing the features of the food chain, increasing invasive species, habitat loss, and ocean acidification are only a few examples of climate change impacts that threaten native biodiversity, both globally and in New Zealand (Christie, 2014). For example, changes in temperature and rainfall, and sea-level rise, are expected to lead to secondary effects, including erosion, landslips, and flooding, affecting coastal habitats and their dependent species, for example, loss of habitat for nesting birds.

About 4000 of New Zealand’s threatened species are pushed towards the brink of extinction, partly due to climate change (MFE, 2019). Many indigenous New Zealand species are already and will be at further risk from climate-related impacts such as river water abstraction for irrigation (in response to reductions in rainfall and higher drought incidence), hydroelectric power schemes (a potential mitigation response to greenhouse gas emissions), and non-climate-related impacts such as predation, habitat loss and fragmentation from land use change, urban area and infrastructure expansion, and pollution (McGlone and Walker, 2011). Many species will be at risk from new and existing pests that are able to colonise and spread further in New Zealand because of climate change (Kean *et al*., 2015).

The direct responses of terrestrial biodiversity to future climate changes will be challenging to predict, due to uncertainty about climate projections, species' responses to climate change and the ability of species to adapt (McGlone and Walker, 2011; Christie, 2014). This is particularly because of the existing pressures of invasive species and human-related habitat loss on native biodiversity. The capacity of native species and ecosystems to adapt to a changing climate is unknown, especially given New Zealand's oceanic setting and existing highly variable climate regime. However, the indirect responses of terrestrial biodiversity to climate change can be predicted with more certainty. Indirect impacts involve the exacerbation of existing invasive species problems and human-related threats, such as habitat loss (Christie, 2014). Land use and land management practice change in anticipation of climate change may result in further restrictions of native species abundance and distribution.

The New Zealand National Climate Change Risk Assessment (AECOM *et al*., 2020) highlights the ten most significant climate change risks to New Zealand, based on urgency. Two of the top ten are in the 'natural environment' domain, with 'major' consequence ratings and urgency scores greater than 70. They are:

- Risks to coastal ecosystems, including the intertidal zone, estuaries, dunes, coastal lakes and wetlands, due to ongoing sea-level rise and extreme weather events; and
- Risks to indigenous ecosystems and species from the enhanced spread, survival and establishment of invasive species due to climate change.

Ten other risks in the natural environment domain were identified which incorporate most ecosystem types in New Zealand and a range of climate-related impacts.

Some mitigation aspects of climate change might have negative impacts on terrestrial biodiversity. Afforestation with exotic tree species (e.g. *Pinus radiata*) may lead to reductions in catchment water yield, with negative impacts on streamflow and freshwater biodiversity, stabilisation of previously dynamic systems (e.g. pines on coastal dunes) with consequent loss of indigenous flora, invading areas where the native forest was either absent or limited and creating flammable forest communities (McGlone and Walker, 2011). The conversion of native scrub and shrubland to forestry may also cause the direct loss of native ecosystems.

Changes to rainfall patterns and river flows, as well as the human impact of greater abstraction of freshwater for irrigation and increasing storage (in the form of reservoirs) for hydroelectricity and urban water supply, will lead to impacts on freshwater ecosystems (Parliamentary Commissioner for the Environment, 2012). The role of floods in New Zealand rivers is extremely important for maintaining ecological integrity, so changes to the hydrological regime may have dramatic impacts on biological communities (Death *et al*., 2016; Crow *et al*., 2013). Altered natural flow patterns may result in invasive predators gaining increased access to habitats crucial for sensitive life cycle stages (e.g. islands in river channels used by nesting birds) and changes in habitat type, and some aquatic species (e.g. invertebrates) are likely to be impacted more than others, depending on their life cycles (McGlone and Walker, 2011). Habitat size, availability and quality may be reduced for some species, and drought may threaten already isolated fish and invertebrate populations.

Egan et al. (2020) carried out a climate change vulnerability assessment for freshwater taonga species in New Zealand. Increasing risk of drought is likely to have negative impacts on several taonga species found in Marlborough, for example tuna (longfin eel), due to changes in habitat availability. The timing of seasonal rainfall and changes to river levels may affect īnanga (whitebait) reproduction cycles. Increasing water temperature may be beneficial in the cooler part of the year for tuna (shortfin eel), because feeding activity increases when temperatures exceed 12°C. However, changes to temperature regimes throughout the year may impact environmental cues for spawning for a number of species including giant kōkopu (whitebait) and kākahi (mussels).

Sea-level rise may increase salinity at river mouths and further upstream than at present, thereby reducing freshwater habitats, particularly in short catchments. Increases in extreme rainfall intensity may lead to more sedimentation and turbidity in waterways, with consequent habitat loss. Banded kōkopu (*Galaxias fasciatus*) have been found to have reduced abundance in turbid streams, so increasing runoff and sediment flowing into streams could limit their distribution (Rowe *et al*., 2000). Other oceanic changes (e.g. changes to salinity, sea temperatures, and pH (Law *et al*., 2018) may also have an impact on diadromous fish species and their migration patterns.

Coastal lakes and lagoons are sensitive to potential climate change impacts resulting from sea-level rise, changes to inflows, rainfall and air and water temperature (Tait and Pearce, 2019). These impacts include:

- Increased sedimentation from extreme rainfall, runoff, and higher flood inflows;
- Reductions in inflows and lower water levels due to reduced rainfall and increased drought conditions;
- The water may become more brackish due to sea-level rise;
- Increased water temperature may increase the abundance of algae and algal blooms and cause heat stress for aquatic species;
- Habitat may become less suitable for aquatic and terrestrial species due to the above physical changes to the lake.

