Climate change and variability - Wellington Region

Prepared for Greater Wellington Regional Council

June 2017

Prepared by:
Petra Pearce
Nava Fedaeff
Brett Mullan
Abha Sood
Rob Bell
Andrew Tait
Daniel Collins
Christian Zammit

For any information regarding this report please contact:

Andrew Tait
Principal Scientist - Climate

+64-4-386 0562
andrew.tait@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Private Bag 99940
Viaduct Harbour
Auckland 1010

Phone +64 9 375 2050

NIWA CLIENT REPORT No: 2017066AK
Report date: June 2017
NIWA Project: WRC17104

Quality Assurance Statement		
	Reviewed by:	Dr Andrew Lorrey Group Manager – Weather and Climate Applications – NIWA Auckland
	Formatting checked by:	Petra Pearce
	Approved for release by:	Ken Becker Regional Manager NIWA Auckland

© All rights reserved. This publication may not be reproduced or copied in any form without the permission of the copyright owner(s). Such permission is only to be given in accordance with the terms of the client's contract with NIWA. This copyright extends to all forms of copying and any storage of material in any kind of information retrieval system.

Whilst NIWA has used all reasonable endeavours to ensure that the information contained in this document is accurate, NIWA does not give any express or implied warranty as to the completeness of the information contained herein, or that it will be suitable for any purpose(s) other than those specifically contemplated during the Project or agreed by NIWA and the Client.

Contents

Tables

Figures

Executive summary

This report describes changes that may occur over this century in the climate of the Wellington Region, and outlines some possible impacts and implications of these changes.

Global climate change

To set the context, we summarise key findings of the recent (2013-2014) global climate change assessment undertaken by the Intergovernmental Panel on Climate Change.

- Warming of the climate system is 'unequivocal', and most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the increase in greenhouse gas concentrations caused by human activities.
- Recent global warming is already having physical and biological effects in many parts of the world.
- Work assessed by the IPCC indicates that limiting future global warming to targets which are currently being discussed internationally would require substantial reductions in global greenhouse gas emissions from human activities.
- Continued emissions of greenhouse gases will cause further warming and changes in all parts of the climate system. There are four scenarios named RCPs (Representative Concentration Pathways) used by the IPCC. These RCPs represent different climate change scenarios – one (RCP2.6) leading to very low anthropogenic greenhouse gas concentrations (requiring removal of CO_2 from the atmosphere), two stabilisation scenarios (RCP4.5 and RCP6.0), and one (RCP8.5) with very high greenhouse gas concentrations. Therefore, the RCPs represent a range of 21st century climate policies.

New Zealand climate change

Next, information is summarised about expected New Zealand national and regional impacts of climate change, from the IPCC chapter on Australia and New Zealand.

- New Zealand has warmed by 0.09 ± 0.03°C per decade since 1909, with more hot extremes, fewer frosts, more rain in the south and west of New Zealand, less rain in the north and east of the North and South Islands, and a rise in sea level since 1900 of 1.7 ± 0.1 mm/yr.
- Ongoing vulnerability in New Zealand to extreme events is demonstrated by substantial economic losses caused by droughts, floods, fire, tropical cyclones, and hail. During the 21st century, New Zealand's climate is virtually certain to warm further, with noticeable changes in extreme events.
- Precipitation changes are projected to lead to increased runoff in the west and south of the South Island and reduced runoff in the northeast of the South Island, and the east and north of the North Island.

- Heat waves and fire risk are virtually certain to increase in intensity and frequency. Floods, landslides, droughts, and storm surges are likely to become more frequent and intense, and frost is likely to become less frequent.

- The potential impacts of climate change on industry are likely to be substantial. New Zealand's predominantly hydroelectric power generation is vulnerable to precipitation variability, and pasture production may be impacted by changing rainfall patterns, warming and elevated CO_2.

Wellington Region's present climate

The present climate of the Wellington Region is then described.

- The present climate across the Wellington Region is strongly influenced by the Cook Strait and rugged local topography. The Wairarapa area experiences more temperature and rainfall extremes than western parts, and wind conditions are strongest around the southwestern tip of the region.

- Upward trends in historical temperature are evident in the Wellington Region. There is a large range of temperature variability from year to year, with some years having mean temperatures over 2.5°C different to other years.

- The Wairarapa currently observes more than 24 hot days (Tmax >25˚C) per year and the west of the region experiences less than 6 hot days per year. The highest elevations of the Tararua Ranges experience over 30 cold nights (Tmin <0˚C) per year, and lower elevations typically observe less than 12 cold nights per year.

- There is substantial year to year variation in rainfall within and between sites in the region. In Wellington city, some years record almost 900 mm more than other years.

- Potential Evapotranspiration Deficit (PED, a measure of climatic drought) varies over time. Annual PED is generally higher at Masterton than at Wellington city.

- Extreme daily rainfall statistics are presented for Wellington city and Masterton. Year-to-year variability is high for both the maximum daily rainfall per year (Rx1day) and the number of days per year with high rainfall (R20mm), but there are no long term trends observed.

- Three natural fluctuations leading to year-to-year variations in climate are the El Niño-Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO), and the Southern Annular Mode (SAM). These factors also lead to fluctuations in sea level.

Future climate of the Wellington Region

Projections of future climate changes for the Wellington Region are presented. Mapped projections are presented for RCP4.5 (one of the stabilisation emissions scenarios) and RCP8.5 (the 'business as usual' scenario which occurs as the result of no reduction in emissions into the future), and tabular projections are also presented for the low-end RCP2.6 and middle-ground RCP6.0. The complete range of model results for temperature and precipitation are presented in graph format for all regions of New Zealand. These graphs demonstrate the difference with season and RCP, and also the range of model sensitivity.

- **Mean temperature:** All future projections of mean temperature for the Greater Wellington Region show a warming signal. Warming is most pronounced for inland areas, and summer and autumn exhibit the most warming. By 2090, annual mean temperature is projected to increase by 1.2°C for RCP 4.5 and 2.7°C for RCP 8.5, compared with 1995 (dynamical downscaled projections).

- **Maximum and minimum temperature:** The positive maximum temperature trends are larger than the minimum temperature trends, resulting in an increase in the diurnal temperature range for the Wellington Region.

- **Growing degree days:** Consistent with the regional warming trend, the number of growing degree days (10˚C base temperature) is projected to increase across the region. Generally, eastern parts of the region experience a larger increase in growing degree days.

- **Hot days:** Hot days (Tmax >25°C) are expected to increase throughout the region, but hot days in the area to the east of the Tararua and Rimutaka Ranges are expected to increase more than in the west. At 1995, most of the Wairarapa observed more than 24 hot days per year and the west of the region experienced less than six hot days per year. At 2090 under RCP4.5, about 30 more hot days are expected per year for central Wairarapa, and 70 more hot days under RCP8.5, compared with 1995. For the west of the region, about 10 more hot days are expected under RCP4.5 at 2090 and about 30 more hot days under RCP8.5.

- **Cold nights:** Cold nights (Tmin <0°C) are projected to decrease in all areas, but the largest decreases are for high elevation areas of the Tararua Ranges. At 1995, the higher elevations of the Tararua Ranges observed over 30 cold nights per year and lower elevations experienced less than 12 cold nights per year. At 2090, the Tararua Ranges is projected to experience about 20 fewer cold nights per year under RCP4.5 and up to 40 fewer cold nights under RCP8.5, compared with 1995.

- **Total rainfall:** In general, rainfall is projected to increase in the west of the Wellington Region and decrease in the east of the region. The amount of change increases with time and RCP. Compared with present, Paraparaumu is projected to experience a 6% increase in autumn rainfall under RCP8.5 at 2040, and up to 10% increase under RCP8.5 at 2090 for winter. Masterton is projected to experience minimal change in rainfall at 2040 but a 10% decrease in summer rainfall and an 8% decrease in autumn rainfall at 2090 under RCP8.5 (dynamical downscaled projections).

- **Rain days:** The number of rain days (daily rain > 1 mm) is projected to decline across the Wellington Region for both scenarios and at 2040 and 2090, compared with 1995. At 2040 under RCP4.5 and RCP8.5, up to 10 fewer rain days per year are expected for the Wairarapa.

By 2090, 5-10 fewer rain days are expected across most of the region per year for RCP4.5, but RCP8.5 shows 15-20 fewer rain days per year for the eastern Rimutaka and Tararua Ranges, as well as eastern Wairarapa.

- **Heavy rain days:** Small increases and decreases in heavy rain days (daily rain > 25 mm) are evident in different parts of the region at the seasonal time scale. However, most parts of the region project an increase in heavy rain days at the annual time scale.

- **Dry days:** In general, dry days (daily rain < 1 mm) are expected to increase in the east of the Wellington Region and decline or stay approximately the same as present in the west, compared with the present. By 2090, over 12 more dry days per year are projected for RCP4.5 in the south Wairarapa region, and most parts of the region experience increases in the number of dry days. For RCP8.5 at 2090, over 12 more dry days per year are projected for virtually the entire region, with the largest increase projected for the winter season.

- **Snow days:** The number of snow days reduces everywhere in the Wellington Region, with the largest decreases in the highest elevations of the Tararua Ranges (this is the area that currently experiences the highest number of snow days).

- **Extreme rainfall events:** Some scenarios for changes in rainfall depth/duration/frequency statistics are provided for Wellington city and Masterton. Rare, large extreme events are likely to increase in intensity due to more moisture being held in a warmer atmosphere.

- Projections for the Wellington Region for the coming century show an increase in the magnitude of very heavy rainfall (99th percentile daily rain, which approximately equates to an annual recurrence interval of 1 year) across the region, with the largest increases in magnitude of approximately 25% around Wellington city and coastal areas under RCP8.5 at 2090, compared with 1995.

- There is a significant variability in the different models used to project precipitation. The average across all models used in the study (ensemble-average) is often less than ± 5% change, with the model range (the 5th and 95th percentile values) varying between quite large (>10%) increases and decreases. By 2040, winter is the season with the most precipitation change, with larger increases for Paraparaumu and some decreases for Masterton. This is the same at 2090, albeit with larger increases and decreases.

- **Potential Evapotranspiration Deficit:** Potential Evapotranspiration Deficit (PED) projections vary across the Wellington Region. The smallest increases in PED are projected for the high elevation areas of the Tararua and Rimutaka Ranges (up to 40 mm/year increase under RCP4.5 and RCP8.5 at 2040 and 2090). Western areas are projected to experience increases around 60-100mm/year under both scenarios at both time periods. The inland Wairarapa region is expected to change the most, with up to 120mm/year increase projected for 2040 under both scenarios but over 160mm/year increase by 2090 under RCP8.5. This means the inland Wairarapa is likely to become more drought prone in the future.

- An increase in drought frequency is projected for all of the Wellington Region except for the Tararua Ranges, by about 10% by 2070-2090. These projections were calculated from the IPCC Fourth Assessment Report emissions scenarios and will be updated in due course.

- **Air pressure:** Mean sea level pressure (MSLP) is projected to increase in summer, resulting in more northeasterly flow and anticyclonic conditions. MSLP is projected to decrease in winter, especially over and to the south of the South Island, resulting in stronger westerlies over central New Zealand.

- **Wind speed:** There is no change projected for annual and seasonal mean wind speed compared with present for the Wellington Region.

- **Windy days:** The number of windy days (daily mean wind speed > 10 m/s) is projected to increase across the region with the largest increases projected for the south of the region. Over eight more windy days per year are projected for much of the central and southern Wellington Region at 2090 under RCP8.5, compared with 1995.

- **Extreme winds:** Most of the Wellington Region is likely to experience stronger extreme winds (99th percentile) into the future, although the magnitude of these changes are small, with a maximum of 4% increase projected for the eastern Wairarapa hill country at 2090 under RCP8.5, compared with the present.

- Storms may become more intense, but there is significant uncertainty surrounding projections of tropical and extra-tropical storms into the future.

- **Solar radiation:** Solar radiation changes the most in spring and summer. Northern parts of the Wellington Region are projected to experience 3-4% more solar radiation in spring under RCP4.5 at 2090 and RCP8.5 at 2040 and 2090, and for summer at 2040 for RCP4.5 and 2090 for RCP8.5, compared with the present. Decreases in solar radiation of up to 4% are projected for summer under RCP4.5 at 2090 and RCP8.5 at 2040 and 2090, particularly for eastern coastal areas. Changes to solar radiation are consistent with increases and decreases in rainfall (and therefore cloudiness) for the Wellington Region.

- **Relative humidity:** Relative humidity is projected to slightly decline by a few per cent into the future, under both scenarios at both time periods.

Three climate change case studies are presented.

- Maps showing the historic climatology of growing degree days (500m resolution) were combined with the lower resolution projections (5km) of future changes to growing degree days, to produce higher resolution maps of the future projected climatology of growing degree days.

- Analysis was undertaken on the variability in seasonal rainfall projections across a transect from west to east of the Wellington Region. This was done to better understand the uncertainty in rainfall projections and the effect of complex mountain terrain.

- Maps showing projections of three different measures of drought were generated (change in annual PED, number of days per year in soil moisture deficit, and number of days per year with PED accumulation >300mm). All three measures of drought show that the Wairarapa region remains the most drought-prone part of the region into the future.

Information has been compiled from existing literature about climate change impacts for different sectors that are important to Greater Wellington Regional Council. Those sectors are: biodiversity, drought impacts on agriculture and horticulture, sea level rise, biosecurity, river flows, wildfire, and soil temperature.

- Biodiversity is already at high risk from predation and human impacts. Many species are at risk from climate-related impacts such as river water abstraction for irrigation and hydroelectric power schemes. Changes to climate will exacerbate the impacts and risks on New Zealand's and Wellington Region's biodiversity, with the major impact (aside from pests, under biosecurity below) being on habitat changes due to air temperature changes, river flow changes, and sea level rise.

- The pH of the oceans around New Zealand is projected to decrease, consistent with global trends (i.e., less alkaline or relatively more acidic). The variability and rate of change in pH will differ in coastal waters as these are also influenced by terrestrial factors and run-off. Changes in ocean pH may have significant impacts on New Zealand fisheries and aquaculture into the future.

- It is likely that much of the Wellington Region, particularly in the east, will experience more climatic drought conditions in the future than at present. Drought causes lower plant yield and slower growth, and prolonged dry periods can cause permanent wilting of plants. The 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.

- Sea-level rise is already having impacts on human activities and infrastructure in coastal areas. Sea-level rise will have a greater influence on storm inundation and rates of coastal erosion in the Cook Strait/Wellington area, due to its small tidal range. Coastal sand dune systems are more susceptible to coastal erosion, and it is likely that these may migrate landward as sea level rises. It is likely that global sea-level will rise by between 0.28m and 0.98m by 2100, compared with present.

- As sea levels rise, total storm inundation levels will threaten low-lying areas of Wellington central city, potentially large areas of Petone and Seaview, and to a limited extent Evans Bay and smaller areas of the Miramar Peninsula. Along the Kapiti Coast, total storm inundation levels will begin to threaten Otaki Beach, low-lying areas of Waikanae, and narrow margins of the Porirua Harbour.

- Climate change (particularly increases in temperature) will allow establishment of new exotic pests, 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 taxa that are already recognised as high risk. Another concern is for ‘sleeping’ pests which currently reside in New Zealand but await some perturbation, such as climate change, which will allow them to spread and flourish.

- Masting events are years with high seed production, particularly in beech forests. Using climate change scenarios to predict future masting events to 2100, it was concluded that ‘mega-masts’ (infrequent widespread events) will continue to occur sporadically and at close to historic levels.

- River flow changes are presented for RCP4.5 and RCP8.5. Variables presented are mean discharge, mean annual low flow, and mean annual flood and changes are represented in term of change in the median of the variable.

    - For mean discharge, there is generally a drying signal in the east of the Wellington Region, and a slight increase in mean discharge in the west. This is most prominent at end-century under RCP8.5.

    - Mean annual low flow (the mean of the lowest 7-day average flows in each year of a projection period) is projected to decrease under both scenarios at both time slices, across the region. The most extreme decreases in mean annual low flow are projected for the eastern half of the region at end-century for RCP8.5.

    - Mean annual flood (the average of the maximum flood discharges experienced over 20 years centred time period) increases at both time slices under both emissions scenarios for parts of the Wellington Region outside the Tararua and Rimutaka Ranges (where mean annual flood decreases at mid-century for RCP 4.5 and RCP 8.5). The largest increases in mean annual flood are in the southwestern part of the region near Wellington city, at end-century under RCP 8.5.

    - There is high uncertainty in flood projections, and in river flow projections in general. Modelling these is very complex and an on-going area of research investigation. However, while the signal is unclear, the risk of significant changes to flood flows is high. Given the potentially high risk, users of flood flow information should take a precautionary and adaptive approach to management.

- Increases to hill country erosion due to changes in extreme rainfall may have impacts on the Wellington Region in terms of agricultural productivity and river sedimentation, which may affect water quality and biodiversity.

- Wildfire risk is projected to increase in the Wellington Region. The number of Very High and Extreme forest fire danger days is projected to increase from 16.8 days per year at Wellington Airport at present to 32.4 days per year by the 2050s. The Seasonal Severity Rating is projected to increase by about 50% for the entire region by the 2090s. Afforestation with exotic tree species, one of the most popular climate change mitigation strategies, may increase the fire hazard in the Wellington Region.

- Projections of soil temperature have received relatively little attention compared to air temperature, although this is crucial in determining seed germination and plant growth. Soil temperatures are projected to warm into the future, albeit at a slower rate than air temperatures. The relationship between soil and air temperatures is complex, therefore the atmospheric warming trend cannot be simply applied to project soil temperature change. Impacts of soil warming are likely to include accelerations of germination timing, impacts on rates of decomposition of soil organic matter and nutrient assimilation by plants. This in turn will impact Wellington Region's primary sectors.

The anthropogenic trends in climate have been presented in this report because they will become the dominant factor as the century progresses. However, natural variability also needs to be factored in, realising that at some times natural variability will be adding to the human-induced trends, while at other times it may be offsetting part of the anthropogenic effect.

Some current large climate change research projects are identified. One major body of work currently being undertaken to address some of these gaps is the Deep South National Science Challenge, which aims to better understand climatic changes in Antarctica and the Southern Ocean, and how this impacts New Zealand's climate. Another major project is the Weather@home project which runs climate model ensemble members on volunteers' computers, thereby allowing models to be run many thousands of times. The results of these exercises are used for attribution studies, to understand how specific events are changing over time and the relative influence of anthropogenic climate change on extreme events. The 'Climate Change Impacts and Implications' project will provide new climate change projections and advancements in understanding their impacts and implications for New Zealand's environment, economy and society. Climate change-related reports that are currently underway at NIWA are mentioned.

1 Introduction

Greater Wellington Regional Council (GWRC) approached NIWA to undertake a review of climate change projections for the region they administer, following the publication of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report in 2013 and 2014, and the New Zealand climate change report published by the Ministry for the Environment in 2016 (Mullan et al., 2016).

This report describes climate changes which may occur over the coming century for the Wellington Region. The report does not address the issue of mitigation (reducing greenhouse gas emissions, or increasing “sinks” such as areas of growing forest), apart from a brief summary of recent findings of the IPCC.

Consideration is given to both natural variations in the climate and to changes that may result from increasing global concentrations of greenhouse gases caused by human activities. Climatic factors discussed include temperature, precipitation, wind, evaporation, soil moisture, storminess, wind, solar radiation, and humidity. River flow variables are also considered, as well as possible changes in sea level. Commentary on climate change impacts and risks on different sectors is provided, including biodiversity, biosecurity, wildfire, and agriculture. Figure 1-1 shows the Wellington Region.

The funding for this report did not cover new data analysis and modelling, but enabled us to draw on pre-published information from various sources. Much of this information resulted from academic studies based on the latest assessments of the Intergovernmental Panel on Climate Change (IPCC, 2013, IPCC, 2014c, IPCC, 2014b). Some of the information was also based on scenarios for New Zealand generated by NIWA scientists that emerged from downscaling of global climate model runs for several IPCC representative concentration pathways for the future (undertaken through NIWA’s core-funded Regional Modelling Programme). The climate change information presented in this report is consistent with recently-updated guidance produced for the Ministry of the Environment (Mullan et al., 2016). Hydrological analyses were funded through Climate Change Impacts and Implications program as well as MPI- SLMACC Project 408657 (Impacts of climate change on river flows for agricultural use).

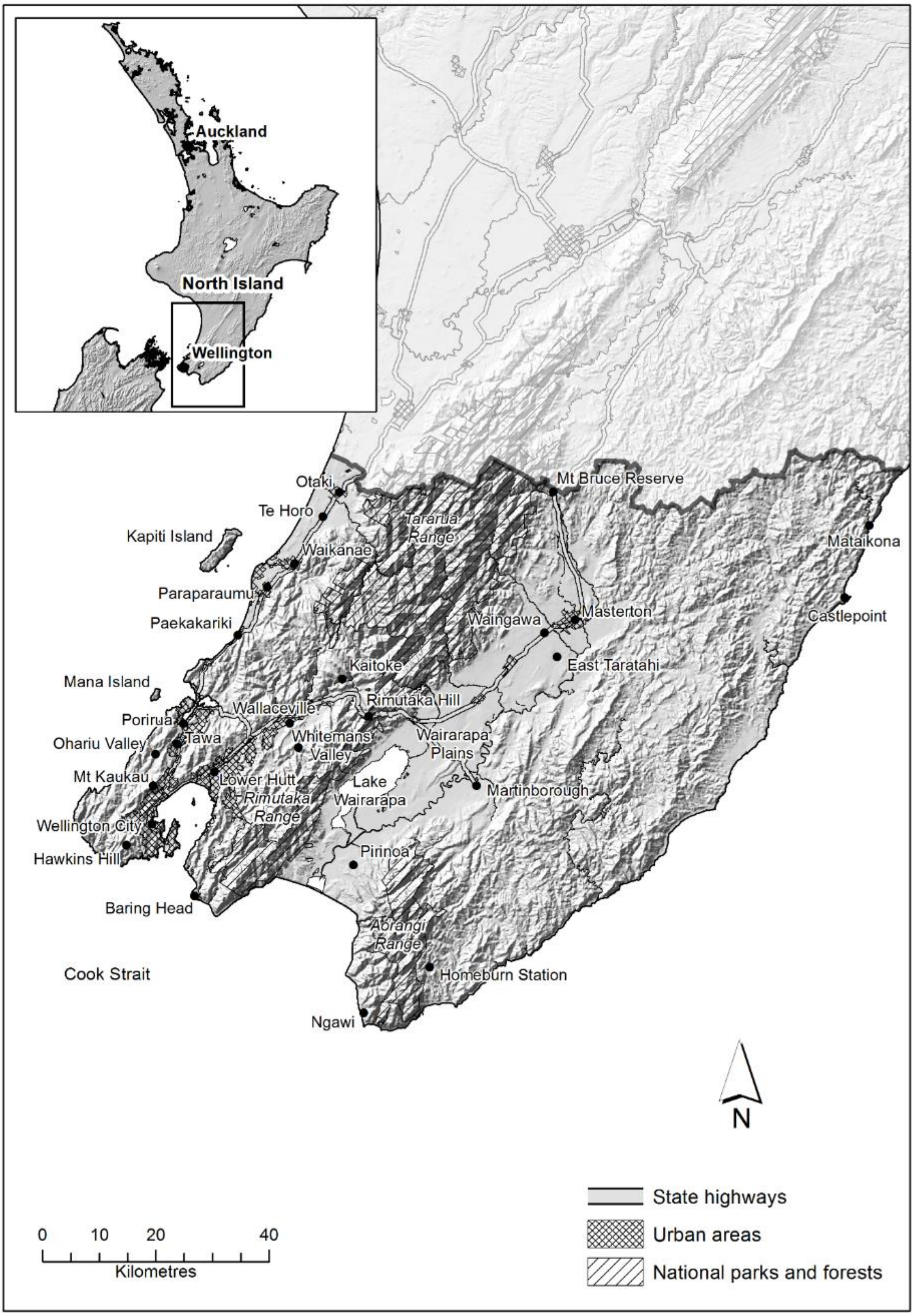

Figure 1-1: The Wellington Region governed by the Greater Wellington Regional Council.

2 Background: Global and New Zealand climate change

2.1 Global climate change

This section summarises some key findings from the 2013 and 2014 IPCC Fifth Assessment Reports (AR5) as contextual information for the discussion of past and future climate changes in the Wellington Region to follow in this report.

2.1.1 The Physical Science Basis (IPCC Working Group I)

The Summary for Policymakers of the IPCC AR5 Working Group I Report (IPCC, 2013) emphasises the following points regarding changes to the climate system:

- Warming of the climate system is 'unequivocal', and since the 1950s, many of the observed climate changes are unprecedented over short and long timescales (decades to millennia). 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.
- The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification.
- Climate change is already influencing the intensity and frequency of many extreme weather and climate events globally.
- It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century.

Continued emissions of greenhouse gases will cause further warming and changes in all parts of the climate system. There are four scenarios named RCPs (Representative Concentration Pathways) by the IPCC. These RCPs represent different climate change mitigation scenarios – one (RCP2.6) leading to very low anthropogenic greenhouse gas concentrations (requiring removal of CO_2 from the atmosphere), two stabilisation scenarios (RCP4.5 and RCP6.0), and one (RCP8.5) with very high greenhouse gas concentrations. Therefore, the RCPs represent a range of 21st century climate policies.

By the middle of the 21st century, the magnitudes of the projected climate changes are substantially affected by the choice of scenario. **Global surface temperature change for the end of the 21st century is likely to exceed 1.5°C relative to 1850-1900** for all scenarios except for the lowest emissions scenario (RCP2.6).

In contrast to the Fourth IPCC Assessment Report which concentrated on projections for the end of the 21st century, the Fifth Assessment Report projects climate changes for earlier in the 21st century as well in its Summary for Policymakers. As such, **the global mean surface temperature change for the period 2016-2035 (relative to 1986-2005) will likely be in the range of 0.3 to 0.7°C.** This assumes that there will be no major volcanic eruptions (which may cause global cooling) and that total solar irradiance remains similar. Temperature increases are expected to be larger in the tropics and subtropics than in the southern mid-latitudes (i.e. New Zealand).

The full range of projected globally averaged temperature increases for all scenario for 2081-2100 (relative to 1986-2005) is 0.3 to 4.8°C (Figure 2-1). As global temperatures increase, it is virtually certain that there will be more hot and fewer cold temperature extremes over most land areas. It is very likely that heat waves will occur with a higher frequency and duration. Furthermore, in general, the contrast in precipitation between wet and dry regions and wet and dry seasons will increase. With increases in global mean temperature, mid-latitude and wet tropical regions will experience more intense and more frequent extreme precipitation events by the end of the 21st century.

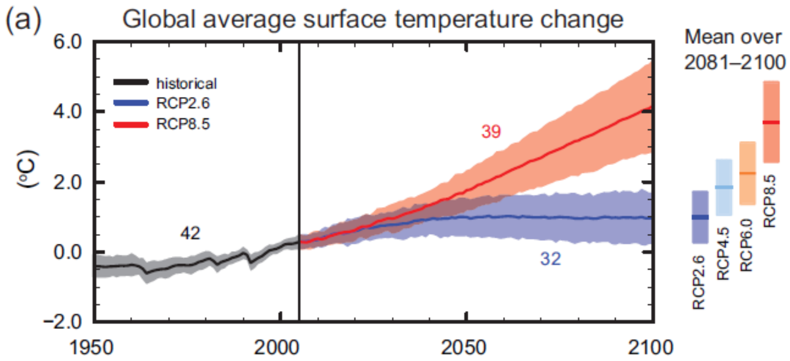

Figure 2-1: CMIP5 multi-model simulated time series from 1950-2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081−2100 are given for all RCP scenarios as coloured vertical bars to the right of the graph (the mean projection is the solid line in the middle of the bars). The numbers of CMIP5 models used to calculate the multi-model mean is indicated on the graph. After IPCC (2013).

The global ocean will continue to warm during the 21st century. Eventually, heat will penetrate the deep ocean and affect ocean circulation. Sea ice is projected to shrink and thin in the Arctic. Some scenarios project that late summer Arctic sea ice extent could almost completely disappear by the end of the 21st century, and a nearly ice-free Arctic Ocean in late summer before mid-century is likely under the most extreme scenario (RCP8.5). Northern Hemisphere spring snow cover will decrease as global mean surface temperature increases. The global glacier volume (excluding glaciers on the periphery of Antarctica) is projected to decrease by 15-85% by the end of the 21st century under different scenarios.

Global mean sea level will continue to rise during the 21st century. All scenarios project that the rate of sea level rise will very likely exceed that observed during 1971-2010 due to increased ocean warming and higher loss of mass from glaciers and ice sheets. For all scenarios, **the total range of projected sea level rise for 2081-2100 (relative to 1986-2005) is 0.26-0.82m.** It is virtually certain that global mean sea level rise will continue beyond 2100, with sea level rise due to thermal expansion expected to continue for many centuries. The range for mean sea level rise beyond 2100 for different scenarios is from less than 1 m to more than 3 m, but sustained mass loss by ice sheets would cause larger sea level rise. Sustained warming greater than a critical threshold could lead to the near complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea level rise of up to 7 m. Current estimates place this threshold between 1 and 4°C global mean warming with respect to pre-industrial mean temperatures.

Cumulative CO_2 emissions largely determine global mean surface warming by the late 21st century and further into the future. Even if emissions are stopped, most aspects of global climate change will persist for many centuries.

2.1.2 Impacts, Adaptation and Vulnerability (IPCC Working Group II)

The IPCC AR5 Working Group II Summary for Policymakers (IPCC, 2014c) concludes that in recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Specifically, these include impacts to hydrological systems with regards to snow and ice melt, changing precipitation patterns and resulting river flow and drought, as well as terrestrial and marine ecosystems, the incidence of wildfire, food production, livelihoods, and economies.

Changes in precipitation and melting snow and ice are altering hydrological systems and are driving changes to water resources in terms of quantity and quality. The flow-on effects from this include impacts to agricultural systems, in particular crop yields, which have experienced more negative impacts than positive due to recent climate change. In response to changes in climate, many species have shifted their geographical ranges, migration patterns, and abundances. Some unique and threatened systems, including ecosystems and cultures, are already at risk from climate change. With increased warming around 1°C, the number of such systems at risk of severe consequences is higher, and many species with limited adaptive capacity (e.g. coral reefs and Arctic sea ice) are subject to very high risks with additional warming of 2°C. In addition, climate change-related risks from extreme events, such as heat waves, extreme precipitation, and coastal flooding, are already moderate/high with 1°C additional warming. Risks associated with some types of extreme events (e.g. heat waves) increase further with higher temperatures.

There is also the risk of physical systems or ecosystems undergoing abrupt and irreversible changes under increased warming. At present, warm-water coral reef and Arctic ecosystems are showing warning signs of irreversible regime shifts. With additional warming of 1-2°C, risks increase disproportionately and become high under additional warming of 3°C due to the threat of global sea level rise from ice sheet loss.

Global climate change risks are significant with global mean temperature increase of 4°C or more above pre-industrial levels and include severe and widespread impacts on unique or threatened systems, substantial species extinction, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year.

Impacts of climate change vary regionally, and impacts are exacerbated by uneven development processes. Marginalised people are especially vulnerable to climate change and also to some adaptation and mitigation responses. This has been observed during recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, where different ecosystems and human systems are significantly vulnerable and exposed to climate variability. In addition, aggregate economic damages accelerate with increasing temperature.

In many regions, climate change adaptation experience is accumulating across the public and private sector and within communities. Adaptation is becoming embedded in governmental planning and development processes, but at this stage there has been only limited implementation of responses to climate change.

The overall risks of climate change impacts can be reduced by limiting the rate and magnitude of climate change.

2.1.3 Mitigation of Climate Change (IPCC Working Group III)

The IPCC AR5 Working Group III Summary for Policymakers (IPCC, 2014b) notes that total anthropogenic greenhouse gas emissions have continued to increase over 1970 to 2010 with larger absolute decadal increases toward the end of this period. Despite a growing number of climate change mitigation policies, annual emissions grew on average 2.2% per year from 2000 to 2010 compared with 1.3% per year from 1970 to 2000. Total anthropogenic greenhouse gas emissions were the highest in human history from 2000 to 2010. Globally, economic and population growth continue to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion.

Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions. The IPCC report considers multiple mitigation scenarios with a range of technological and behavioural options, with different characteristics and implications for sustainable development. These scenarios are consistent with different levels of mitigation.

The IPCC report examines mitigation scenarios that would eventually stabilise greenhouse gases in the atmosphere at various concentration levels, and the expected corresponding changes in global temperatures. Mitigation scenarios where temperature change caused by anthropogenic greenhouse gas emissions can be kept to less than 2°C relative to pre-industrial levels involve stabilising atmospheric concentrations of carbon dioxide equivalent (CO_2-eq) at about 450 ppm in 2100. If concentration levels are not limited to 500 ppm CO_2-eq or less, temperature increases are unlikely to remain below 2°C relative to pre-industrial levels.

Without additional efforts to reduce emissions beyond those in place at present, scenarios project that global mean surface temperature increases in 2100 will be from 3.7 to 4.8°C compared to pre-industrial levels. This range is based on the median climate response, but when climate uncertainty is included the range becomes broader from 2.5 to 7.8°C.

In order to reach atmospheric greenhouse gas concentration levels of about 450 ppm CO_2-eq by 2100 (in order to have a likely chance to keep temperature change below 2°C relative to pre-industrial levels), anthropogenic greenhouse gas emissions would need to be cut by 40-70% globally by 2050 (compared with levels in 2010). Emissions levels would need to be near zero in 2100. The scenarios describe a wide range of changes to achieve this reduction in emissions, including large-scale changes in energy systems and land use.

Estimates of the cost of mitigation vary widely. Under scenarios in which all countries begin mitigation immediately, there is a single carbon price, and all key technologies are available, there will be losses of global consumption of goods and services of 1-4% in 2030, 2-6% in 2050, and 3-11% in 2100.

Delaying mitigation efforts beyond those in place today through 2030 is estimated to substantially increase the difficulty in obtaining a longer term low level of greenhouse gas emissions, as well as narrowing the range of options available to maintain temperature change below 2°C relative to pre-industrial levels. Global surface temperature for the end of the 21st century is likely to exceed 1.5°C relative to 1850-1900 for all RCP scenarios except RCP2.6, and it is likely to exceed 2°C for RCP6.0 and RCP8.5, and more likely than not to exceed 2°C for RCP4.5 (IPCC, 2014a).

2.2 New Zealand climate change

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

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

The region has exhibited warming to the present and is virtually certain to continue to do so. New Zealand mean annual temperature has increased by 0.09°C (± 0.03°C) per decade since 1909.

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

Uncertainty in projected rainfall changes remains large for many parts of New Zealand, which creates significant challenges for adaptation.

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 past New Zealand climate change can be found in Mullan et al. (2016).

2.2.1 Sectoral Impacts

Some New Zealand sectors have the potential to benefit from projected changes in climate and increasing CO_2, including reduced winter plant and stock mortality, reduced energy demand for winter heating, and forest and pasture growth in currently cooler regions. The information in this section is from Reisinger et al. (2014). Key impacts identified by Greater Wellington Regional Council are discussed in Section 6.

Freshwater resources: In New Zealand, precipitation changes are projected to lead to increased runoff in the west and south of the South Island and reduced runoff in the northeast of the South Island, as well as the east and north of the North Island. Annual flows of eastward-flowing rivers with headwaters in the Southern Alps are projected to increase by 5-10% by 2040 in response to higher alpine precipitation. Most of the increases occur in winter and spring, as more precipitation falls as rain and snow melts earlier. Climate change will affect groundwater through changes in recharge rates and the relationship between surface waters and aquifers.

Natural ecosystems: Existing environmental stresses will interact with, and in many cases be exacerbated by, shifts in mean climatic conditions and associated changes in the frequency or intensity of extreme events, especially fire, drought, and floods. Ongoing impacts of invasive species and habitat loss will dominate climate change signals (i.e., environmental changes attributed to climate change) in the short to medium term. The rich biota of the alpine zone is at risk through increasing shrubby growth and loss of herbs, especially if combined with increased establishment of native species. Some cold water-adapted freshwater fish and invertebrates are vulnerable to warming and increased spring flooding may increase risks for braided river bird species.

Coastal and ocean ecosystems: The increasing density of coastal populations and stressors such as pollution and sedimentation from settlements and agriculture will intensify non-climate stressors in coastal areas. Coastal habitats provide many ecosystem services including coastal protection and carbon storage, which could become increasingly important for mitigation. Variability in ocean circulation and temperature plays an important role in local fish abundance, and this could change with climate-related oceanic changes. A strengthening East Auckland Current in northern New Zealand is expected to promote establishment of tropical or subtropical species that currently occur as vagrants, potentially changing the production and profit of both wild fisheries and aquaculture. Estuarine habitats will be affected by changing rainfall or sediment discharges, as well as connectivity to the ocean. Loss of coastal habitats and declines in iconic species will result in substantial impacts on coastal settlements and infrastructure from direct impacts such as storm surge, and will affect tourism. 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.

Forestry: Warming is expected to increase *Pinus radiata* growth in the cooler south, whereas in the warmer north, temperature increases can reduce productivity, but CO_2 fertilisation may offset this. *Dothistroma* blight, a pine disease, has a temperature optimum that coincides with New Zealand's warmer, but not warmest, pine growing regions; under climate change, its severity is, therefore, expected to reduce in the warm central North Island but increase in the cooler South Island where it could offset temperature-driven improved plantation growth.

Agriculture: Projected changes in national pasture production for dairy, sheep, and beef pastures range from an average reduction of 4% across IPCC AR4 climate scenarios for the 2030s, to increases of up to 4% for two scenarios in the 2050s. Studies modelling seasonal changes in fodder supply show greater sensitivity in animal production to climate change and elevated CO_2 than models using annual average production, with some impacts expected even under modest warming. New Zealand agro-ecosystems are subject to erosion processes strongly driven by climate - greater certainty in projections of rainfall, particularly storm frequency, are needed to better understand climate change impacts on erosion and consequent changes in the ecosystem services provided by soils.

Energy supply, demand, and transmission: New Zealand's predominantly hydroelectric power generation is vulnerable to precipitation variability. Increasing winter precipitation and snow melt, and a shift from snowfall to rainfall will reduce this vulnerability as winter/spring inflows to main hydro lakes are projected to increase by 5-10% over the next few decades. Further reductions in seasonal snow and glacial melt as glaciers diminish, however, would compromise this benefit. Increasing wind power generation would benefit from projected increases in mean westerly winds but face increased risk of damages and shutdown during extreme winds. Climate warming would reduce annual average peak electricity demands by 1-2% per degree Celsius across New Zealand.

Tourism: Changes in snow cover are likely to have a significant impact on the ski industry, but tourist numbers from Australia to New Zealand may increase due to the rapid reduction in snow cover in Australia, and the greater perceived scenic attractiveness of New Zealand. Warmer and drier conditions mostly benefit tourism but wetter conditions and extreme climate events undermine tourism. A large part of the tourism industry in New Zealand is dependent on river flow (e.g. fishing, jet boating, rafting) so changes to flows will have a direct effect on these tourism operations (Becken et al., 2014).

3 Present-day climate of the Wellington Region

3.1 Spatial climatic patterns

The climate and weather of the Wellington Region is characterised by strong spatio-temporal variation that is influenced by the presence of Cook Strait and the rugged local topography. In general, the climate of the region reflects the general prevailing westerly flow, which includes west-to-east "lows" interspersed with "highs" (anticyclones) weather systems. The local impacts from variabile weather is modified in specific places by the local topography. To the east of the Tararua and Rimutaka Ranges, the Wairarapa area, which is sheltered from prevailing westerlies, experiences more temperature and rainfall extremes than the western part of the region. Wind conditions are the strongest around the southwestern tip of the Wellington region. The region as a whole is generally sunny and windy compared with other New Zealand locations.

The spatial variation in annual average temperature over the Wellington Region is shown in Figure 3-1. Figure 3-2 shows the annual number of hot days (Tmax >25°C) in the Wellington Region, and Figure 3-3 shows the number of frosts (cold nights, Tmin <0°C)) in the region. Figure 3-4 shows the spatial pattern of annual rainfall and the median seasonal total rainfalls. Temperature varies with elevation, with the coolest mean annual temperatures of the Wellington Region experienced at the highest elevations in the Tararua and Rimutaka Ranges. Mean annual temperatures are highest closer to the coast and inland around Martinborough. There is a significant difference between the number of hot days for the east and west of the Wellington region. Most of the Wairarapa experiences more than 24 hot days per year while the western part of the region mostly experiences less than six hot days per year. The highest elevations in the Tararua Ranges experience over 30 cold nights per year, but lower elevations typically observe less than 12 cold nights per year. The area that receives the most annual rainfall are the Tararua Ranges and Rimutaka Ranges, along with the southeastern part of the Aorangi Ranges, which receive over 2000 mm per year. The driest area is in the lee of the Tararua and Rimutaka Ranges, in particular around Martinborough, which receives less than 800 mm rainfall per year on average.

More detailed information about the climate of the Wellington Region can be found in Chappell (2014).