Coastal systems are particularly sensitive to three key drivers related to climate change: sea level, ocean temperature, and ocean acidity (Wong *et al*., 2014). Soft shorelines (beaches and estuaries) are likely to be more severely affected by sea-level rise than hard (rocky and consolidated cliffs) shores. Due to the extensive development near beaches, estuaries and marshes, it is unlikely that natural adjustment of the coast will be readily allowed in the future (i.e. coastal retreat and reconfiguration as sea level rises). A potential human response to sea-level rise will be by building hard barriers, protecting sand dunes, replenishing beaches, and infilling estuaries to prevent erosion and to protect property and infrastructure.

The lack of space for natural coastal adjustment is often termed *coastal squeeze.* Coastal squeeze has varying definitions, but a narrower focus is the definition by Pontee (2013): "Coastal squeeze is one form of coastal habitat loss, where intertidal habitat is lost due to the high water mark being fixed by a defence or structure (i.e. the high water mark residing against a hard structure such as a sea wall) and the low water mark migrating landwards in response to sea level rise".

Consequently, running in parallel with the impacts of climate change and sea-level rise (SLR) on coastal and estuarine/marsh systems will be the ongoing direct and indirect pressures of society's responses to climate-change adaptation (Swales *et al*., 2020). If cascading climate-change effects are not thoroughly explored and evaluated in a holistic manner, attempts to counteract the SLR impacts on the built environment and existing land-use rights (e.g. shoreline protection works, reclamations to reinstate shoreline buffers, stopbanks and alteration to drainage schemes), will invariably lead to coastal squeeze and loss of intertidal habitats and beaches (Kettles and Bell, 2015).

There are numerous examples of coastal squeeze around New Zealand as coastal erosion affects the areas around hard defences. In one such example, Figure 9-3 shows erosion next to a sea wall in Whitianga, Coromandel. In addition, the potential erosion and inundation of coastal areas caused by a significant storm event (e.g. ex-tropical cyclones) will be enhanced under future sea-level rise projections. See Paulik *et al.* (2019) for further information on national, regional and district-level risk exposure to inundation in low-lying coastal areas of New Zealand.

Figure 9-3: Erosion beside a sea wall in Whitianga. Photo: R. Bell, NIWA.

Loss of productive estuarine habitats and biota is likely to accelerate with SLR and other climate-related impacts discussed above, with the more visible ecological effects being reduced populations and altered migratory patterns of coastal birds, and declines in certain commercially-important marine fishes that use estuaries for part of their life cycle (e.g. snapper, *Pagrus auratus*) (McGlone and Walker, 2011). The effects of changes in waves and freshwater inputs will also have significant adverse impacts on coastal ecosystems (Hewitt *et al*., 2016).

Warming has been observed in coastal and oceanic waters around New Zealand over the past few decades, with the strongest warming happening off the coast of Wairarapa and the weakest warming signal between East Cape and North Cape (Sutton and Bowen, 2019). Projections for the Southwest Pacific show an increase in SST by mid- and end-century, regardless of RCP and climate model (Law *et al*., 2016). The mean increase is ~1°C by mid-century, and ~2.5°C by end-century for RCP8.5. Figure 9-4 shows the spatial variation of change in SST for end-century under RCP8.5, with surface warming across the entire Southwest Pacific. The most striking feature is the strong warming of +4°C in the western Tasman Sea (in region 2 on Figure 9-4 associated with the southerly penetration of the East Australian Current off southeast Australia in region 2 (Ridgway, 2007). The western Tasman Sea region is warming at a rate four times that of the global average as a result of the climate-driven spin-up of the South Pacific gyre (Roemmich *et al*., 2016). This warming propagates across the northern Tasman Sea (region 3) along 35°S in association with the Tasman Front, causing the most significant regional SST increase in the New Zealand Exclusive Economic Zone.

Warming oceans are likely to have impacts on the distribution of marine species as well as pests from warmer areas. For example, distribution shifts and changes in abundance of numerous fish species have been observed in the southeast Australia region due to substantial ocean warming that has already occurred there (Last *et al*., 2011). During the 2017/18 marine heatwaves in the South Island, bull kelp suffered losses in Kaikōura and was completely lost from some reefs in Lyttelton (Thomsen *el al.*, 2019). In aquaculture, heatwaves can increase mortality with associated loss of revenue (MFE & STATS NZ, 2019). In Marlborough Sounds, the 2017/18 marine heatwave impacted mussel growth and yields, and led to an algal bloom that can cause Paralytic Shellfish Poisoning in humans (Sanford, 2018). Warming waters in summer are already affecting fish, with the reproduction of some fish species (e.g. snapper and hoki) appearing to be affected by sea-surface temperature (MFE & STATS NZ, 2019).