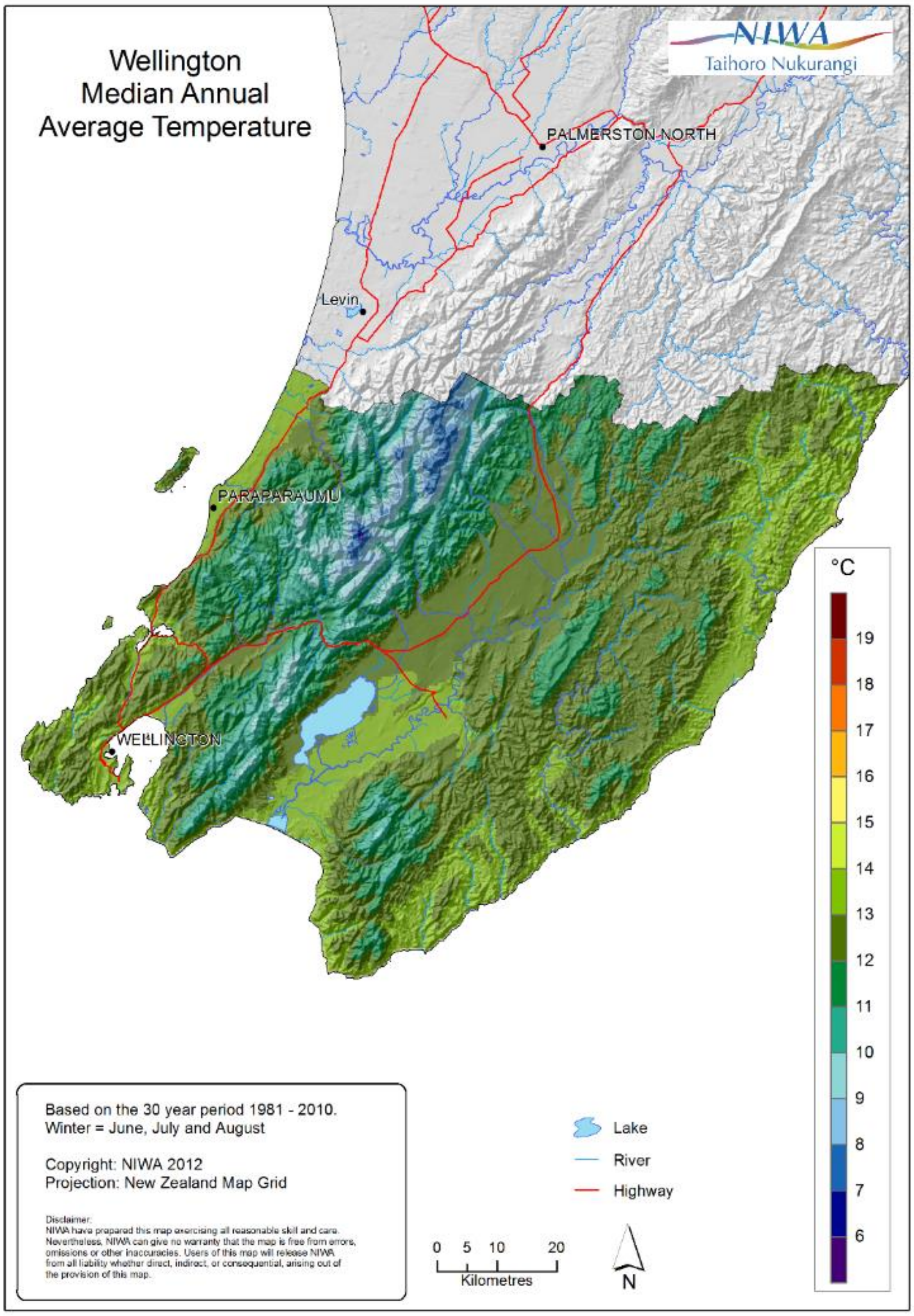

Figure 3-1: Annual average temperature for the Wellington Region (median for 1981-2010).

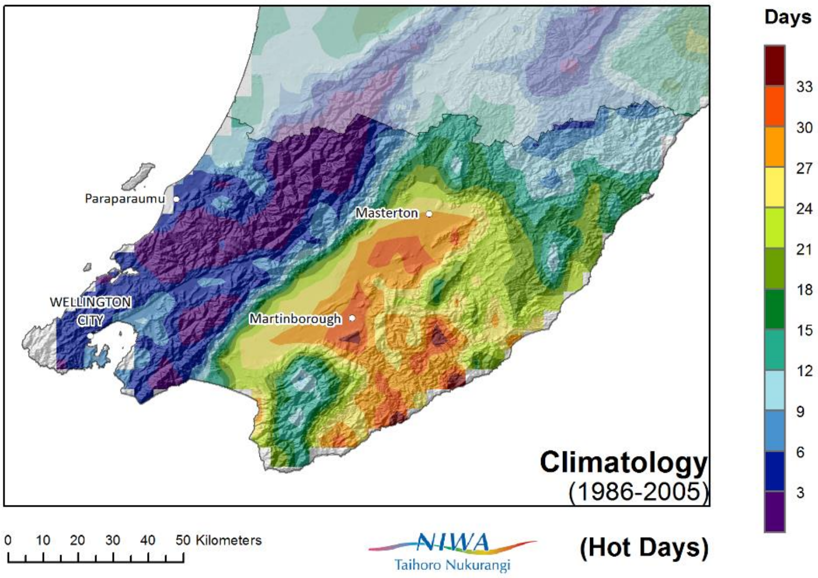

Figure 3-2: Annual number of hot days in the Wellington Region (Tmax >25°C). Climatology period 1986-2005. This map shows modelled data (from RCM simulations) and therefore may not be directly comparable to station data.

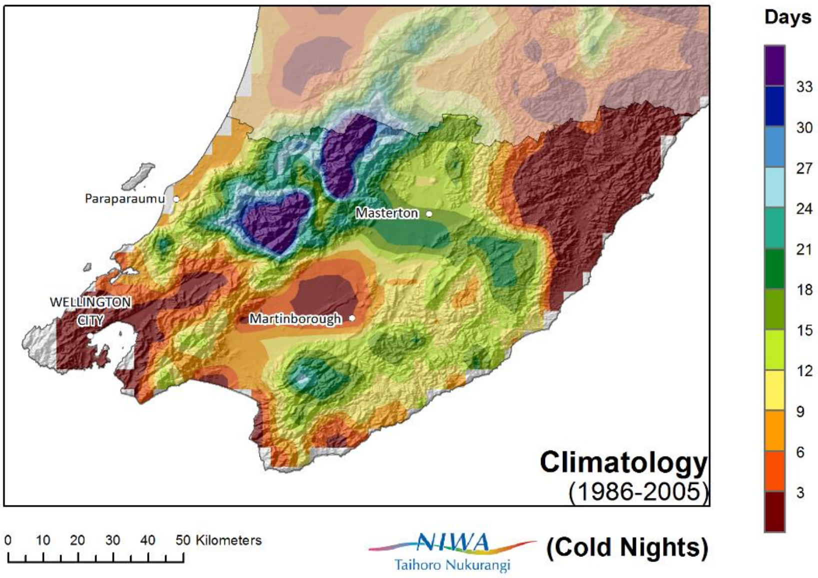

Figure 3-3: Annual number of cold nights (frosts) in the Wellington Region (Tmin <0°C). Climatology period 1986-2005. This map shows modelled data (from RCM simulations) and therefore may not be directly comparable to station data.

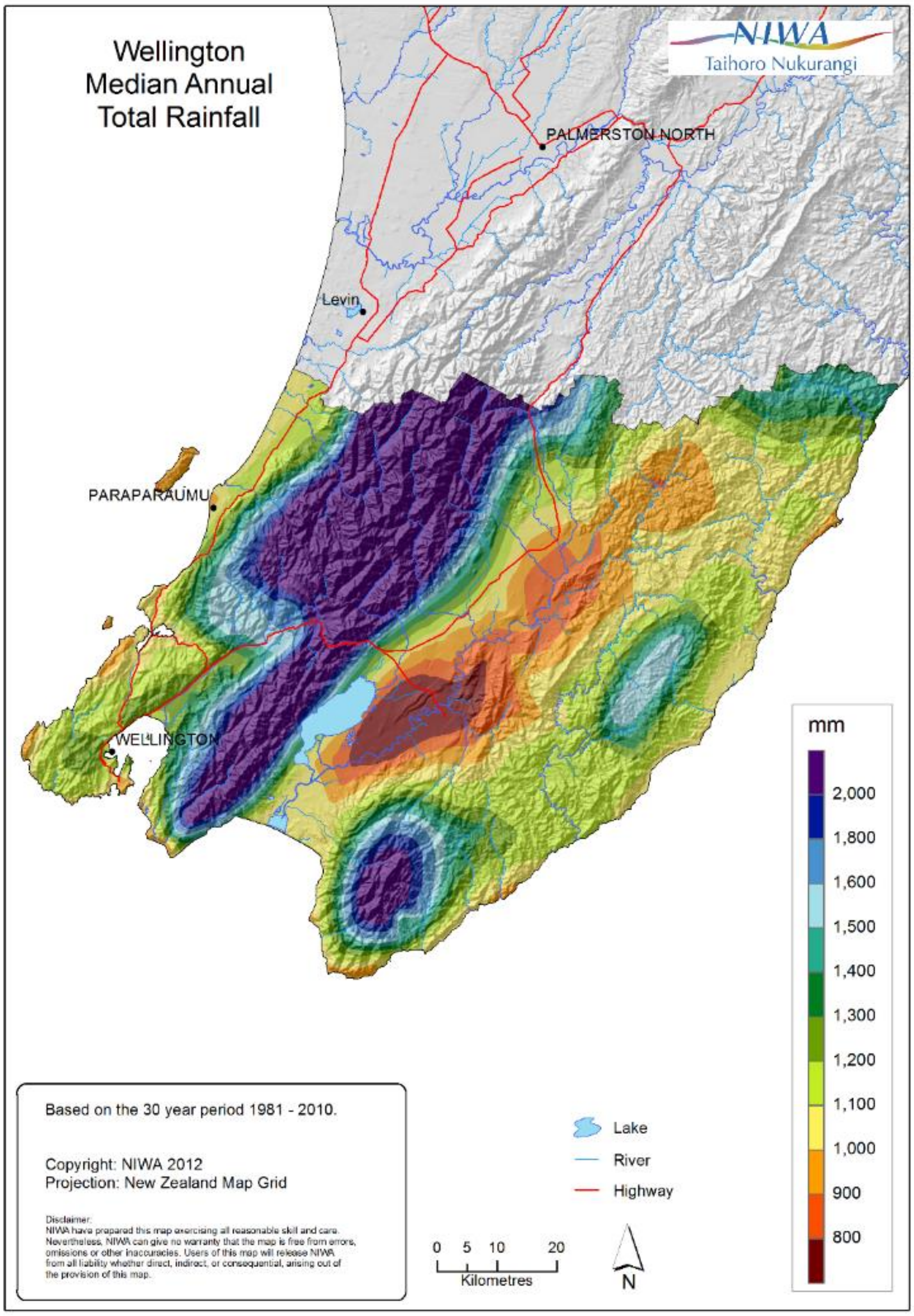

Figure 3-4: Details on following page.

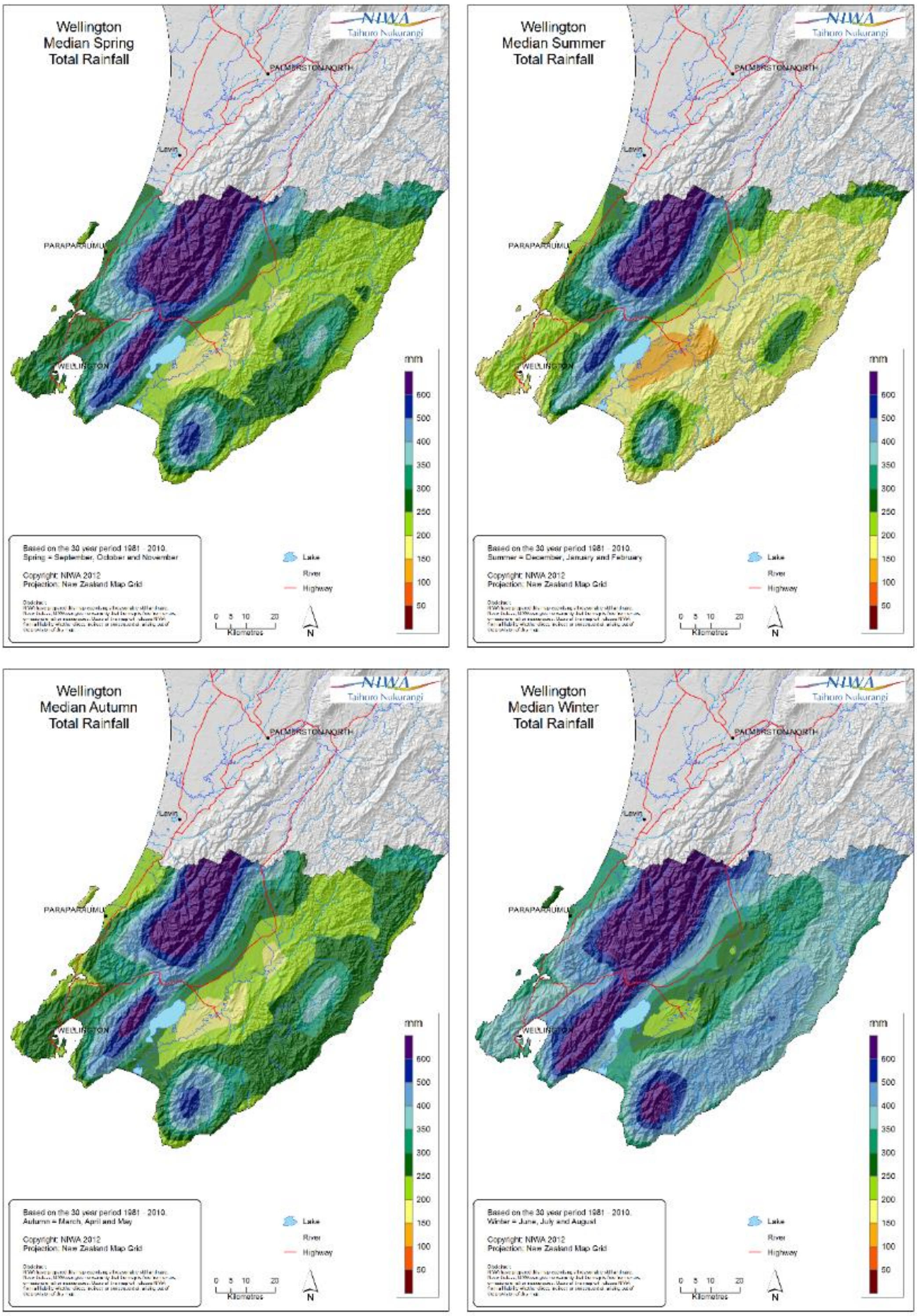

Figure 3-4: Annual and seasonal rainfall totals for the Wellington Region. Climatology period 1981-2010. Note that some climate stations in the Tararua Ranges managed by GWRC record well over 7 metres of rainfall per year. Only climate station data in the NIWA National Climate Database was used to generate this map.

3.2 Temporal climatic variability

3.2.1 Temperature

There is significant year-to-year variability for the climate of Wellington. For example, Figure 3-5 shows the average annual temperature for Wellington (Kelburn) from 1909 to 2016, and Figure 3-6 shows the same for Masterton from 1912 to 2016. There are substantial differences between years, with some having mean temperatures over 2.0°C different to others.

There is a trend toward increasing mean annual temperature at both Wellington (Kelburn) and Masterton. Figure 3-7 shows the number of hot days (when Tmax >25°C) per year since 1931 at Kelburn and Figure 3-8 shows the same for Masterton. There is no long-term trend in the number of hot days per year at Kelburn, but there has been an increase in the number of hot days per year at Masterton. However, the length of record between these two sites is very different, and the positive trend at Masterton over this short time frame is due to the record beginning in cooler years during the 1990s as a result of the Mt Pinatubo eruption and numerous El Niño events. A large number of hot days were recorded in the 1930s and 1970s at Kelburn, thus keeping the long-term trend more subdued at that site. The annual variability in the temperature records is due to a combination of natural causes, such as the El Niño-Southern Oscillation, together with random year-to-year fluctuations ("climate noise"), as well as anthropogenic influences (e.g. greenhouse gases).

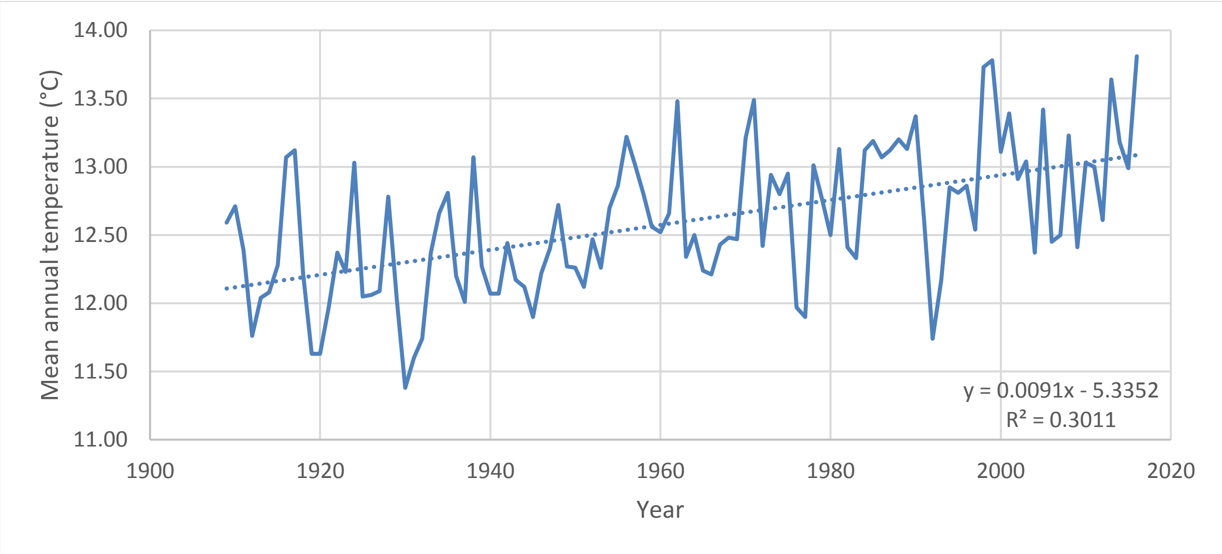

Figure 3-5: Mean annual temperature for Wellington, Kelburn site. This site is part of the 'seven station'[1] series, so data homogenisation has been carried out. Trend is approximately +0.09°C/decade, which is significant at $p < 0.05$.

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

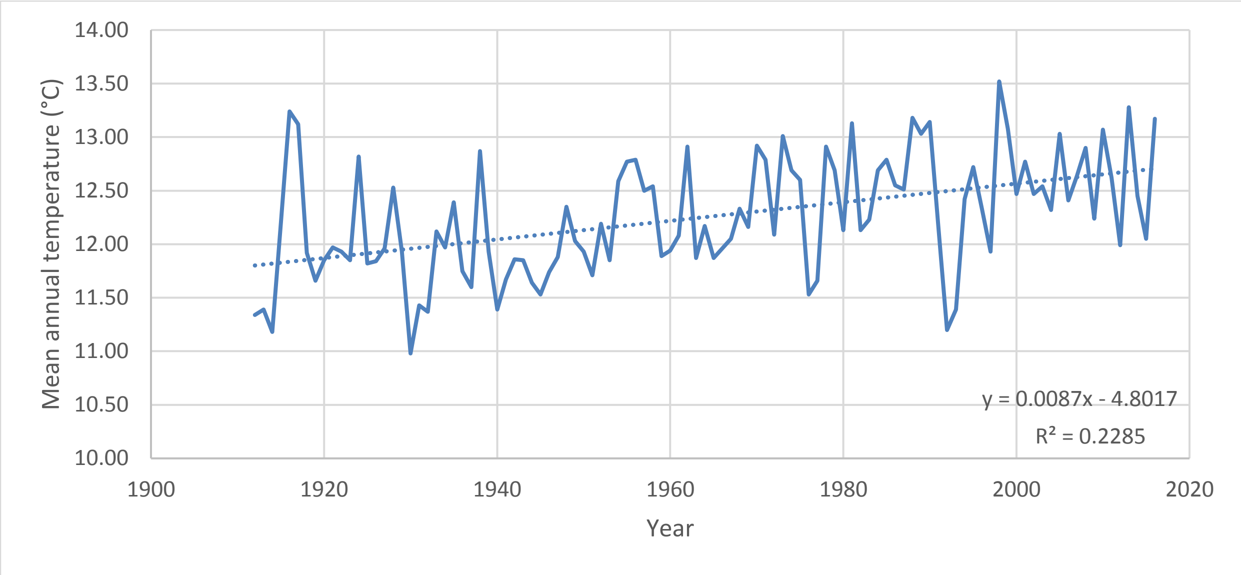

Figure 3-6: Mean annual temperature for Masterton. This site is part of the 'seven station' series, so data homogenisation has been carried out. Trend is approximately +0.09°C/decade, which is significant at $p < 0.05$.