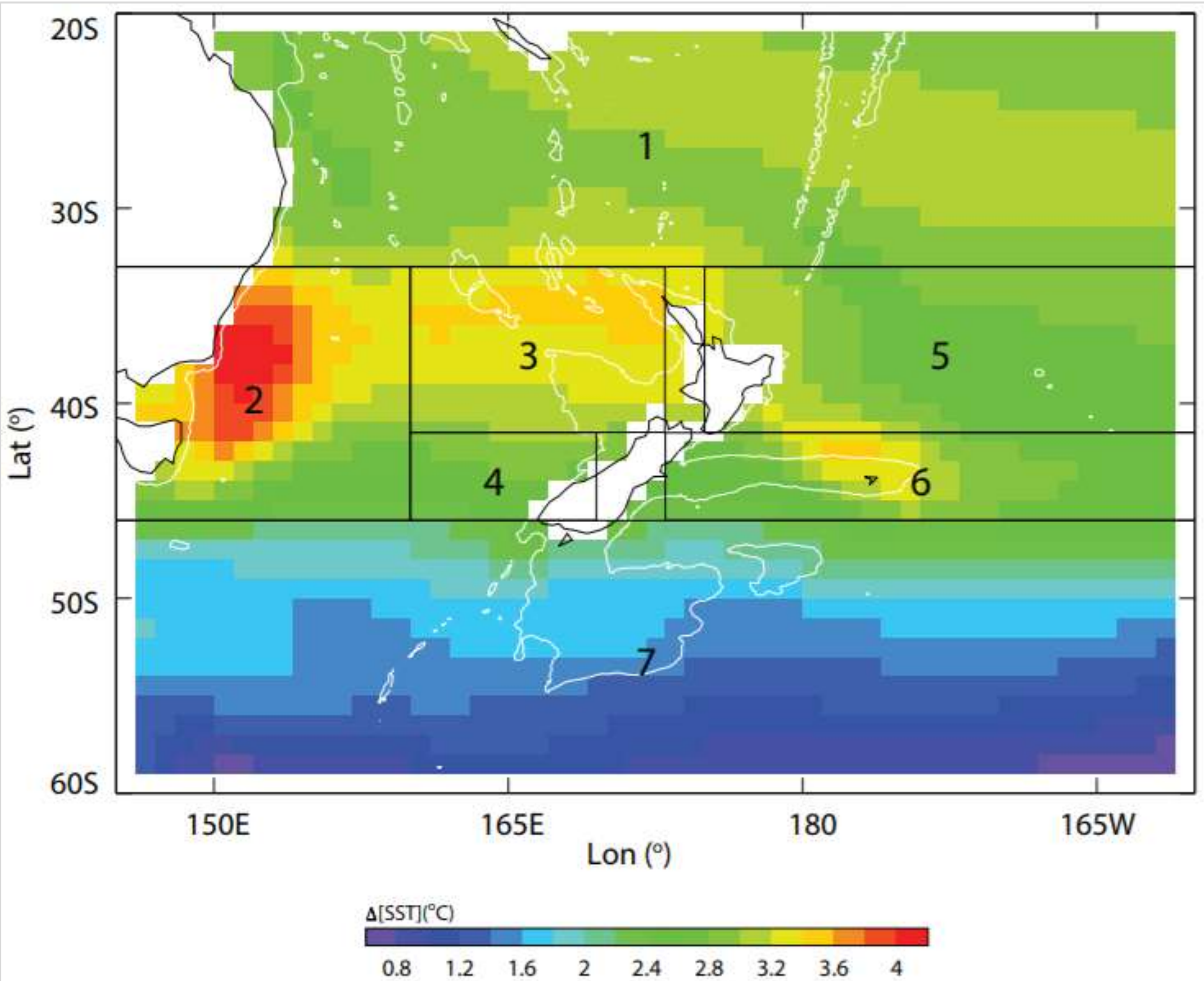


Figure 9-4: Regional variation of the projected change in SST for the End-Century (2081-2100) compared with present-day (1976-2005) under RCP8.5. Source: Law *et al.* (2016).

As pH is primarily determined by atmospheric carbon dioxide exchanging with the surface waters and there is no upwelling of low pH water in the Southwest Pacific, surface pH is relatively uniform. The decline in surface pH at mid- and end-century is clearly apparent in Figure 9-5, which shows that the effect of future changes in atmospheric carbon dioxide concentration on pH override spatial variation arising from natural processes. Minor regional variation is evident, with higher pH in northern subtropical waters and the East Australian Current, and lower pH in the south. This meridional gradient of ~0.03 partially reflects the higher solubility of carbon dioxide, and so lower pH, in colder water. Surface waters in the Subtropical Front on the Chatham Rise have marginally higher pH, due to carbon dioxide uptake by phytoplankton in this region.

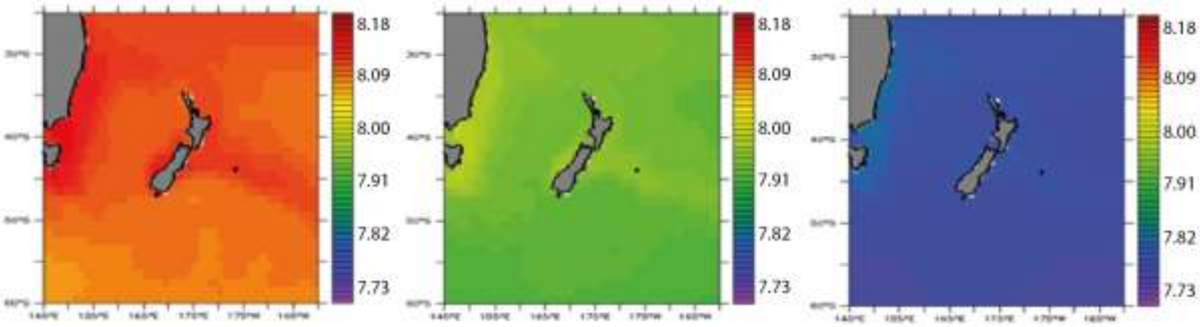


Figure 9-5: The spatial variation in mean surface pH in the Southwest Pacific. For the present-day (1976-2005, left panel), and projected for Mid-Century (2036-2055, central panel) and End-Century (2081-2100, right panel) using the GFDL-ESM2G model under RCP8.5. The legend shows pH.