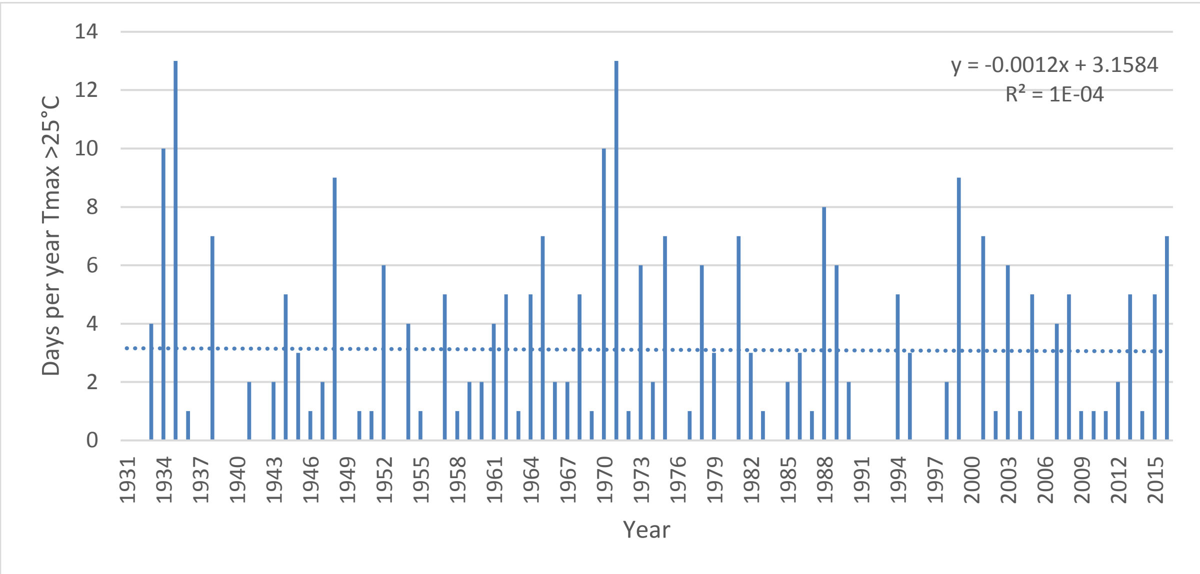

Figure 3-7: Number of hot days (Tmax >25°C) per year at Wellington (Kelburn). Data pre-2005 are from agent number 3385, including 2005 and post-2005 from 25354 (located at same site). Although these data have not been homogenised, they are all from a single site in the Kelburn botanical gardens. Trend indicates a decrease of 0.01 hot days per decade, which is not significant at $p < 0.05$.

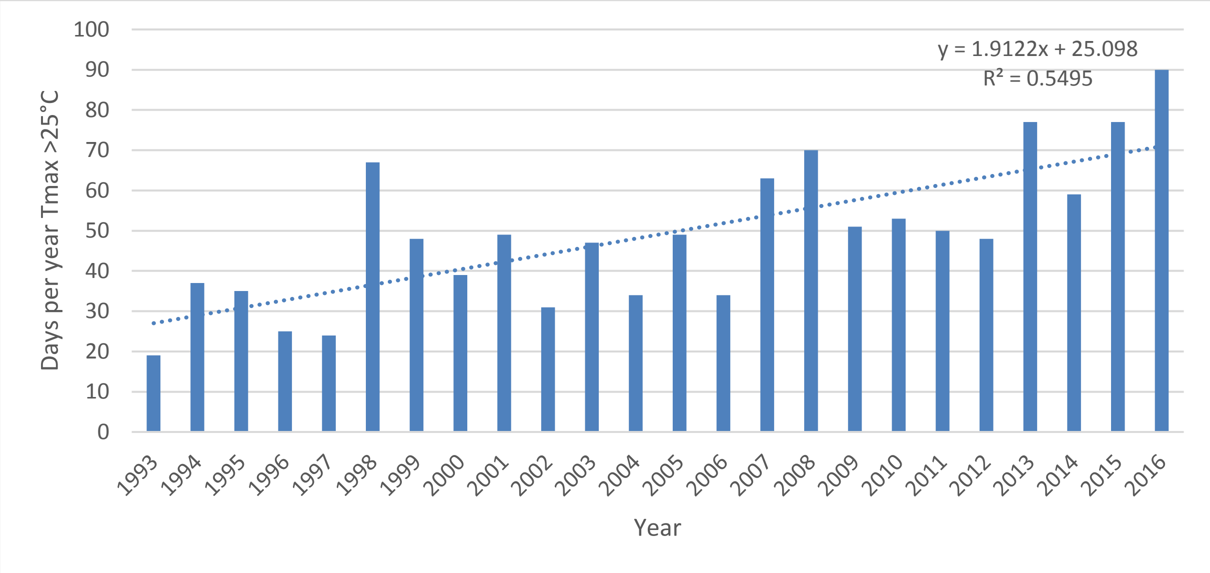

Figure 3-8: Number of hot days (Tmax >25°C) per year at Masterton (combined record from Te Ore Ore (agent number 7578) and Te Ore Ore CWS (agent number 37662)). Trend shows an increase of approximately 1.9 hot days per year, which is significant at $p < 0.05$.

3.2.2 Rainfall

Total annual precipitation is presented for Wellington (Kelburn) in Figure 3-9 and for Bagshot Station (12 km northeast of Masterton) in Figure 3-10. There is year-to-year variability in the data, with some years recording almost 900 mm more than other years at Wellington. There is a minimal positive long term trend in rainfall at Wellington and Bagshot Station shows a small declining trend in annual rainfall.

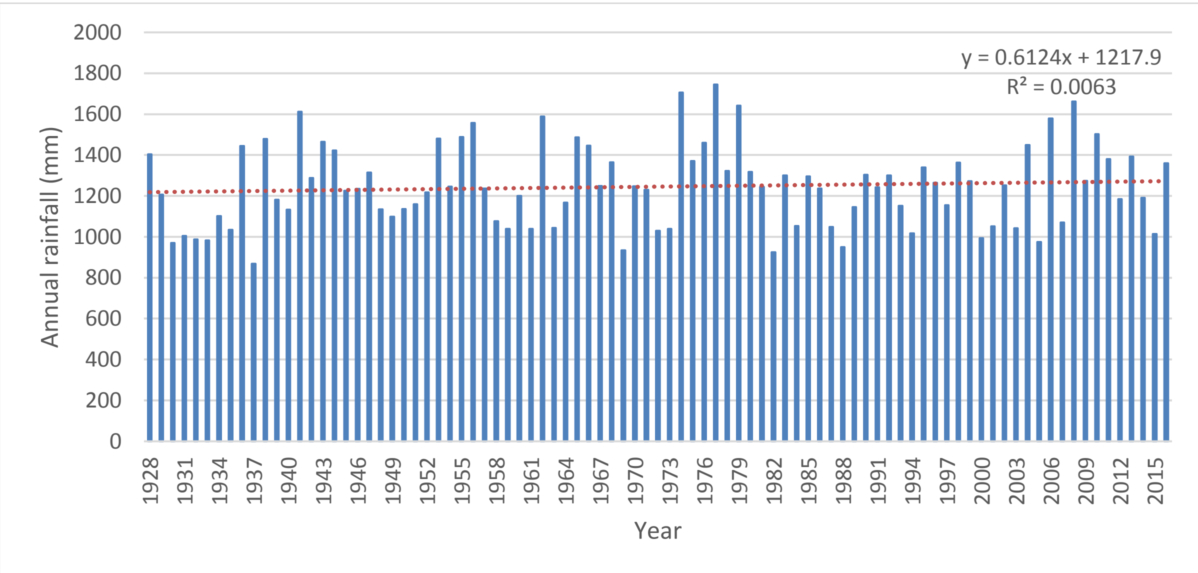

Figure 3-9: Total annual precipitation at Wellington (Kelburn), 1928-2016, combined record from agent numbers 3385 and 25354. Trend indicates an increase in rainfall of approximately 6 mm per decade, which is not significant at $p < 0.05$. Note that there is 1 day of data missing in 2013, 2 missing in 2014, and 4 in 2015.

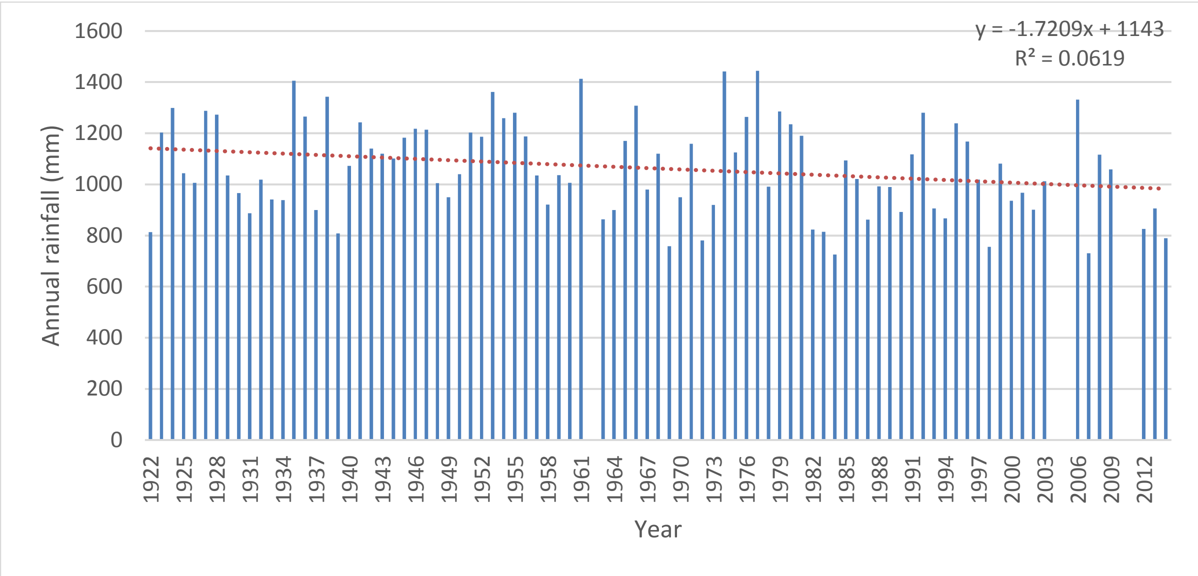

Figure 3-10: Total annual precipitation at Bagshot Station (12 km northeast of Masterton), 1922-2009, agent number 2446. 2010-2014 data are from Masterton, Te Ore Ore CWS station (agent number 37662). Note that data have not been homogenised. Years with no bars have too much missing data to calculate annual total rainfall. Trend indicates a decrease in annual rainfall of approximately 17mm per decade, which is significant at $p < 0.05$.

3.2.3 Climatic drought

Parts of the Wellington Region are particularly prone to climatic drought conditions. Due to the importance of primary production to New Zealand's economy, the occurrence of drought is of major concern. The measure of climatic drought that is used in this report is 'potential evapotranspiration deficit' (PED). Evapotranspiration is the combined loss of soil water by transpiration through plants and evaporative loss from the soil and other surfaces. Days when water demand is not met, and pasture growth is reduced, are often referred to as days of potential evapotranspiration deficit. PED, in units of mm, can be thought of as the amount of rainfall needed in order to keep pastures growing at optimum levels.

The following plots (Figure 3-11 and Figure 3-12) show PED accumulations over growing years (July-June) through the historical record for Wellington and Bagshot Station (near Masterton). The higher the PED accumulation, the drier the soils were during that year.

Wellington (Kelburn) has highly variable PED from year to year. The highest PED accumulation for Wellington (Figure 3-11) occurred in 2015-2016, with a secondary maximum in 1997-1998. Accumulated PED was approximately 500 mm in 2015-2016. For Bagshot Station, the highest accumulated PED on record was during 1997-1998 when over 450 mm was recorded (Figure 3-12). There does not appear to be a long-term trend in PED at either site.

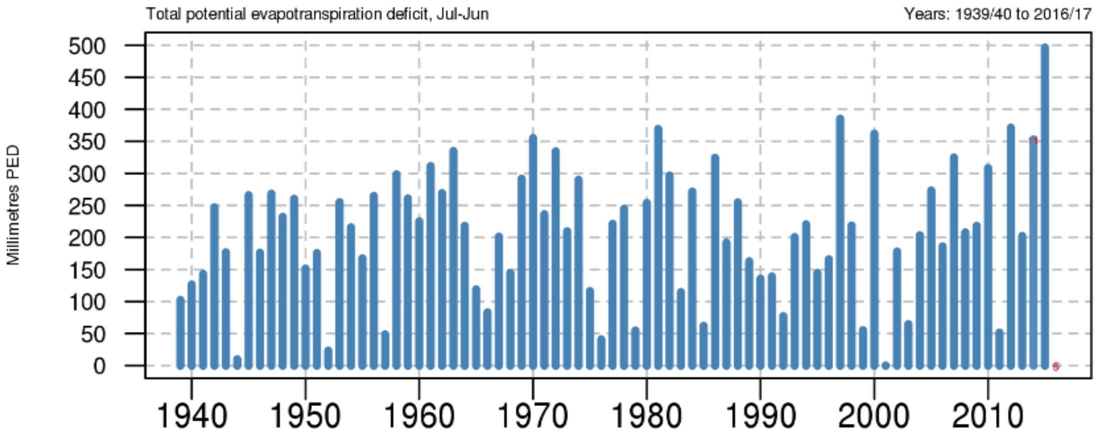

Figure 3-11: PED accumulation from 1939/40-2016/17 (July-June years) for Wellington (Kelburn). Light blue bars indicate years where there are missing data, and small red numbers indicate the amount of months in that year that are represented (months with full data).

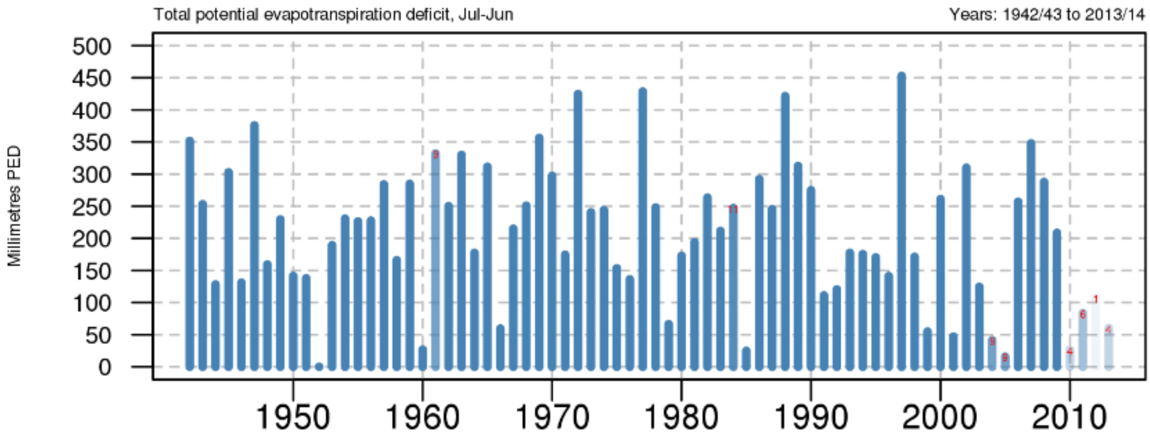

Figure 3-12: PED accumulation from 1942/43-2013/14 (July-June years) for Bagshot Station (12 km northeast of Masterton). Light blue bars indicate years where there are missing data, and small red numbers indicate the amount of months in that year that are represented (months with full data).

3.2.4 Extreme rainfall events

Extreme rainfall may be expressed as the maximum daily rainfall per year at a location (Rx1day) and the number of days per year when rainfall occurs over a certain threshold (R20mm, here the threshold used is 20 mm).

Extreme rainfall statistics are presented for 1928-2016 for Wellington (Kelburn) and for 1924-2009 for Bagshot Station (near Masterton). There is no long-term trend in maximum daily rainfall at Kelburn, which has an average of around 70 mm (Figure 3-13). However, year-to-year variability is high. This is also true for the number of days per year with rain over 20 mm (Figure 3-14), which has an average of about 16 days. For Bagshot Station, the year-to-year variability is also high for maximum daily rainfall (Figure 3-15) and the number of heavy rain days (Figure 3-16). For both sites, maximum daily rainfall and the number of heavy rain days has very slightly declined over the historical period.

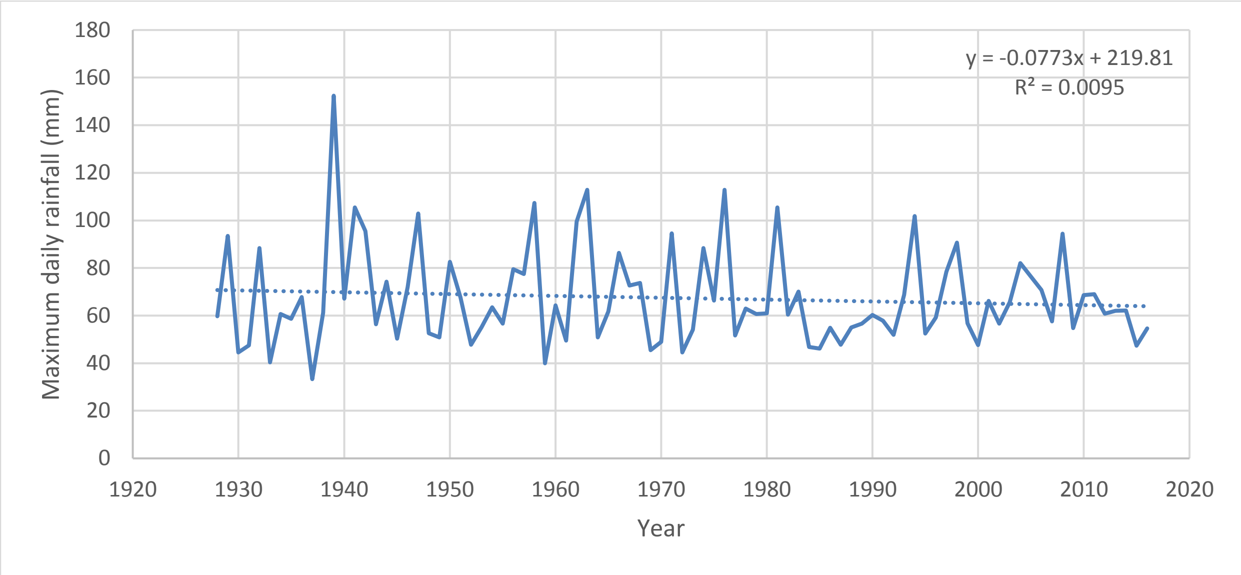

Figure 3-13: Maximum daily rainfall for Wellington (Kelburn), 1928-2016 (Rx1day). Trend indicates decrease in Rx1day of approximately 0.8mm/decade, which is not significant at $p < 0.05$.

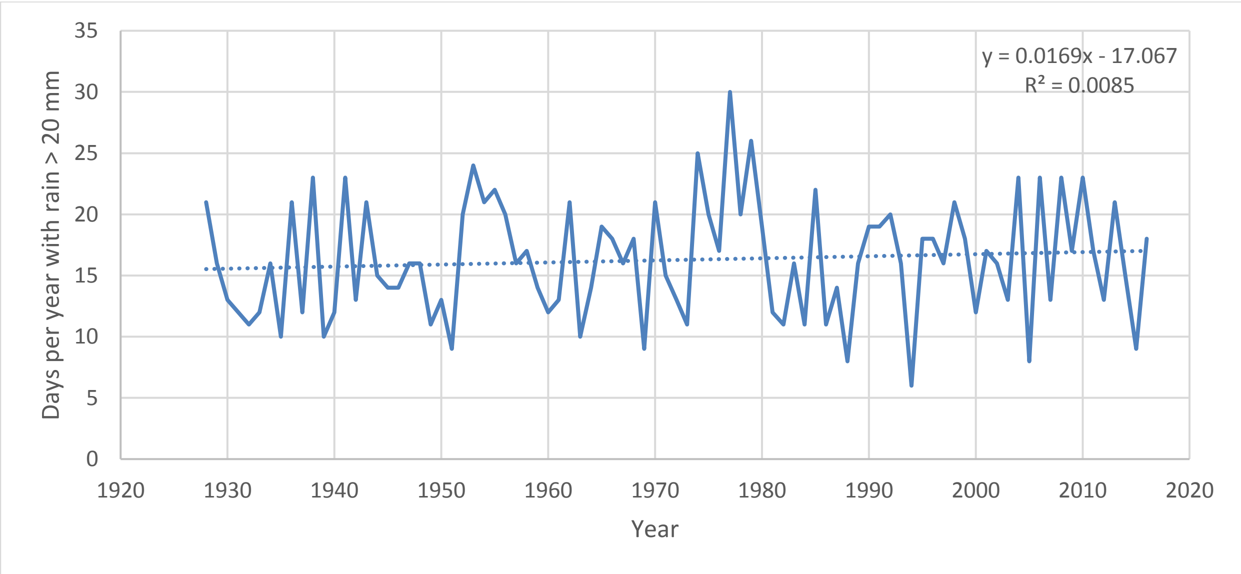

Figure 3-14: Number of days per year with >20 mm rainfall for Wellington (Kelburn), 1928-2016 (R20mm). Trend indicates an increase of heavy rain days of approximately 2 days per century, which is not significant at $p < 0.05$.