Marine species are likely to be affected by ocean acidification. Growth rates and shell development of species with carbonate shells, such as oyster, paua, and some phytoplankton are reduced in more acidic waters (Cummings *et al*., 2013). An investigation into the effects of ocean acidification and heatwave conditions on juvenile snapper (*Pagrus auratus*) was undertaken in New Zealand by McMahon *et al*. (2019). They found that critical swimming speed and maximum metabolic rates increased with higher temperatures but decreased with higher carbon dioxide (i.e. higher acidity), which means ocean acidification could have negative effects on snapper population recruitment. However, it is uncertain at this stage whether the same behaviours will be affected in a wider range of New Zealand temperate and subantarctic fish species (Law *et al*., 2018).

9.5.2 Pests and biosecurity

Climate change hazards such as rising temperatures, heatwaves, and changes in precipitation patterns are likely to increase biosecurity issues including rising numbers of invasive species, pests and pathogens (Luck *et al*., 2014).

Terrestrial biosecurity

Climate change is widely regarded as one of the greatest challenges facing indigenous ecosystems in the coming century. As New Zealand has an economy based on very efficient primary production systems, the risk of exotic pests and diseases affecting the primary industries also needs to be minimised. Climate change will create new biosecurity challenges by enabling the establishment of new exotic pest animals, weeds and diseases which are currently prevented by New Zealand’s climate. The potential establishment of subtropical pests and current seasonal immigrants are of greatest concern, along with species that are already recognised as high risk (Kean *et al*., 2015).

Although climate change may affect organisms and ecosystems in a range of ways, the most important driver of pest invasion is likely to be temperature, modified by rainfall, humidity and carbon dioxide (Kean *et al*., 2015). In addition, changes in large-scale weather patterns will influence the frequency and intensity of extreme weather events (e.g. flooding, drought, damaging wind). Regional winds and currents may affect the ability of potential invaders to reach New Zealand and establish. Myrtle rust (*Austropuccinia psidii*) is a fungus that has been recently (in 2017) found in northern New Zealand. It attacks plants belonging to the Myrtaceae family, including pōhutukawa, mānuka, rātā, and feijoa. There is concern that myrtle rust may spread further in New Zealand as the climate warms and other fungi that are spread by wind may become established in the country in the future with changes to atmospheric circulation, temperature, wind patterns, and storminess.

Big headed (*Pheidole megacephla*) and Argentine (*Linepithema humile*) ants are some of the worst invasive pest species in the world, as they can wreak havoc on the native arthropod fauna, and they are already present in New Zealand. Continued warming and drying of eastern climates such as in Marlborough are likely to encourage their spread. Wasps are highly responsive to climate conditions; wet winters with flooding do not favour nest survival and can lower populations, while warm, dry conditions are ideal for explosive population growth (McGlone and Walker, 2011). Subtropical fruit flies are already considered major threats to the New Zealand horticulture industry. A modelling exercise done for the Queensland fruitfly (Figure 9-6) shows that in the historic period, only the northern parts of New Zealand are suitable for population establishment. However, the envelope of suitability (indicated by red and orange shades) spreads further south during the future periods of 2030-2049 and 2080-2099. Marlborough had low suitability under the historic climate, but suitability increases over time to cover coastal parts of the region between 2080-2099 (Kean *et al*., 2015).

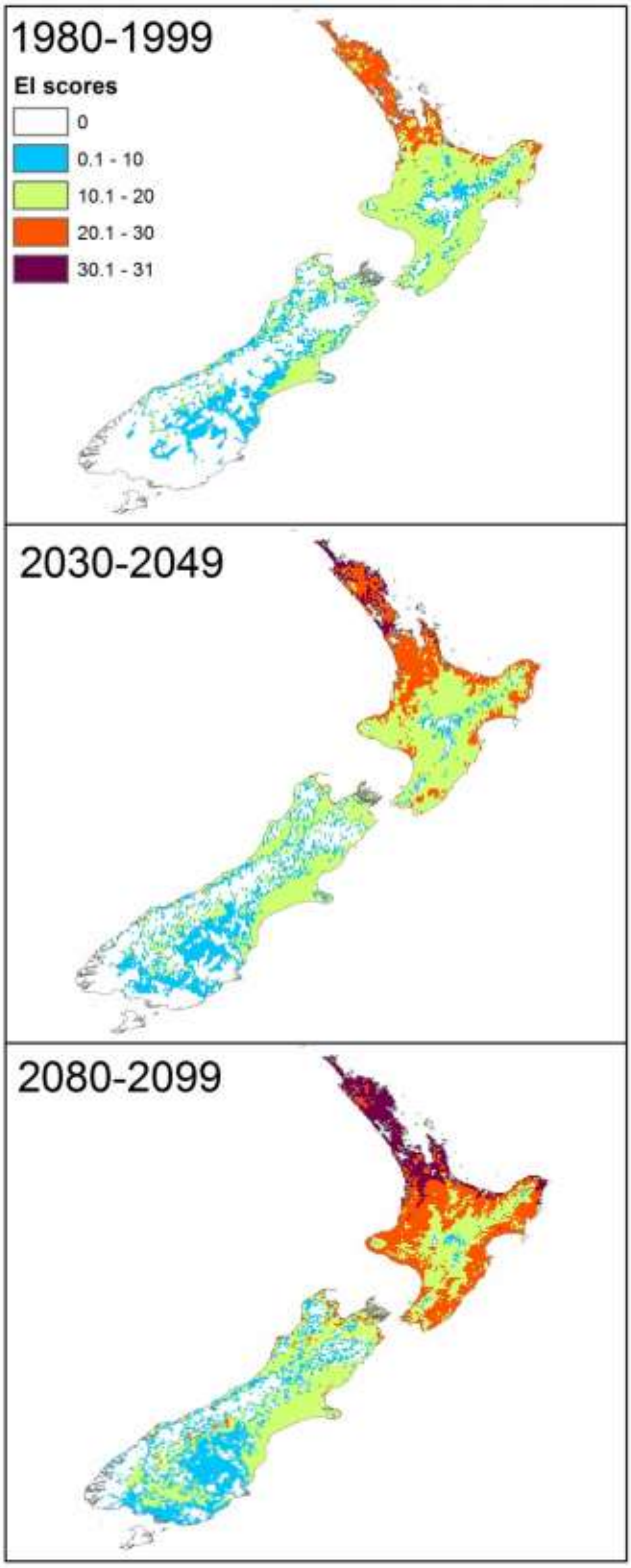


Figure 9-6: Ecoclimatic Index scores for the Queensland fruitfly, Bactrocera tryoni, for three periods 1980-1999, 2030-2049, and 2080-2099. EI scores >19 indicate a high probability that the site is suitable for long-term population persistence (e.g. red and orange shades). The climate data are for the A1B scenario (equivalent to RCP6.0) and the CM2.1-GFDL general circulation model. Source: Kean *et al*. (2015).

The arrival of new pest plants and the increased invasiveness of existing weeds is one of the most significant likely consequences of climate change. More plant species are present in warmer regions, so as frost declines in frequency, winters warm, and more insect pollinator species are able to survive in warmer temperatures, a much larger range of weed species will be able to compete with local species (McGlone and Walker, 2011). Ornamental plants may escape cultivation when climatic constraints (such as frosts) are reduced and subsequently may naturalise and become invasive (Sheppard *et al*., 2016). Sheppard (2013) modelled the potential distribution of recently naturalised plant species in New Zealand with future climate change (*Archontophoenix cunninghamiana* (bangalow palm)*, Psidium guajava* (common guava), and *Schefflera actinophylla* (Queensland umbrella tree)). All three species, which are currently only present in northern New Zealand (Northland and Auckland), have the potential to significantly increase their range further southward in the future, particularly into coastal areas around the country.

The shift towards reliance on drought and heat tolerant plants (in particular, pasture grasses) may cause new pest species to spread and for new host/pest associations to develop (Kean *et al*., 2015). The 2014 emergence of two native moths (*Epyaxa rosearia* and *Scopula rubraria)* as major plantain (a variety of pasture grass) pests demonstrates how a large increase in usage elevated these previously harmless species to pest status. In addition, as kikuyu grass (*Cenchrus clandestinus*) is likely to become the most prevalent forage grass with increasing temperatures, pests that affect kikuyu grass are likely to be important. Some pest species from Australia (e.g. the *Sphenophorus venatus vestitus* weevil) have already been recorded on kikuyu in Northland and pests such as this are likely to spread further in New Zealand as the climate warms. However, the projected reduction in rainfall and humidity in some areas may actually reduce certain fungal disease pressures that require a wetter environment (Coakley *et al*., 1999).

It is important to note that although much of the biosecurity risk with climate change will come from beyond New Zealand's borders, many of the future's pest, disease and weed problems are currently dormant in New Zealand, awaiting some perturbation, such as climate change, to allow them to spread and flourish. These types of pests are often weeds but may also be invertebrates. A few examples of sleeper invertebrate pests that are affected by temperature include (after Kean *et al*. (2015)):

- Migratory locust *Locusta migratoria,* found in grassland from Christchurch northwards. Because existing temperatures are not usually high enough to trigger swarming behaviour, the insect currently is not regarded as a pest. However, the locusts have retained the capacity to swarm with a small swarm observed near Ahipara, Northland in the 1980s.

- Tropical armyworm *Spodoptera litura.* While this pest can be found through many lowland North Island districts, epidemic outbreak populations, when caterpillars move 'like an army' through crops and pastures, are rare. However, the combination of events that cause outbreaks will be more common under projected climate change scenarios and include above-average summer and autumn temperatures, allowing for additional generations to develop.

For more detailed information about the potential effects of climate change on current and potential terrestrial biosecurity pests and diseases in New Zealand, see Kean *et al*. (2015).

Aquatic biosecurity

The primary source of entry for aquatic biosecurity risk organisms into New Zealand is and will continue to be through international shipping. These risk organisms are contained within ballast water or attached to the hulls of ships. However, changes in water temperature and ocean currents into the future, because of climate change, may result in species (including pests and pathogens) not usually seen in New Zealand waters to arrive and establish. Sea temperatures are projected to increase around New Zealand, particularly to the west of the country, and seawater is likely to become more acidic (Law *et al*., 2018).