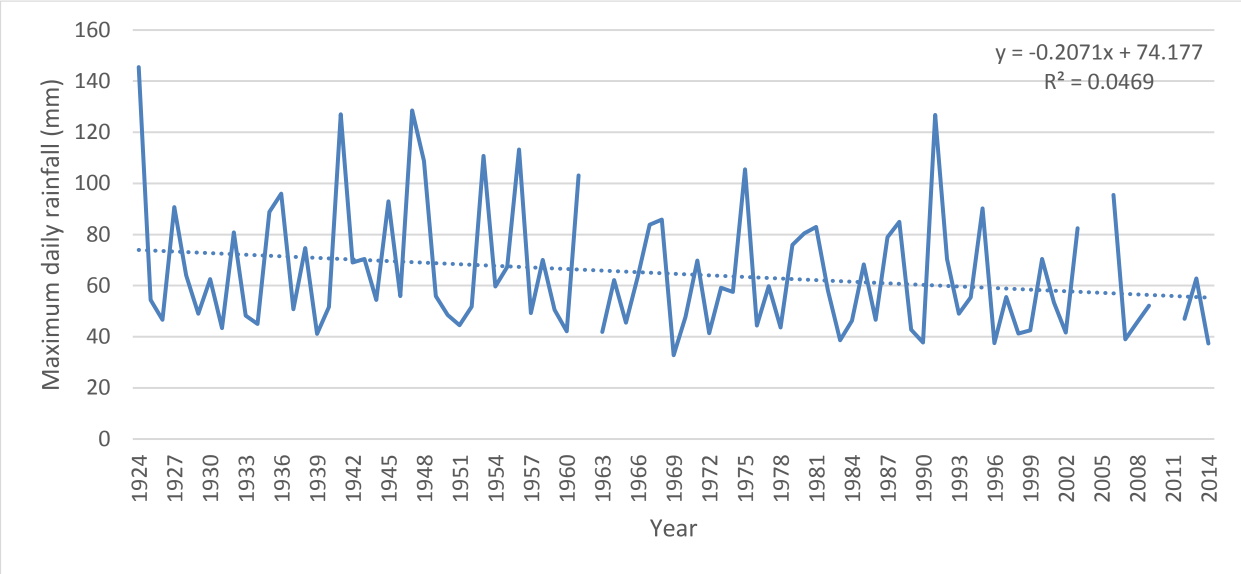

Figure 3-15: Maximum daily rainfall for Bagshot Station (12 km northeast of Masterton) – agent number 2446, 1924-2009 (Rx1day). 2012-2014 data are from Masterton, Te Ore Ore CWS station (agent number 37662). Note that data have not been homogenised. Trend indicates decrease in Rx1day of approximately 2mm/decade, which is significant at $p < 0.05$.

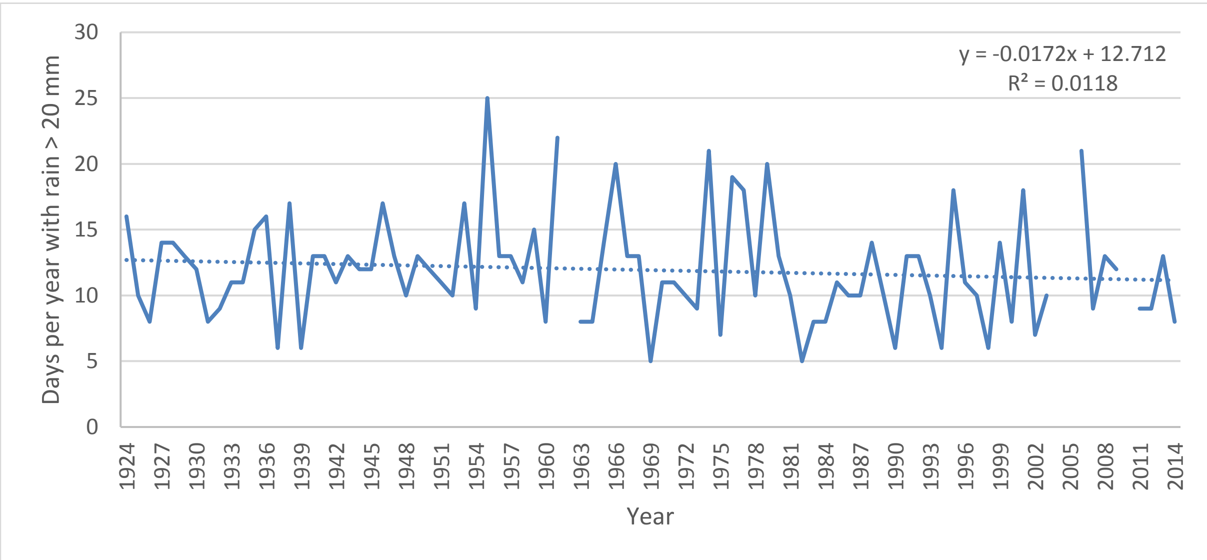

Figure 3-16: Number of days per year with >20 mm rainfall for Bagshot Station (12 km northeast of Masterton) – agent number 2446 (R20mm). 2010-2014 data are from Masterton, Te Ore Ore CWS station (agent number 37662). Note that data have not been homogenised. Trend indicates a decrease of heavy rain days of approximately 2 days per century, which is not significant at $p < 0.05$.

3.2.5 Growing degree days

The departure of mean daily temperature above a base temperature, which has been found to be critical to the growth or development of a particular plant, is a measure of the plant's development on that day. The sum of these departures above the base temperature then relates to the maturity or harvestable state of the crop. Thus, as the plant grows, updated estimates of harvest time can be made. These estimates have been found to be very valuable for a variety of crops with different base temperatures. Degree-day totals indicate the overall effects of temperature for a specified period, and can be applied to agricultural and horticultural production.

Growing degree-days (GDD) express the sum of daily temperatures above a selected base temperature (10˚C) that represent a threshold of 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. Figure 3-17 shows the median annual growing degree-day totals for base 10°C for the Wellington Region.

The daily GDD total is the amount the daily average temperature exceeds the threshold value (e.g. 10°C). The annual GDD total is usually accumulated over the period 1 July to 30 June.

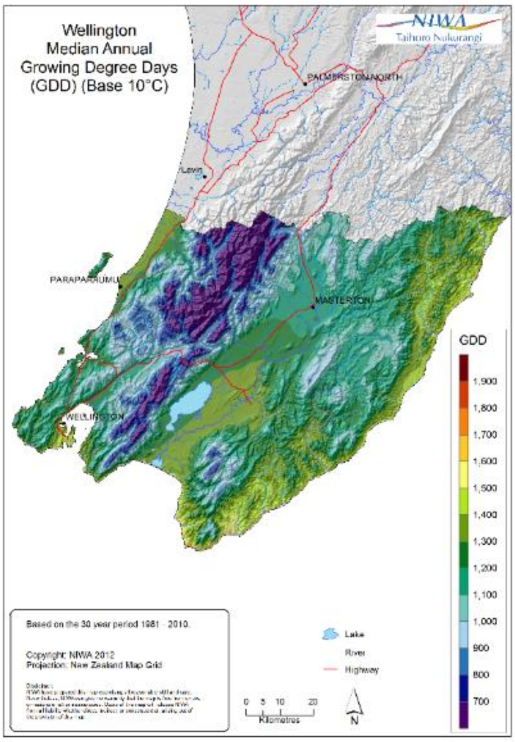

Figure 3-17: Median annual growing degree-days (base 10˚C) in the Wellington Region, 1981-2010. See text for explanation. © NIWA.

Air temperatures in the Wellington Region have increased over the past century (Section 3.2.1). As the calculation of growing degree-days is inherently dependent on temperature, there is also an upward trend in the number of growing degree-days (Figure 3-18). This will likely influence the types of crops that can be grown at a particular location, and also 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 may shift to an earlier time in the season.

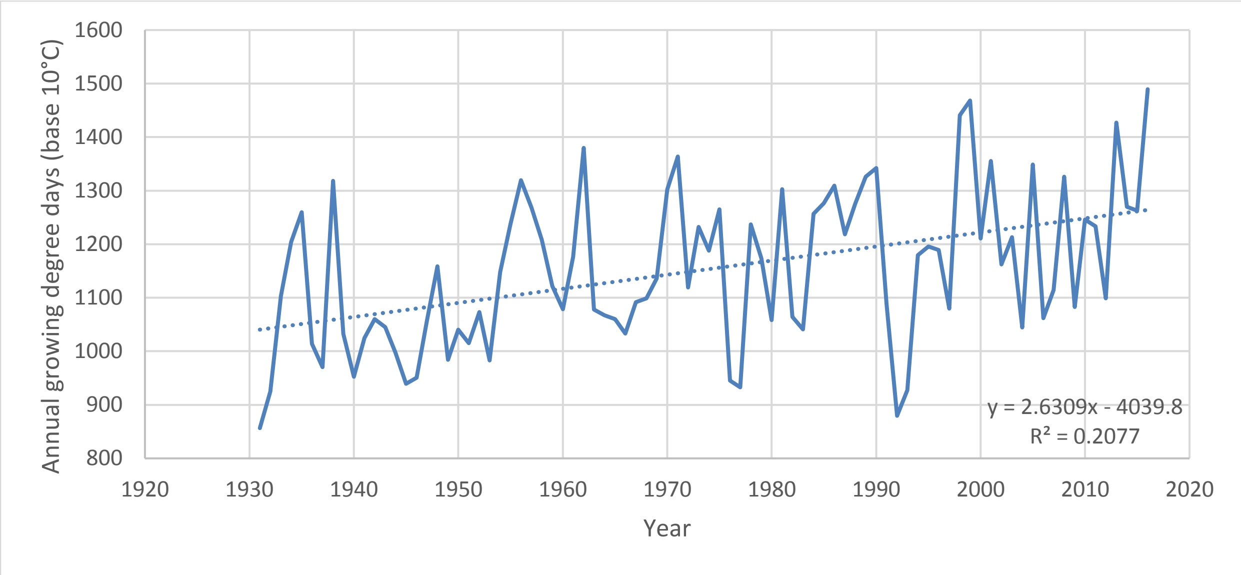

Figure 3-18: Annual growing degree days (base 10°C) at Wellington (Kelburn). This trend indicates an increase of approximately 3 GDD per year, which is significant at $p < 0.05$.

3.3 Natural factors causing fluctuation in climate patterns over New Zealand

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, 2008a).

3.3.1 The effect of El Niño and La Niña

The 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, 2008a). The oscillation involves a movement of warm ocean water from one side of the Pacific to the other, and the movement of rainfall across the Pacific associated with this warm water.

During El Niño, easterly trade winds weaken and warm water 'spills' across the Pacific towards the east, accompanied by higher rainfall than normal in the central-east Pacific. La Niña is essentially the opposite of this and is an intensification of 'normal' conditions, where the warm ocean waters remain over the western Pacific and the trade winds strengthen.

El Niño events occur on average 3 to 7 years apart, typically becoming established in April or May and persisting for about a year thereafter. The Southern Oscillation Index, or SOI, uses the pressure difference between Tahiti and Darwin to determine the state and intensity of ENSO. Persistence of about -1 signifies El Niño events, whereas +1 signifies La Niña (Figure 3-19).

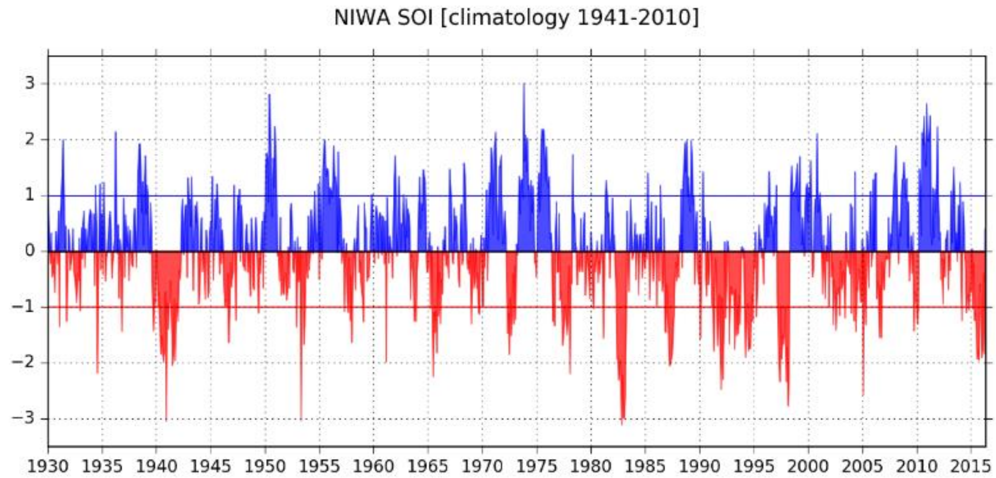

Figure 3-19: Time series of the Southern Oscillation Index from 1930 to 2016. Blue shades are indicative of La Niña periods and red shades are indicative of El Niño periods.

The effects of El Niño and La Niña are most clearly observed in the tropics, but impacts are well-recognised in New Zealand also. During El Niño events, the weakened trade winds cause New Zealand to experience a stronger than normal south-westerly airflow. This generally brings lower seasonal temperatures to the country and drier than normal conditions to the north and east of New Zealand.

During La Niña conditions, the strengthened trade winds cause New Zealand to experience more north-easterly airflow than normal, higher temperatures, and wetter conditions in the north and east of the North Island. In the South Island higher pressures are often dominant, which can cause drought conditions there. Therefore, drought conditions can persist in either El Niño or La Niña phases in the South Island. Figure 3-20 shows average summer rainfall anomalies in New Zealand associated with El Niño and La Niña conditions. However, individual ENSO events may have significantly different rainfall patterns to those pictured.

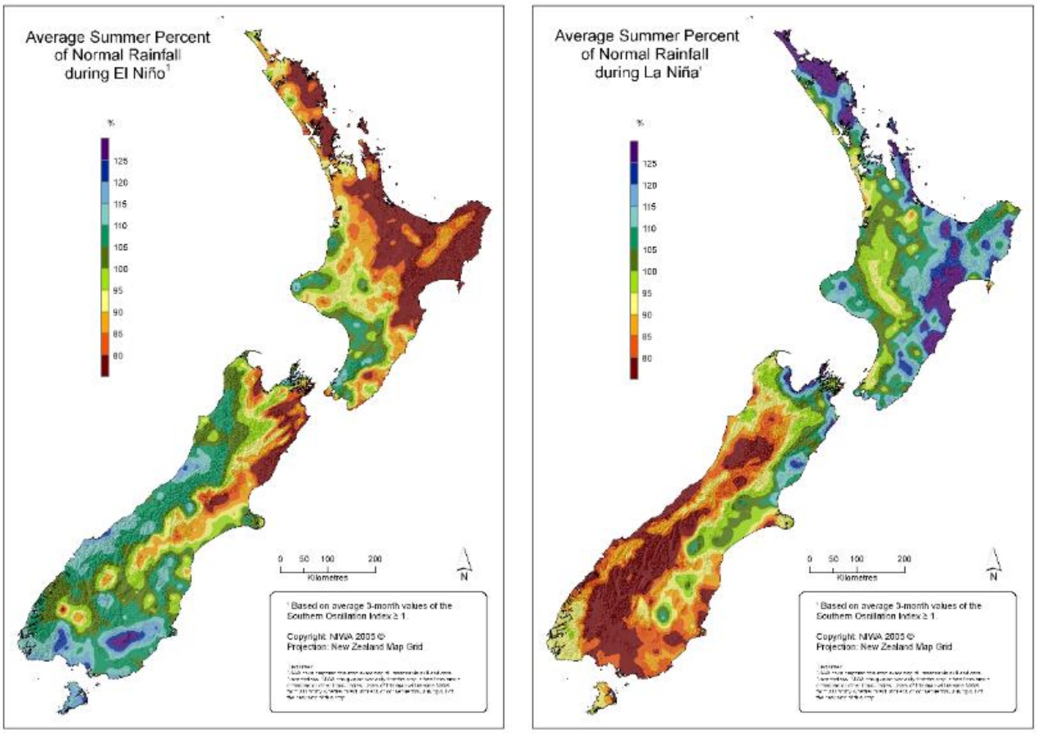

Figure 3-20: Average summer percentage of normal rainfall during El Niño (left) and La Niña (right). El Niño composite uses the following summers: 1963/64, 1965/66, 1968/69, 1969/70, 1972/73, 1976/77, 1977/78, 1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98, 2002/03. La Niña composite uses the following 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 and will be updated for the GWRC climate drivers project in 2018. © NIWA.

From Figure 3-20 it is evident that on average summer rainfall for the Wairarapa and around Wellington City is near or below normal during El Niño periods and near or above normal during La Niña periods. The Kapiti Coast and the ranges receive near or above normal rainfall during El Niño periods and near or below normal rainfall during La Niña periods.

According to the IPCC Assessment Report from Working Group I (IPCC, 2013), precipitation variability relating to ENSO will likely intensify due to increased moisture availability in the atmosphere. There is high confidence that ENSO will remain the dominant mode of natural climate variability in the 21st century. However, variations in the amplitude and spatial pattern of ENSO are large and therefore any specific projected changes in ENSO remain uncertain at this stage.

3.3.2 The effect of the Interdecadal Pacific Oscillation

The Interdecadal Pacific Oscillation, or 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 (Figure 3-21). During the positive phase of the IPO, sea surface temperatures around New Zealand tend to be lower, and westerly winds stronger, with the opposite occurring in the negative phase.

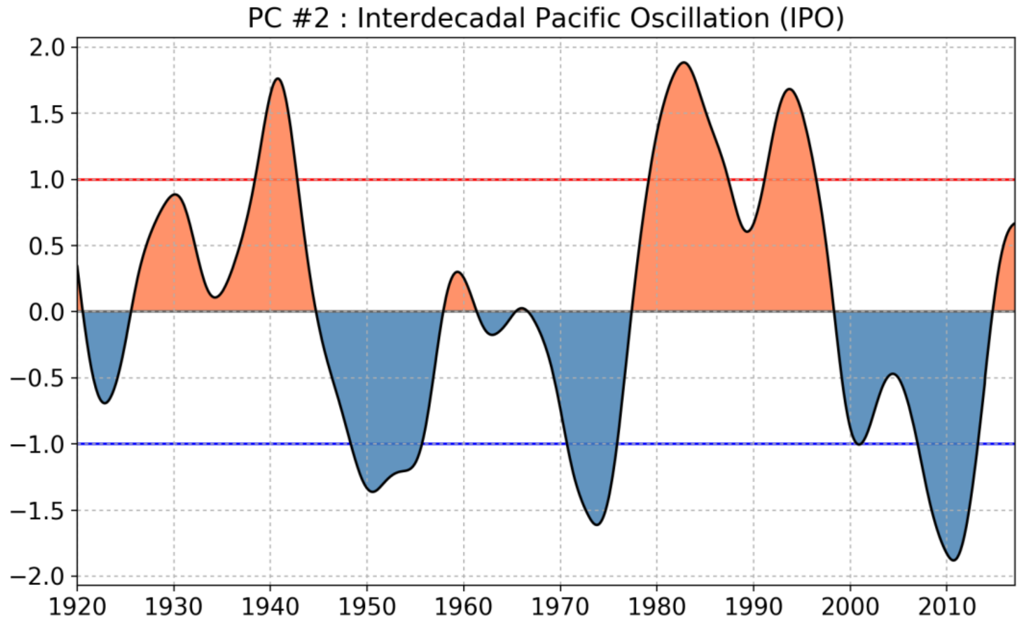

Figure 3-21: The Interdecadal Pacific Oscillation (IPO) index. Positive values indicate periods when stronger-than-normal westerlies occur over New Zealand, with more anticyclones than usual over northern New Zealand. Negative values indicate periods with more northeasterlies than normal over northern regions of the country. Vertical axis is the IPO index, and horizontal axis is the year. The IPO index used in this report is calculated as the 2nd Principal Component (PC) of time-filtered (low-pass filter, keeping only low frequency oscillations over 11 years) monthly sea surface temperature anomalies in the Pacific domain (50°S- 50°N, 120°E- 295°E) over the January 1920 – February 2017 period. The Dataset used is the Extended Reconstructed SST (ERSST) Dataset (Version 4) developed by the US National Oceanic and Atmospheric Administration (NOAA) and made available by the US National Climate Data Centre (NCDC).

New Zealand's climate appears to be affected by the long-term IPO cycle. The increase in New Zealand-wide temperatures around 1950 occurred shortly after the change from positive to negative phase of the IPO. In addition, the switch from negative to positive IPO phase in 1977-78 coincided with significant rainfall changes (Ministry for the Environment, 2008a).