Long-term changes in marine environmental variables, such as seawater temperature, may lead to new ecological compatibilities and may alter existing host-pathogen interactions. It is commonly accepted that warmer sea and freshwater temperatures modify host-pathogen interactions by increasing host susceptibility to disease. Such changes could contribute to the emergence of aquatic diseases in new regions (Castinel *et al*., 2014).

In terms of freshwater biosecurity, increased water temperatures are likely to favour the expansion of warm water species such as koi carp, goldfish, tench, rudd, and catfish (Office of the Prime Minister's Chief Science Advisor, 2017). These fish can cause water quality degradation and reduced indigenous biodiversity. Increased water temperatures may also facilitate the establishment of tropical fish that are sold in the New Zealand aquarium trade and intentionally or accidentally released. Increasing water temperatures will also favour warm-climate invasive aquatic plant species such as water hyacinth (*Eichhornis crassipes*) and water fern (*Salvinia molesta*).

As discussed above for terrestrial biosecurity, aquatic organisms already established within the New Zealand region that are not currently pests may become problematic under changed environmental conditions with climate change – these are called “sleeper pests”.

9.6 Human health

Most of the information in this section is summarised from Royal Society of New Zealand (2017) – a report titled *Human health impacts of climate change for New Zealand.*

Around the world, climate change has already contributed to increased levels of ill health, particularly in connection with summer heatwaves. Climate change affects human health in numerous ways. The ideal healthy human has complete physical, mental and social wellbeing, and not merely the absence of disease or infirmity. Changes to the climate can impact on these:

- Directly via air and sea temperature, flooding or storms;
- Indirectly due to changes to the environment and ecosystems; and
- Indirectly due to social and economic changes, such as migration stresses, health inequality and socioeconomic deprivation.

In New Zealand, children, the elderly, people with disabilities and chronic disease, and low-income groups are particularly vulnerable to climate change-related health impacts. Māori are also particularly vulnerable due to existing health inequalities, having an economic base invested in primary industries, housing and economic inequalities, and a greater likelihood of having low-income housing in areas vulnerable to flooding and sea-level rise.

9.6.1 Direct health impacts

Increased flooding, fires and infrastructure damage

Increased frequency and magnitude of fires, floods, storm tides and extreme rainfall events will affect public health directly through injury (e.g. being burnt by fire or swept away by floods or landslides). These extreme events may also have negative effects on wellbeing through disease outbreaks, toxic contamination, effects of damp buildings, mental health issues, disruption to healthcare access and damage to homes (lasting from weeks to months after the initial event).

Displacement

Sea-level rise and coastal erosion, as well as river flooding, may require people to leave their homes. This can cause uncertainty and lead to mental health issues from the trauma of leaving familiar surroundings, the breaking of social ties, and the difficulty of resettlement.

Extreme heat

Hot days have well-established negative impacts on the levels of illness and death, and diabetes and cardiovascular disease increase sensitivity to heat stress. Heat stress is particularly significant when hot spells occur at the beginning of the hot season before people have become acclimatised to hotter weather. The increasing number of hot days in Marlborough will likely cause detrimental impacts on health.

Heat also poses health risks for people who work outdoors, including heatstroke and renal (kidney) impairment. The increased heat is also associated with increased incidences of aggressive behaviour, violence, and suicide. Individuals with mental health conditions are especially vulnerable to high temperatures or heat waves, primarily due to not drinking enough fluids, getting access to cool places, or recognising symptoms of heat exposure.

9.6.2 Indirect health impacts

Harmful algal blooms

Increasing temperatures will increase the likelihood of blooms of harmful algae, including blue-green algae (cyanobacteria). These algae produce toxins that can, by either contact or ingestion, cause liver damage, skin disorders, and gastrointestinal, respiratory and neurological symptoms. These blooms can be widespread and long-lasting and can have impacts on commercial seafood harvesting and people reliant on non-commercial harvesting (particularly Māori and Pasifika people), as well as drinking water supplies and recreational water use.

Microbial contamination

Changing weather patterns, including more extreme rainfall events, flooding, and higher temperatures, are likely to interact with agricultural runoff and affect the incidence of diseases transmitted through contaminated drinking and recreational water. Conditions may also be more suitable for bacterial growth – extreme rainfall may be a key climatic factor influencing the incidence of waterborne diseases like *Norovirus. Vibrio* marine bacteria are highly responsive to rising sea temperatures and may cause infected wounds, diarrhoea and septicaemia.

Food availability, quality and safety

Climate change-induced changes to weather patterns and sea-level rise have direct effects on food production, which can affect food affordability and availability, locally and globally. Changes in air and water temperatures, rainfall patterns and extreme events can also shift the seasonal and geographic occurrence of bacteria, viruses, parasites, fungi and other pests and chemical contaminants. This can lead to reduced food safety prior to, during and after harvest, and during transport, storage, preparation and consumption. For example, higher temperatures can increase the number of microorganisms already present on fruit and vegetables, and flooding is a factor in the contamination of irrigation water and farm produce and the *E. coli* contamination of shellfish.

Mental health and wellbeing

Increased temperatures, extreme weather events, and the displacement of people from homes and communities will have significant mental health and wellbeing consequences. These range from minimal stress and distress symptoms to clinical disorders such as anxiety, depression, post-traumatic stress and suicidal thoughts. For New Zealanders, the natural environment is at the heart of the nation's identity. Disruption of bonds with the natural environment (e.g. through relocation of communities) can cause grief, loss and anxiety.

Outdoor air quality

Changes in temperature, rainfall, and air stagnation can affect air pollution levels and human health. Chronic health conditions such as asthma and chronic obstructive pulmonary disease are particularly affected by outdoor air quality. Climate change is expected to increase the risk of fire, which may cause more particulate emissions (PM10 and PM2.5) as well as ozone. Particulate matter smaller than 2.5 µm in diameter (PM2.5) is associated with severe chronic and acute health effects, including lung cancer, chronic obstructive pulmonary disease, cardiovascular disease, and asthma development and exacerbation. The amount of soil-derived PM10 dust in the air may also increase in areas more frequently affected by drought. Due to extended growing seasons with climate change (due to higher CO_2 and higher temperatures), allergenic pollen may become more abundant in the atmosphere (seasonally, spatially and at higher volumes).

However, improvements in outdoor and indoor air quality may be realised with ongoing warming and consequent reductions in wintertime domestic fire use, as well as a move towards an electrified vehicle fleet.

Carriers of new diseases

There are a number of organisms, including mosquitoes, ticks, and fleas that can transmit infectious diseases between humans or from animals to humans. The seasonality, distribution and common occurrence of diseases spread by these carriers are largely influenced by climatic factors, particularly high and low-temperature extremes and rainfall patterns. Therefore, climate change may create favourable conditions and increase the risk of infectious disease transmission in some areas. Increased temperature, in particular, heightens the risk for mosquito-borne diseases which are currently absent from New Zealand because the mosquitoes that carry these diseases (*Aedes aegypti* and *Aedes albopictus*) are not established in our current climate (it is too cold) (Derraik and Slaney, 2015). These diseases include West Nile virus, dengue fever, Murray Valley encephalitis, Japanese encephalitis, Ross River virus, and Barmah Forest virus (most of these are present in Australia). Mosquito-borne diseases like Zika and chikungunya that are already present in the Pacific Islands could become more of a risk for New Zealand if climate change allows important disease-transmitting mosquitoes to become established here. Disease-carrying mosquitoes are often intercepted in New Zealand, particularly at seaports.

Summary

Overall, climate change-induced hazards are likely to expose Marlborough to a variety of direct and indirect health impacts. Both types of impacts could threaten residents' life (existential threats) or degrade their health and wellbeing. Increased flooding and bushfire events and extreme heat are examples of direct drivers of potential health issues in these regions. The indirect impacts include the drivers that cause some secondary health issues over time. These impacts include harmful algal blooms and microbial contamination which release toxic substances to drinking water resources, reduced rainfall or flooding that impact food production and distribution system, or increased abundance and distribution pattern of pathogens and disease due to rising temperature. Mental health and wellbeing are other aspects of human health issues that could be impacted by climate change-oriented hazards such as heat stress, flooding and fire events.

10 Summary and conclusions

This report presents climate change projections for Marlborough. Historic 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, “2040”, and 2081-2100, “2090”.

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 an ongoing high emissions 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 high-end scenario). The six climate models used to project New Zealand’s future climate were chosen by NIWA because they produced the best 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 downscaling simulations derived 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 taking averages over a number of simulations reduces the effect of ‘noise’ in the climate signal.

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

- The projected temperature changes increase with time and greenhouse gas concentration scenario. Future annual average warming spans a wide range: 0.5-1.5°C by 2040, and 0.5-2.0°C (RCP4.5) or 2.0-3.5°C (RCP8.5) by 2090.
- Annual average maximum temperatures are expected to increase by 0.5-1.5°C by 2040 under RCP4.5. By 2090, maximum temperatures are projected to increase by 1.0-3.0°C (RCP4.5) or 2.0-5.0°C (RCP8.5). Increasing maximum temperatures will result in more hot days (days with the maximum temperature above 25°C). Up to 15 more annual hot days are projected by 2040, with up to 65 more annual hot days by 2090 (RCP8.5).
- Annual average minimum temperatures are expected to increase by up to 1.0°C by 2040. By 2090, minimum temperatures are projected to increase by 0.5-1.0°C (RCP4.5) or 1.0-2.5°C (RCP8.5). Increasing minimum temperatures will likely result in fewer frost days for the region (days with the minimum temperature below 0°C). The largest decreases are projected for high elevation and inland locations, with up to 20 fewer frost days projected by 2040, and 10-60 fewer days by 2090 (RCP8.5). Smaller decreases are generally projected for coastal locations because fewer frosts historically occur in those locations.

- Maximum temperatures are projected to increase more than minimum temperatures, resulting in an increased diurnal temperature range (i.e. the difference between the daily maximum and minimum temperature will increase). Diurnal temperature range is projected to increase by up to 1.0°C by 2040 under RCP4.5, and by up to 3.0°C by 2090 under RCP8.5.
- Projected changes in rainfall show variability across Marlborough. By 2040 under both medium and high greenhouse gas concentration pathways, annual rainfall is expected to change by a small amount for most of the region (±5%). By 2090, annual rainfall changes of -10 to +15% (RCP4.5) or -10% to +30% (RCP8.5) are projected. Larger and more extensive changes to rainfall are projected at the seasonal scale. By 2090, some parts of the region have projected summer decreases of up to 20% and winter increases of up to 40% (RCP8.5).
- Extreme, rare rainfall events are projected to become more severe in the future. Short duration rainfall events have the largest relative increases compared with longer duration rainfall events. For the selected locations analysed in this report, rainfall depths for 1-in-50-year and 1-in-100-year events are projected to increase across the representative concentration pathways and future time periods.
- Drought potential is projected to increase across Marlborough, with annual accumulated Potential Evapotranspiration Deficit (PED) totals increasing with time and increasing greenhouse gas concentrations. By 2040, PED totals are projected to increase by 50-150 mm. By 2090, PED totals are projected to increase by 50-200 mm (medium concentration pathway) or 75-250 mm (high concentration pathway).