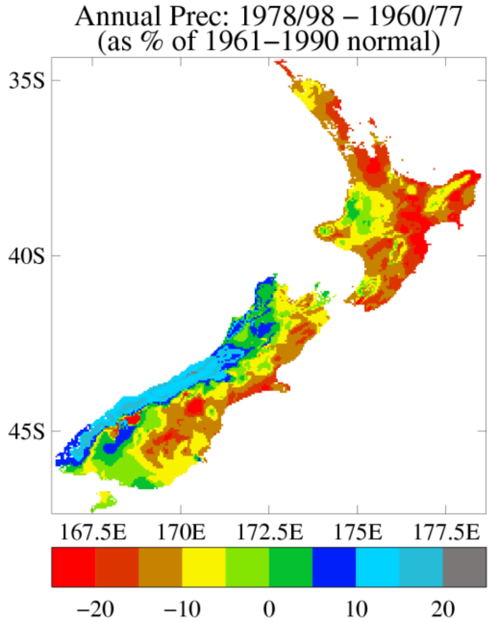

Figure 3-22: Percentage change in average annual rainfall, for the 1978-1998 period compared to the 1960-1977 period. (Note: From 1978-98 the IPO was in its positive phase, compared to the previous 18 years when the IPO was negative. Any local rainfall response due to global warming would also be contained within this pattern of rainfall trends). ©NIWA.

As suggested by Figure 3-22, periods of positive IPO (which generally coincide with increased El Niño activity) tend to be drier, on average, for the eastern parts of the Wellington Region (as well as Wellington City) and wetter for western parts of the region and the ranges. The IPO has recently switched to the positive phase.

During the period 1950-2004, a trend to increases in mean and extreme 1-day rainfall was generally observed in the west of both the North Island and South Island[2] (Griffiths, 2006). These results suggest a trend to increased westerly circulation across New Zealand between 1950 and 2004. This trend is consistent with enhanced warming since 1950 (as predicted by climate change modelling); the stronger IPO westerly phase since 1977; the increased frequency of El Niño events since 1977; or a mixture of all these considerations.

3.3.3 The effect of the Southern Annular Mode

The Southern Annular Mode (SAM) is a ring of climatic variability that encircles the South Pole and extends out to the latitudes of New Zealand, which affects 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 the Wellington Region, the positive SAM phase is associated with higher than normal daily maximum temperatures in central and western parts. 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. In the Wellington Region, lower than normal daily maximum temperatures are observed for central and western parts during the negative phase.

[2] The opposite behaviour – i.e. a trend to decreases in mean and extreme rainfall – was observed in the east of the North and South Islands.

In contrast to the longer-lived oscillations of ENSO and the IPO, each phase of the SAM may only last for a few weeks before switching to the opposite phase. The phase and strength of the SAM is influenced by the size of the ozone hole, with the past increase in ozone depleting substances giving rise to a positive trend in the phase of the SAM (Thompson et al., 2011). However, with the recovery of the ozone hole and reduction of ozone-depleting substances projected into the future, the trend of summertime SAM phases is expected to become more negative and stabilise slightly above zero (i.e., it is expected that there will be slightly more positive SAM phases than negative phases. Note that the phases of the SAM are defined relative to the historical climate). However, increasing concentration of greenhouse gases in the atmosphere will have the opposite effect, of an increasing positive trend in summer and winter SAM phases, i.e. there will be more positive phases than negative phases into the future (Figure 3-23). The net result for SAM behaviour, as a consequence of both ozone recovery and greenhouse gas increases, is therefore likely to be relatively little change from present by 2100. However, other drivers are likely to have an impact on SAM behaviour into the future, particularly changes to sea ice around Antarctica as well as changing temperature gradients between the equator and the high southern latitudes which could have an impact on zonal (westerly) wind strength in the mid-high latitudes.

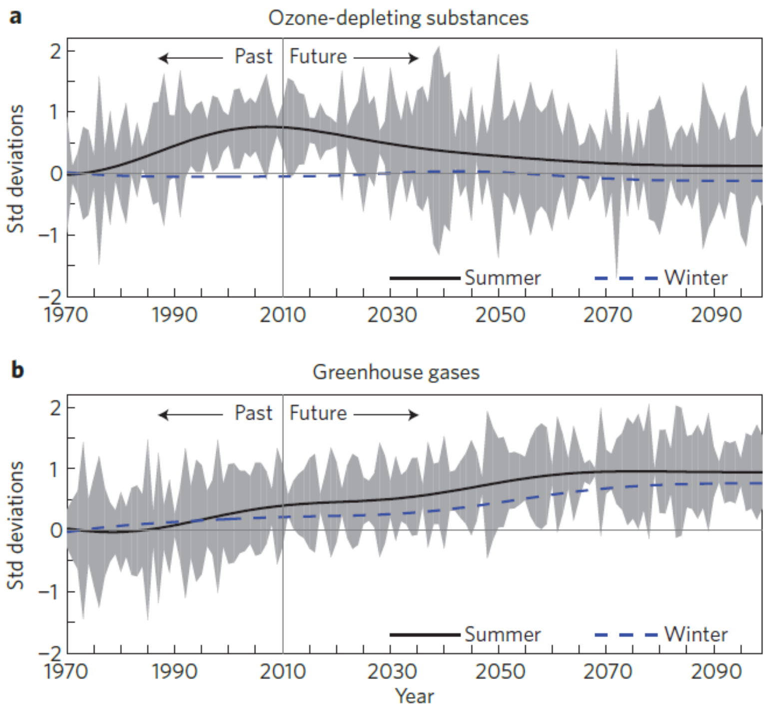

Figure 3-23: Time series of the Southern Annular Mode from transient experiments forced with time-varying ozone-depleting substances and greenhouse gases. a. Forcing with ozone-depleting substances; b. forcing with greenhouse gases. The SAM index is defined as the leading principal component time series of 850-hpa Z (i.e. westerly wind flow) anomalies 20-90°S; positive values of the index correspond to anomalously low Z (i.e. fewer westerly winds) over the polar cap, and vice versa. Lines denote the 50-year low-pass ensemble mean response for summer (DJF, solid black) and winter (JJA, dashed blue). Grey shading denotes +/- one standard deviation of the three ensemble members about the ensemble mean. The long-term means of the time series are arbitrary and are set to zero for the period 1970-1975. Past forcings are based on observational estimates; future forcings are based on predictions. After Thompson et al. (2011).

4 Projections of future climate changes to 2100

The future climate of the Wellington Region will be influenced by a combination of the effects of anthropogenic climate change (increasing global concentrations of greenhouse gases, Section 2) plus the natural year-to-year and decade-to-decade variability resulting from “climate noise” and activity from phenomena such as El Niño-Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO), and the Southern Annular Mode (SAM) as discussed in Section 3. This section outlines the projected changes due to anthropogenic climate change in the Wellington Region, and then returns to the issue of natural variability in Section 7. Note that the projected changes use 20-year averages, which will not entirely remove effects of natural variability.

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

This has been dealt with by the Intergovernmental Panel on Climate Change through consideration of ‘scenarios’ that describe concentrations of greenhouse gases in the atmosphere associated with a range of possible economic, political, and social developments during the 21st century, and via consideration of results from several different climate models for any given scenario. In the 2013 IPCC Fifth Assessment Report, the atmospheric greenhouse gas concentration component of these scenarios are called Representative Concentrations Pathways (RCPs).

In Sections 4.1 and 4.2, global climate model outputs based on two RCPs have been downscaled to produce future projections of temperature and precipitation for the Wellington Region. The RCPs are based on 21st century climate policies, and thus differ from the previous IPCC SRES emissions scenarios and their ‘no-climate policy’ (IPCC, 2013). RCP4.5 is a low-to-mid range emissions scenario, which is also referred to a ‘stabilisation’ scenario where radiative forcing stabilises by 2100. RCP8.5 is a scenario with very high greenhouse gas emissions, and radiative forcing continues to increase beyond 2100. RCP8.5 is also known as the ‘business as usual’ scenario. Each RCP provides spatially-resolved data sets of land use change and sector-based emissions of air pollutants, and it specifies annual greenhouse gas concentrations and anthropogenic emissions up to 2500 (although this report only considers changes to 2100). RCPs are based on a combination of integrated assessment models, simple climate models, atmospheric chemistry and global carbon cycle models.

NIWA has used climate model simulation data from the IPCC Fifth Assessment (IPCC, 2013) to update climate change scenarios for New Zealand through both a regional climate model (dynamical) and statistical downscaling processes. The dynamical and statistical downscaling processes are described in detail in an updated climate guidance manual prepared for the Ministry for the Environment (Mullan et al., 2016), but a short explanation is provided below. Dynamical downscaling results are presented for all variables, and statistical downscaling results are presented for mean temperature and precipitation projections.

All climate projections start as simulations from global climate models, which have coarse spatial resolution of the atmosphere and ocean. Dynamical downscaling utilises a high-resolution climate model or weather prediction model to obtain finer scale detail from a coarser global model simulation (5 km resolution in this report, which corresponds to the VCSN[3] grid). Statistical downscaling uses statistical relationships (or sometimes simple interpolation) to relate the large-scale climate simulation outputs (which are gridded) to the smaller scale (either regional, catchment or local station scale). Several different models are used to simulate future New Zealand climate (six for dynamical downscaling and up to 41 for statistical downscaling). The projections from each of these models are averaged together, creating an ensemble average (which is displayed in the figures in this section). See Glossary for IPCC definition of downscaling.

Note that in the maps in the following sections there are some pixels around the coast of the Wellington Region where no projection data are displayed. Data is downscaled only where low resolution cells in the model consist of land coverage and where they overlap high resolution cells. In most cases, interpolating over mixed sea and land points creates artificial biases, for example lower temperatures. A total of 40 data points are missing from the 5km VCSN grid. In addition, some coastal features seen in the downscaled results arise due to coarse 5 km grid resolution.

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

4.1 Changes to temperature

The magnitude of the temperature change projections varies with the RCP and also with the climate models used. In this report, temperature projections were carried out by dynamical downscaling of two RCPs using NIWA's Regional Climate Model - a stabilisation scenario (RCP4.5) and a high emissions scenario (RCP8.5).

4.1.1 Mean temperature projections

The seasonal patterns of projected temperature changes over the Wellington Region for 2040 based on the RCP4.5 scenario are shown in Figure 4-1. Figure 4-2 shows corresponding patterns for 2090. Figure 4-3 shows the seasonal patterns of projected temperature increase for 2040 for the RCP8.5 scenario, and Figure 4-4 shows the corresponding patterns for 2090. These nominal years represent the mid-points of bi-decadal periods: 2040 is the average over 2031-2050, and 2090 the average over 2081-2100. All maps show changes relative to the baseline climate of 1986-2005 (1995).

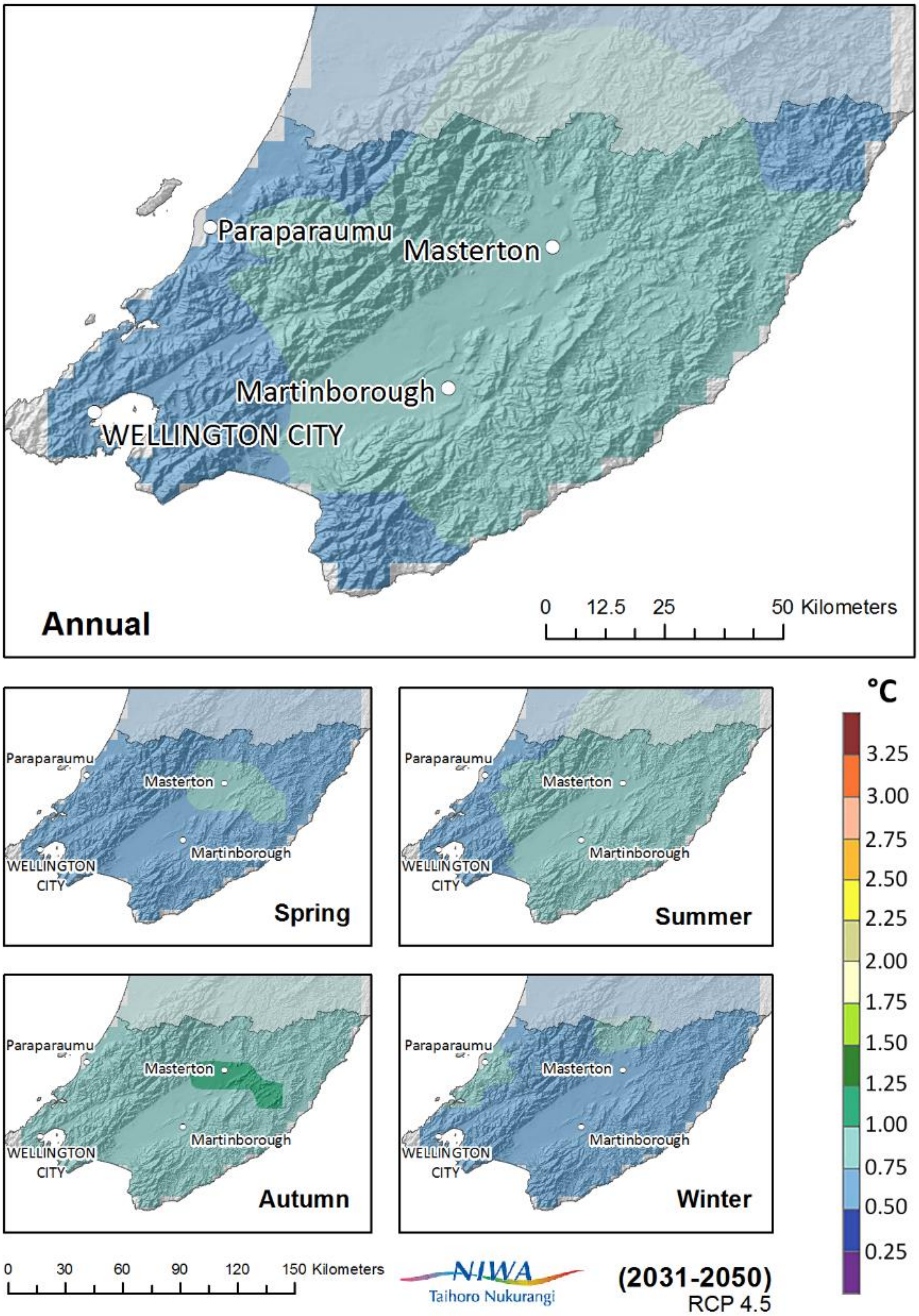

Figure 4-1: Projected annual and seasonal mean temperature changes at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

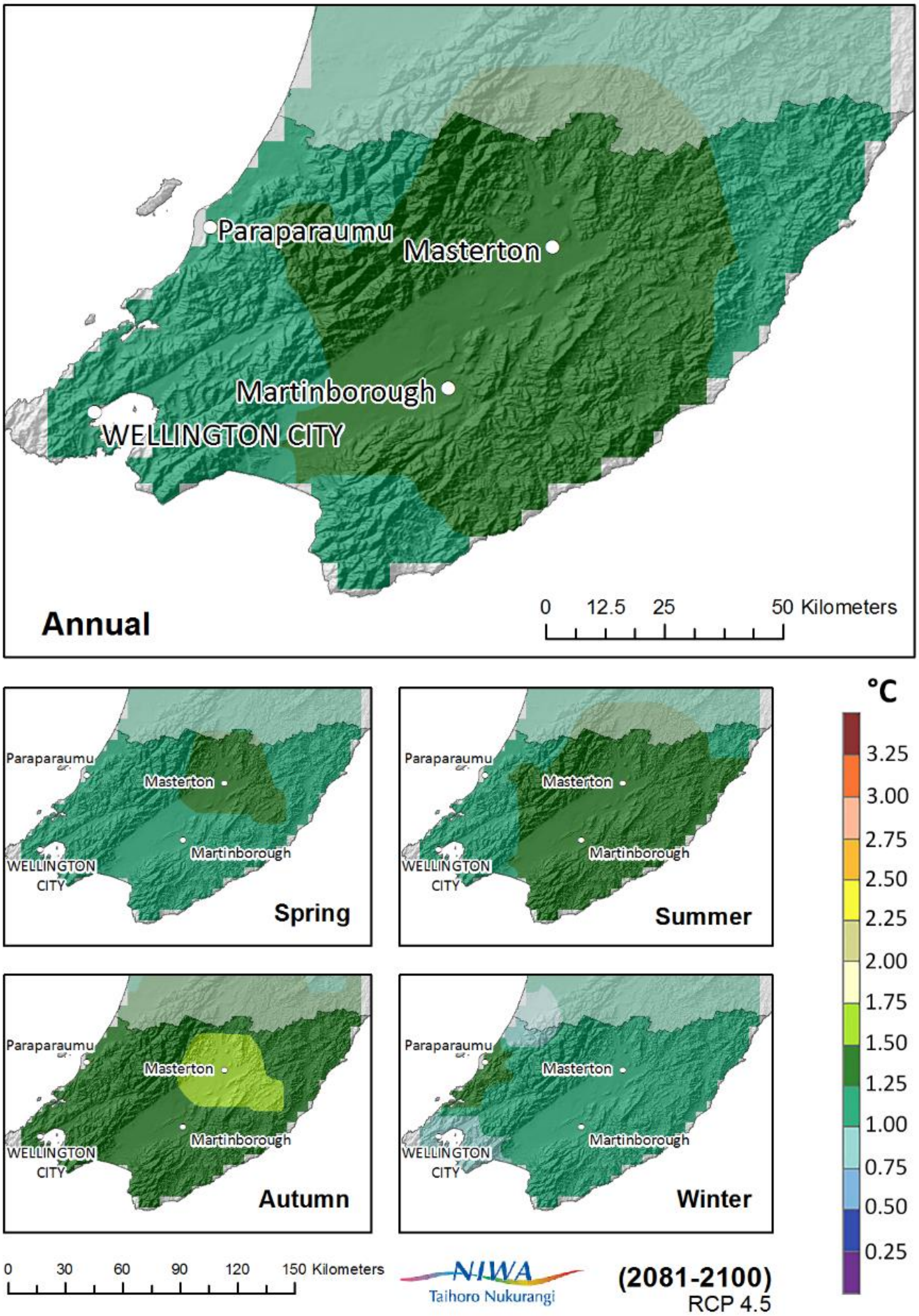

Figure 4-2: Projected annual and seasonal mean temperature changes at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

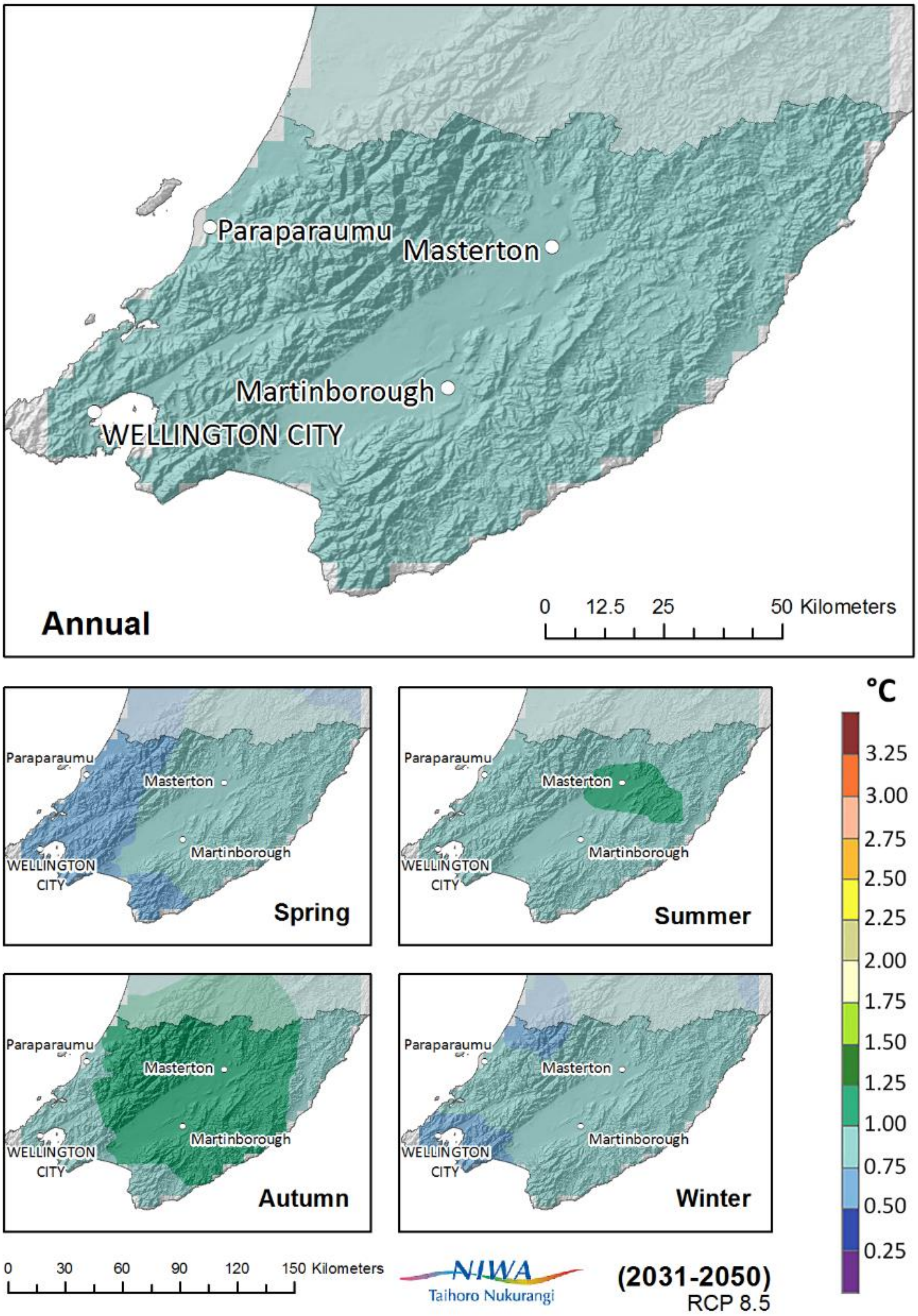

Figure 4-3: Projected annual and seasonal mean temperature changes at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

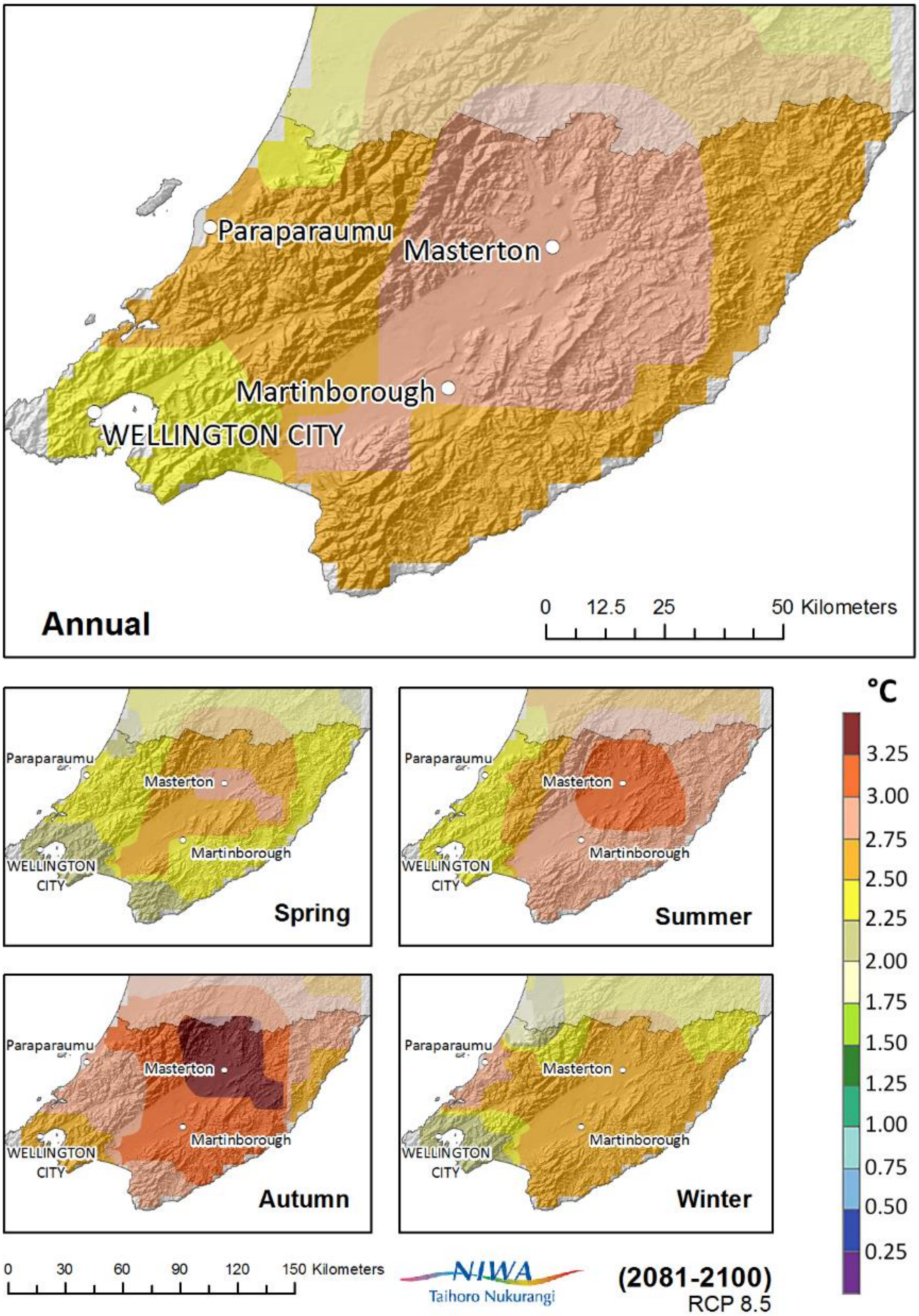

Figure 4-4: Projected annual and seasonal mean temperature changes at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

As shown by Figure 4-1, projected future warming in the Wellington Region at 2040 under the RCP4.5 scenario is more pronounced for inland and eastern areas, when the average result from six downscaled climate models is considered. Most warming is between 0.50-1.00˚C under this scenario. Around and to the east of Masterton, warming of up to 1.25˚C is observed in autumn. Figure 4-2 shows mean seasonal temperature change under RCP4.5 at 2090. A similar pattern is shown to Figure 4-1, but the magnitude of warming is larger. The season with the largest change is autumn, with a large area around Masterton projected to experience increases of up to 1.75°C.

Figure 4-3 shows projected warming for the Wellington Region under RCP8.5 at 2040 – warming of >0.5˚C is observed everywhere, and most of the region inland from the coastal margins is projected to warm by up to 1.25°C in autumn. By 2090 under RCP8.5 (Figure 4-4), significant warming is observed over the entire Wellington Region, with spring observing the least amount of warming and autumn observing the most. The area around and to the north and east of Masterton is projected to experience increases by more than 3.25°C in autumn. At the annual scale, minimum warming of 2.25°C is projected for the region.

Model agreement is very good for mean temperature projections as all models project an increase under both RCPs at both time periods.

Some models indicate less warming while others show a faster rate of warming (IPCC, 2013). The full range of model-projected warming for the Wellington Region as a whole based on statistical downscaling methods, is given in Table 4-1, while Table 4-2 shows the results from dynamical downscaling methods (the maps in this report present dynamical downscaled projections). The temperature ranges are relative to the baseline period 1986-2005 (1995; as used by IPCC). Hence the projected changes at 2040 and 2090 should be thought of as 45-year and 95-year projected trends. The seasonal and annual ensemble average projection (the number outside the brackets) in Table 4-1 is the temperature increase averaged over all 23 models for RCP2.6, 37 models for RCP4.5, 18 models for RCP6.0, and 41 models for RCP8.5 analysed by NIWA. The bracketed numbers give the range (5th and 95th percentile) for each RCP for each season and the annual projection. For Table 4-2, the ensemble average projection is given outside the brackets (six models) and the bracketed numbers give the range (minimum and maximum) for each RCP for each season and the annual projection.

Table 4-1: Projected changes in seasonal and annual mean temperature (in °C) for the Wellington Region for 2031-2050 (2040) and 2081-2100 (2090), as derived from statistical downscaling. Changes are relative to the baseline period, 1986-2005 (1995). The changes are given for all four RCPs (2.6, 4.5, 6.0, 8.5), where the ensemble-average is taken over (23, 37, 18, 41) models, respectively. The first number is the ensemble average, with the bracketed numbers giving the range (5th and 95th percentile). This table is based on statistical downscaled projections. After Mullan et al. (2016).

Period	RCP	Summer	Autumn	Winter	Spring	Annual
2040	RCP8.5	1.1 (0.5, 1.7)	1.1 (0.7, 1.5)	1.2 (0.7, 1.6)	0.9 (0.4, 1.3)	1.1 (0.6, 1.6)
	RCP6.0	0.8 (0.3, 1.4)	0.9 (0.2, 1.2)	0.8 (0.3, 1.3)	0.7 (0.2, 1.1)	0.8 (0.3, 1.2)
	RCP4.5	0.9 (0.4, 1.4)	0.9 (0.4, 1.4)	1.0 (0.6, 1.3)	0.8 (0.4, 1.1)	0.9 (0.5, 1.2)
	RCP2.6	0.7 (0.2, 1.2)	0.8 (0.3, 1.2)	0.7 (0.3, 1.1)	0.7 (0.3, 1.0)	0.7 (0.3, 1.1)
2090	RCP8.5	3.1 (2.2, 4.7)	3.1 (2.2, 4.4)	3.2 (2.4, 4.2)	2.7 (1.9, 3.6)	3.0 (2.2, 4.3)
	RCP6.0	1.9 (1.0, 3.6)	1.9 (1.0, 3.1)	1.9 (1.2, 2.9)	1.6 (1.0, 2.4)	1.8 (1.1, 2.8)
	RCP4.5	1.4 (0.7, 2.6)	1.5 (0.8, 2.2)	1.5 (0.9, 2.1)	1.3 (0.7, 1.9)	1.4 (0.9, 2.1)
	RCP2.6	0.7 (0.2, 1.4)	0.7 (0.1, 1.5)	0.7 (0.3, 1.3)	0.6 (0.2, 1.2)	0.7 (0.3, 1.3)

By 2040 (the central year of the 2031-2050 interval, relative to 1986-2005), annual average temperatures are projected to increase by between about 0.7°C (RCP2.6) and 1.1°C (RCP8.5). Summer, autumn and winter have similar projections for warming across the regions, and the least warming is projected for spring. By 2090 (2081-2100, relative to 1986-2005), annual average temperatures are projected to increase by between 0.7°C (RCP2.6) and 3.0°C (RCP8.5). Similar to 2040, summer, autumn and winter have similar projections for warming, and the least warming is projected for spring. Note that the mitigation scenario (RCP2.6) temperature change for 2090 is less than or the same as the change for 2040 for some seasons in all regions, whereas all other emissions scenarios show increased warming at 2090 relative to 2040.

Although there is considerable variability between the ensemble members for each RCP (the numbers inside the brackets show the 5th and 95th percentiles), the direction of change in mean annual and seasonal temperature is positive for all RCPs.

Table 4-2: Projected changes in seasonal and annual mean temperature (in °C) for the Wellington Region for 2031-2050 (2040) and 2081-2100 (2090), as derived from dynamical downscaling. Changes are relative to the baseline period, 1986-2005. The changes are given for all four RCPs (2.6, 4.5, 6.0, 8.5), where the ensemble-average is taken over six models. The first number is the ensemble average, with the bracketed numbers giving the range (minimum and maximum). This table is based on dynamical downscaled projections.

Period	RCP	Summer	Autumn	Winter	Spring	Annual
2040	RCP8.5	0.9 (0.5, 1.3)	1.0 (0.8, 1.4)	0.8 (0.6, 1.1)	0.8 (0.5, 1.1)	0.9 (0.6, 1.2)
	RCP6.0	0.7 (0.5, 1.0)	0.9 (0.6, 1,1)	0.7 (0.5, 0.9)	0.6 (0.4, 0.7)	0.7 (0.5, 0.9)
	RCP4.5	0.8 (0.3, 1.1)	0.9 (0.5, 1.2)	0.7 (0.5, 0.9)	0.7 (0.4, 0.9)	0.8 (0.5, 1.0)
	RCP2.6	0.7 (0.3, 1.1)	0.6 (0.3, 0.8)	0.6 (0.3, 0.9)	0.5 (0.3, 0.8)	0.6 (0.4, 0.9)
2090	RCP8.5	2.8 (1.9, 3.5)	3.0 (2.2, 3.8)	2.5 (1.9, 3.0)	2.4 (1.9, 2.9)	2.7 (2.0, 3.2)
	RCP6.0	1.7 (1.1, 2.4)	1.9 (1.2, 2.4)	1.6 (1.1, 2.0)	1.6 (1.2, 2.0)	1.7 (1.2, 2.2)
	RCP4.5	1.3 (0.6, 2.0)	1.4 (0.9, 1.9)	1.1 (0.8, 1.6)	1.2 (0.7, 1.6)	1.2 (0.7, 1.7)
	RCP2.6	0.6 (0.1, 1.0)	0.7 (0.3, 1.2)	0.6 (0.2, 1.0)	0.5 (0.3, 0.8)	0.6 (0.2, 1.0)

The dynamical downscaled mean temperature projections in Table 4-2 are consistent with the statistical downscaled projections in Table 4-1, in that warming is projected everywhere, and the results for each RCP and each time period, season, and annual scale are similar.

4.1.2 Maximum and minimum temperature projections

Projected changes in daytime maximum (Tmax), nighttime minimum (Tmin) and diurnal temperature range (Trange, the difference between Tmax and Tmin) are presented in this section. These variables are available from the Regional Climate Model dynamical downscaling.

The ensemble of regional climate model temperature projections is based on the six best performing models for the New Zealand region (Mullan et al., 2016). The temperature trends are positive over the whole Wellington Region for both RCP 4.5 and RCP 8.5, but are neither spatially homogeneous nor of equal magnitude. The minimum, maximum and the diurnal range of temperature changes are documented for all seasons and two future periods in Figure 4-5 to Figure 4-16.

The positive maximum temperature trends (Tmax) (Figure 4-5 to Figure 4-8) are larger than minimum temperature trends (Tmin) (Figure 4-9 to Figure 4-12), resulting in an increase in the diurnal temperature range (Trange) (Figure 4-13 to Figure 4-16). Tmax is projected to increase by more than 3.25°C for most of the Wellington Region under RCP8.5 at 2090 for all seasons and the annual average, but the extent of Tmax increase is less for spring (less than 3.25°C). Tmin is projected to increase by around 2.00-2.25°C for most of the region in spring, summer, and for the year as a whole at 2090 for RCP8.5, but more (around 2.75°C) in autumn and less (around 1.75-2.00°C) in winter.

The Trange increase is largest in the summer and winter seasons over eastern parts of the Wellington Region, with eastern parts of the region expected to experience approximately 1.50°C increase in Trange for the year as whole by 2090 under RCP8.5. In general for NIWA's 7-station series (including two sites in Wellington Region at Masterton and Kelburn), the historical warming rates have been higher for the minimum than the maximum temperatures at all but one site (Nelson) (i.e., Trange has been decreasing over time).

Model agreement is good for maximum and minimum temperature projections, as well as temperature range, as all models project an increase under both RCPs at both time periods.

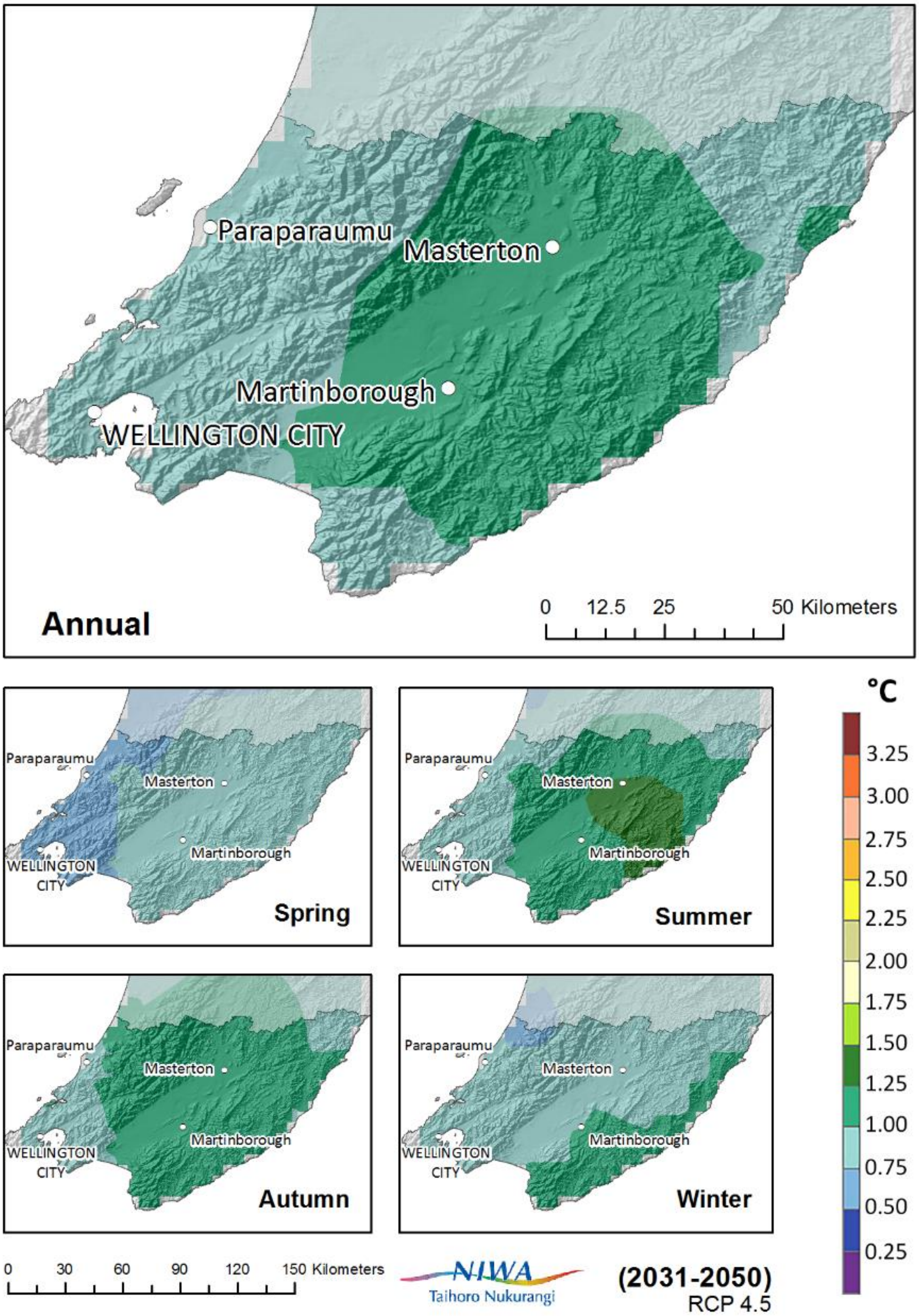

Figure 4-5: Projected annual and seasonal daily mean maximum temperature changes at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

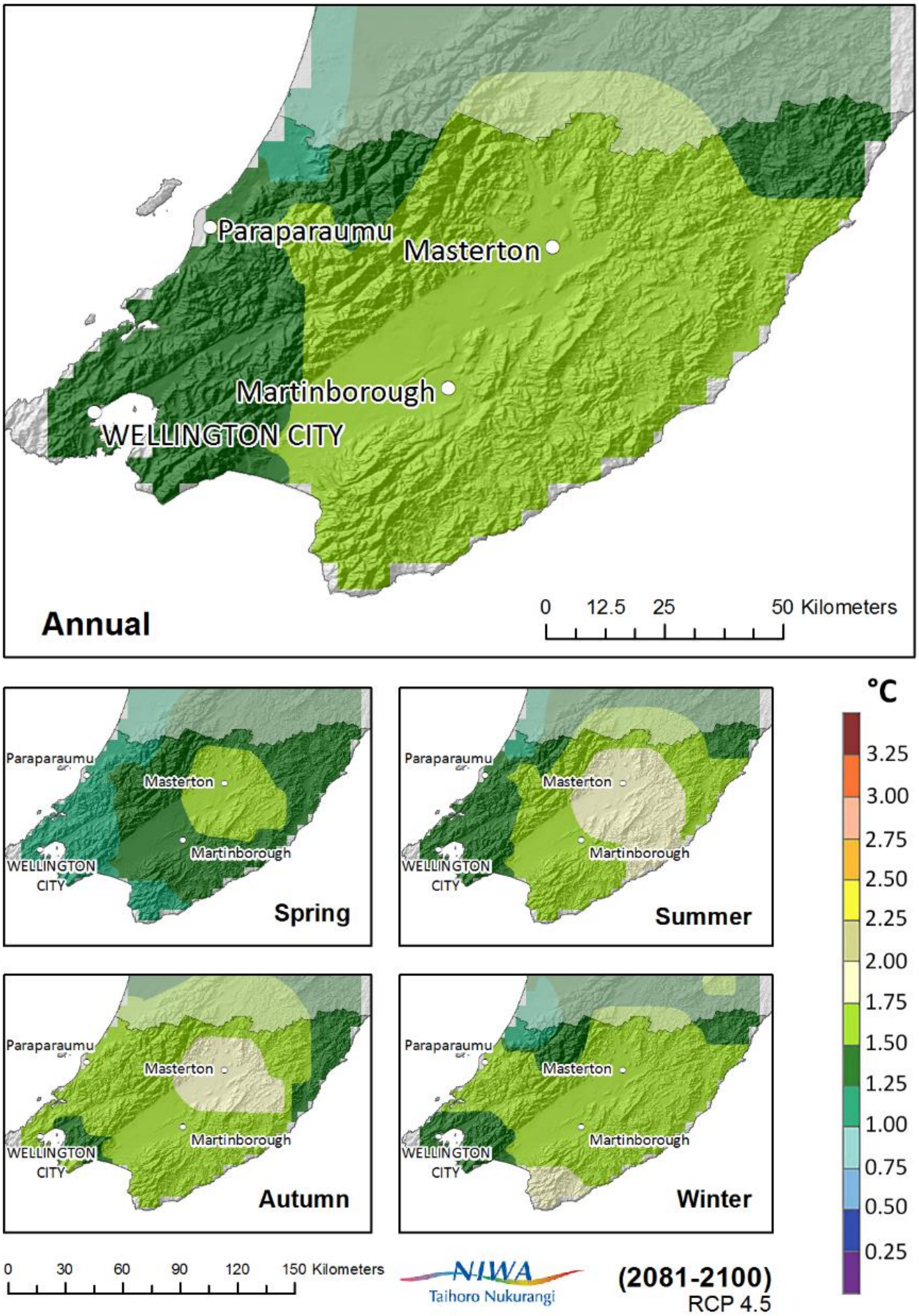

Figure 4-6: Projected annual and seasonal daily mean maximum temperature changes at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