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 concentrations and climatic responses. The changing climate over this century is projected to lead to the following hydrological effects, resulting in the region's hydrological regime shifting towards more hydrological extremes (wet or dry):

- Annual average discharge is projected to remain stable or slightly increase across RCPs and future time periods.
- Mean annual low flows (MALF) are expected to decrease across RCPs and future periods for most catchments. The reduction in MALF is expected to exceed 50% for most of the river systems in the region with increased greenhouse gas concentrations and time.

One of the major and most certain (and so foreseeable) consequences of increasing concentrations of greenhouse gases and associated warming, is the rising sea level. Rising sea level in past decades have already affected human activities and infrastructure in coastal areas is New Zealand, with a higher base mean sea level contributing to increased vulnerability to storms and tsunami.

- Absolute sea-level rise (SLR) in Marlborough, calculated from satellite altimetry, is trending at around 4 mm/year (trend for 1993-present): close to the New Zealand-wide average of 4.4 mm/year (calculated up to the end of 2015).

- As sea levels rise, so will the probability of current high-water marks being exceeded, while the average recurrence interval of rare storm-tide event will become smaller. A 0.65 m SLR (estimated to be reached by 2070-2155) would mean that any coastal location currently affected by the present-day mean high water spring (MHWS-10 level), which is exceeded by only 10% of all high tides (tide only), will be exceeded by all high tides by 2070 (under RCP8.5).

A changing climate will have impacts on different sectors and environments in Marlborough, which are summarised in the table below:

Sector	Potential climate change impact/opportunity
Exotic forestry	Increased productivity due to increased temperatures and carbon dioxide
	Increased severity of droughts and fire risk
	Increased rainfall intensity – impacts on erosion, landslides, movement of slash, access to forests for trucks and machinery
	Increased incidence of pests and diseases as temperatures increase
Horticulture	Increased temperature causing changes to plant development stages and evaporation rates, affecting the quality and quantity of the harvested crop
	Extreme heat may impact suitability of some crop types
	Reduced frost damage, new opportunities for crop diversification
	Increased biomass with increased carbon dioxide
	Rainfall reductions and more severe droughts mean more irrigation may be needed
	Increased rainfall intensity – impacts on erosion, sedimentation, quality of fruit and vegetables
Ecosystems	Loss of habitat due to sea-level rise and coastal erosion (coastal squeeze) – this could be made worse by human responses to climate impacts e.g. sea walls
	Risks to indigenous ecosystems and species due to the increased spread of invasive species
	Warming oceans may impact the distribution of marine species (native and invasive)
	Ocean acidification may affect marine species with carbonate shells (e.g. paua and oysters) and fish behaviour
Human health	Direct impacts on health via increased flooding, fires, and infrastructure damage, displacement of people, extreme heat
	Indirect impacts on health via things such as harmful algal blooms, microbial contamination, food availability and quality, mental health and wellbeing, outdoor air quality, and carriers of new diseases

10.1 Recommendations for future work

This report provides the most comprehensive and up-to-date climate change projections for New Zealand currently available. However, there are areas that were out of scope for this report, or where there is currently no New Zealand-specific information available, which may be considerations for future work. Some of these are indicated below:

- Projections of changes to large floods (magnitude and frequency) are not currently available, but investigations into how large floods may change in the future are the subject of a new 5-year research programme led by NIWA. It is anticipated that data will likely become available for use by councils in due course.

- A detailed analysis of wildfire risk in the context of projected climate change was beyond the scope of this report and there is much potential for future research on this front. One possibility for such work could be to analyse and map future areas of high fire risk by combining projected climate data such as temperature, precipitation, and wind with relevant fire risk factors such as vegetation type and flammability. Such work would likely require a collaborative research effort between NIWA and an institute specialised in wildfire research such as Scion.

Potential changes to crop suitability with climate change – modelling specific to Marlborough could be carried out as this has been done for other parts of New Zealand for a range of crop types (e.g. Ausseil *et al*., 2019; Teixeira *et al*., 2020)[12].

[12] For additional information about this work, refer to the "Climate change & its effect on our agricultural land" project at: https://www.deepsouthchallenge.co.nz/projects/climate-change-its-effect-our-agricultural-land

11 Acknowledgements

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12 Glossary of abbreviations and terms

CMIP5	Fifth Coupled Model Inter-comparison Project
ENSO	El Niño-Southern Oscillation
GCM	General circulation models
HIRDS	High Intensity Rainfall Design System
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
MALF	Mean annual low flow
MSLP	Mean sea level pressure
NEMS	National Environmental Monitoring Standards
NIWA	National Institute of Water and Atmospheric Research
ppm	Parts per million
RCM	Regional climate modelling
RCP	Representative Concentrations Pathway
RSLR	Relative sea-level rise
SAM	Southern Annular Mode
SST	Sea surface temperature
VCSN	Virtual Climate Station Network
VLM	Vertical land movement

13 References

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