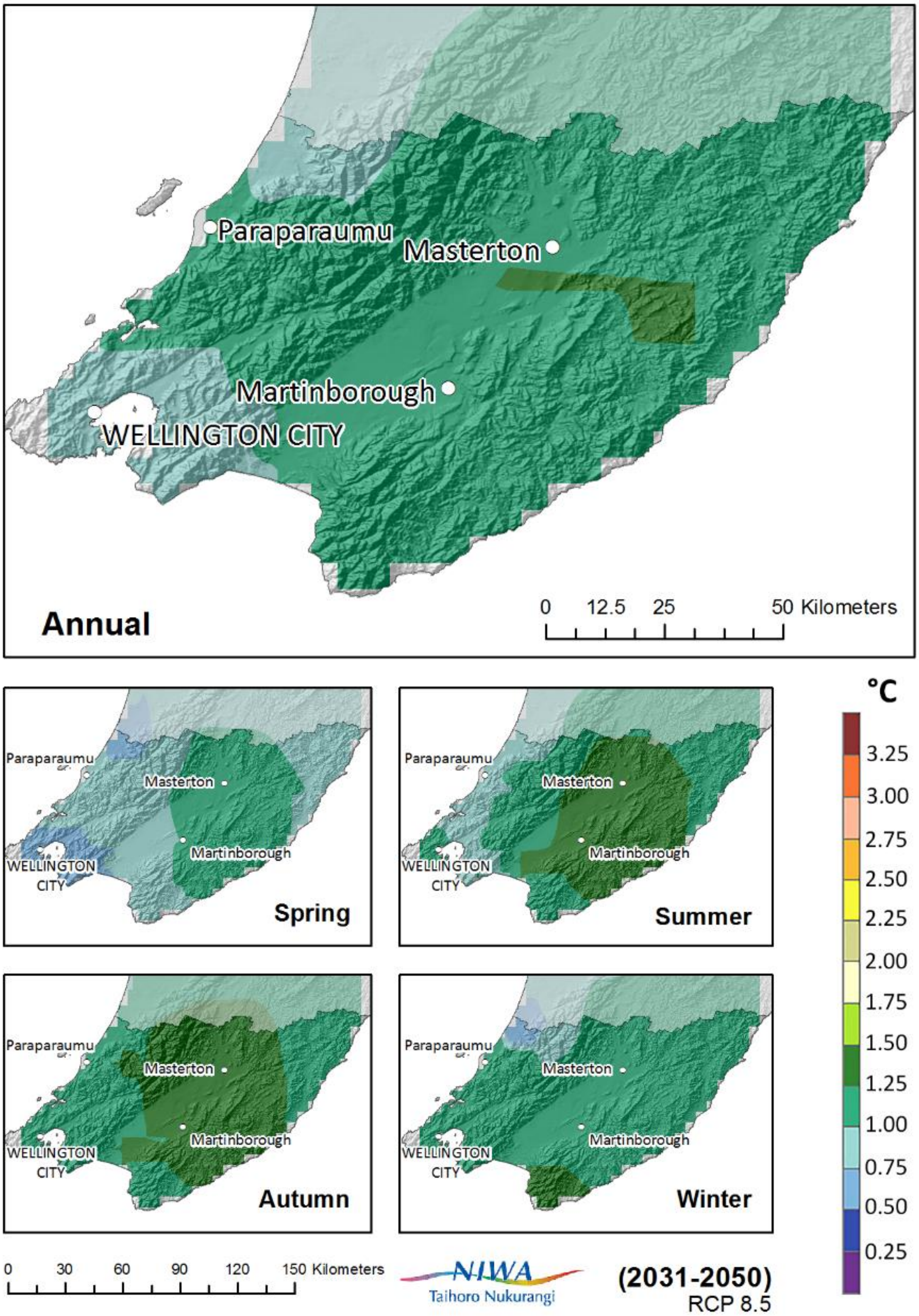

Figure 4-7: Projected annual and seasonal daily mean maximum temperature changes at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

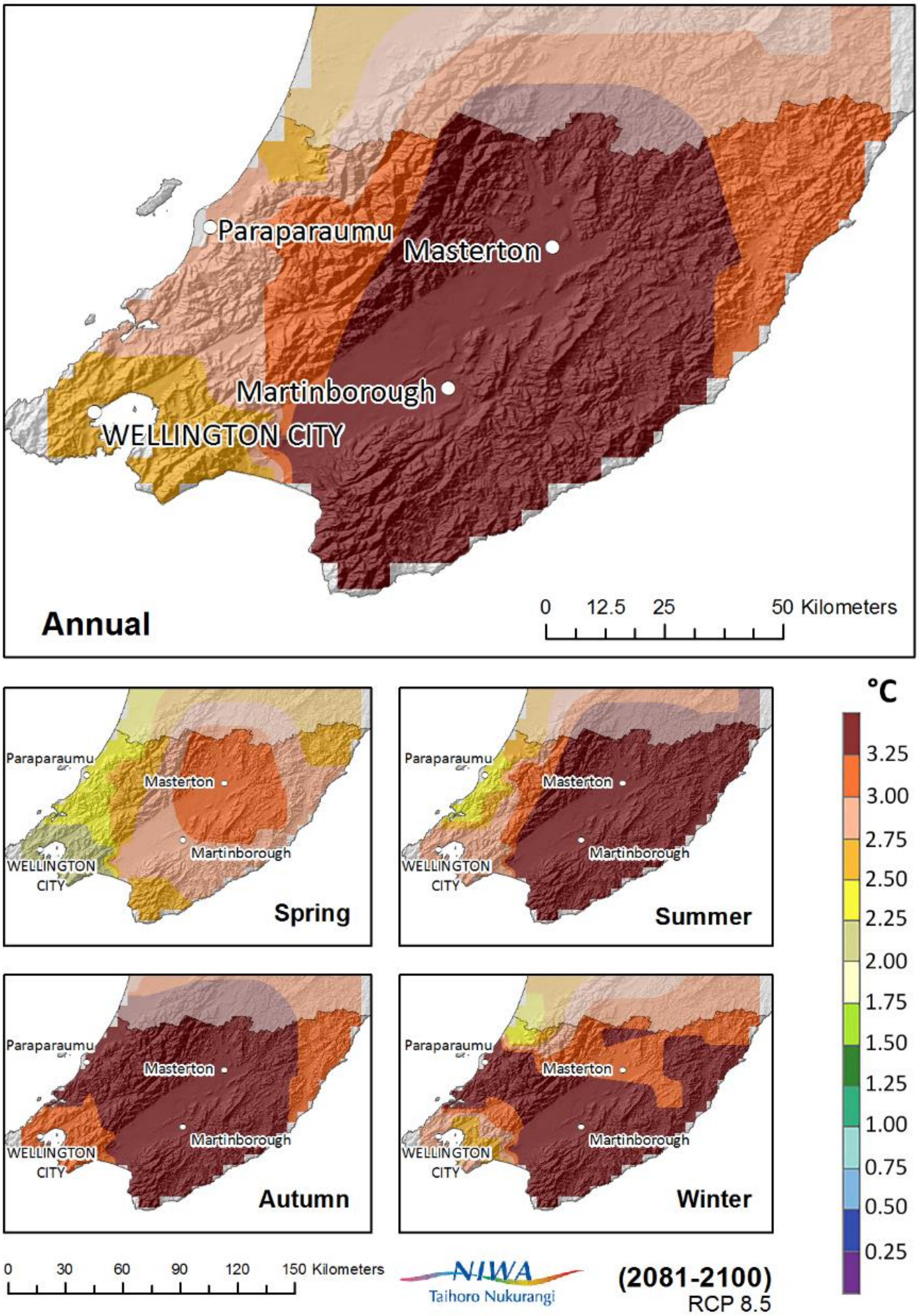

Figure 4-8: Projected annual and seasonal daily mean maximum temperature changes at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

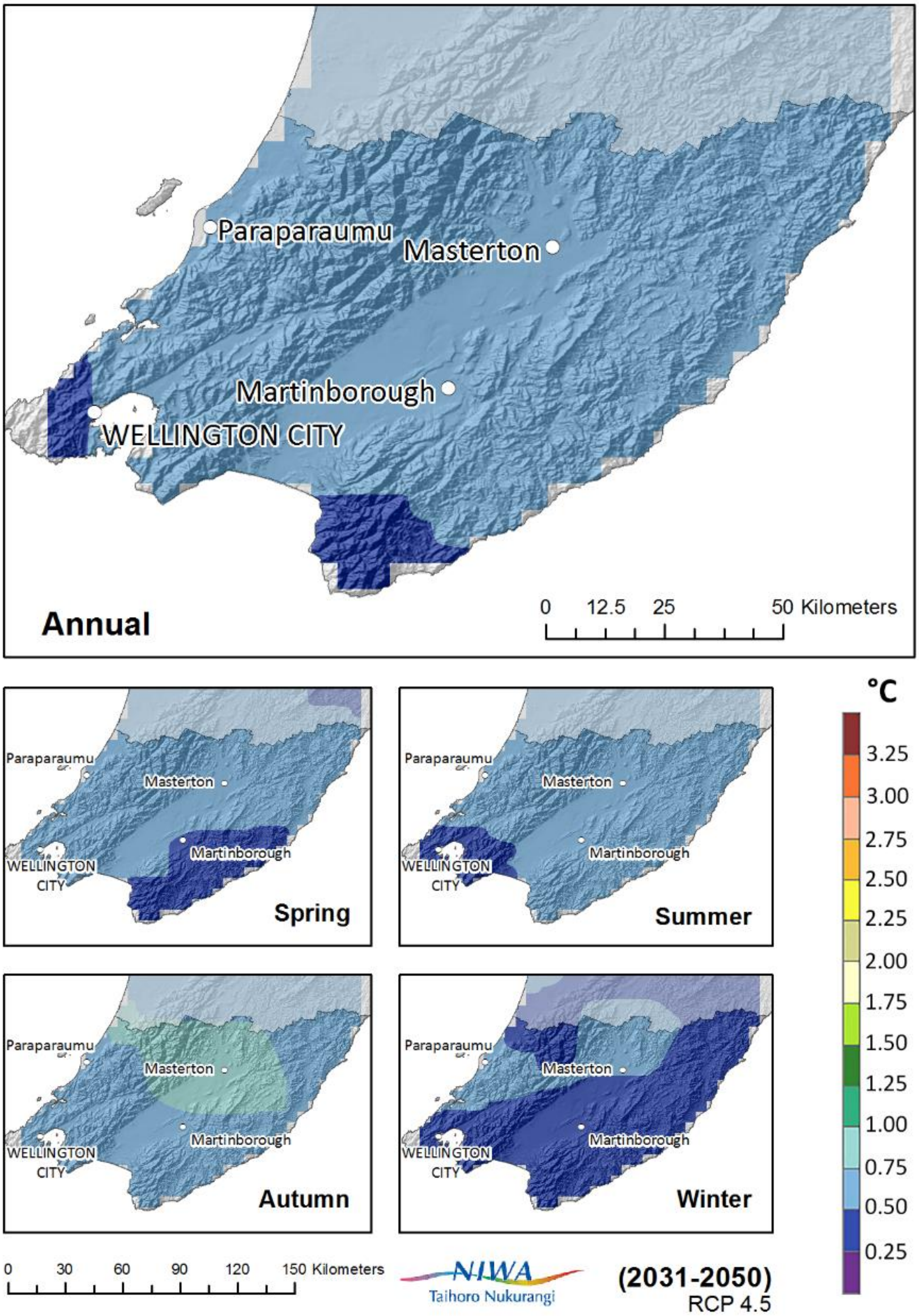

Figure 4-9: Projected annual and seasonal daily mean minimum temperature changes at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

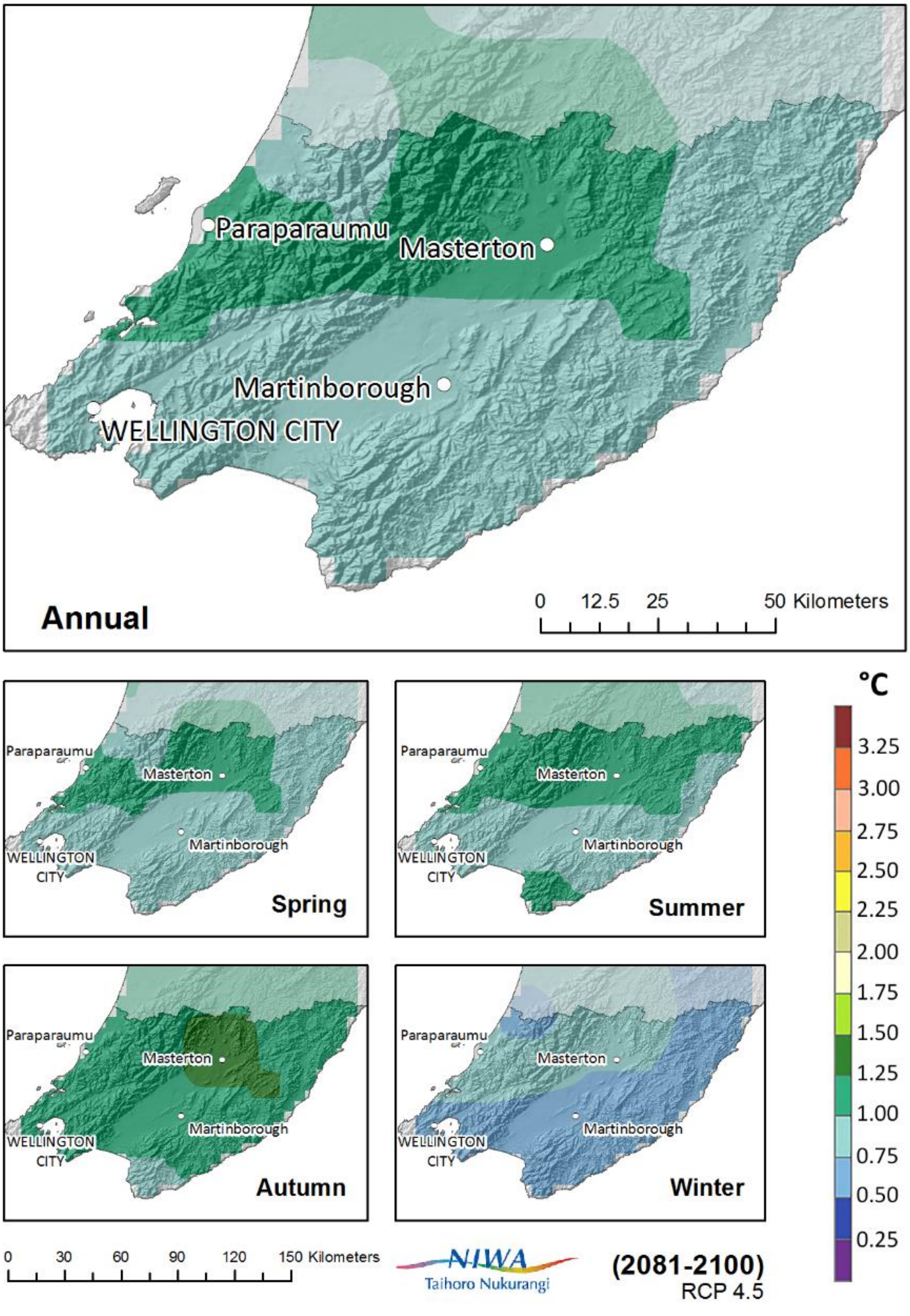

Figure 4-10: Projected annual and seasonal daily mean minimum temperature changes at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

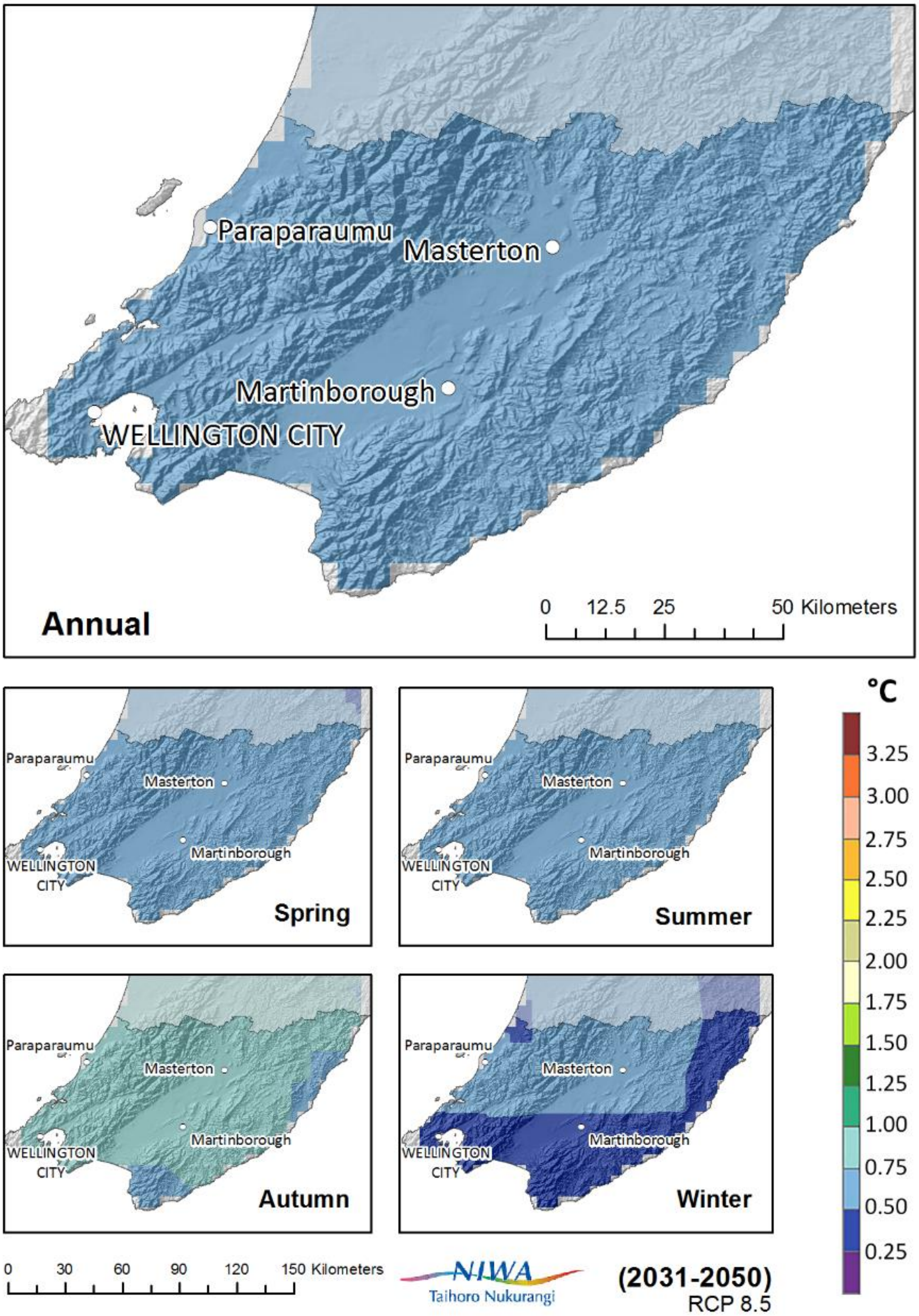

Figure 4-11: Projected annual and seasonal daily mean minimum temperature changes at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

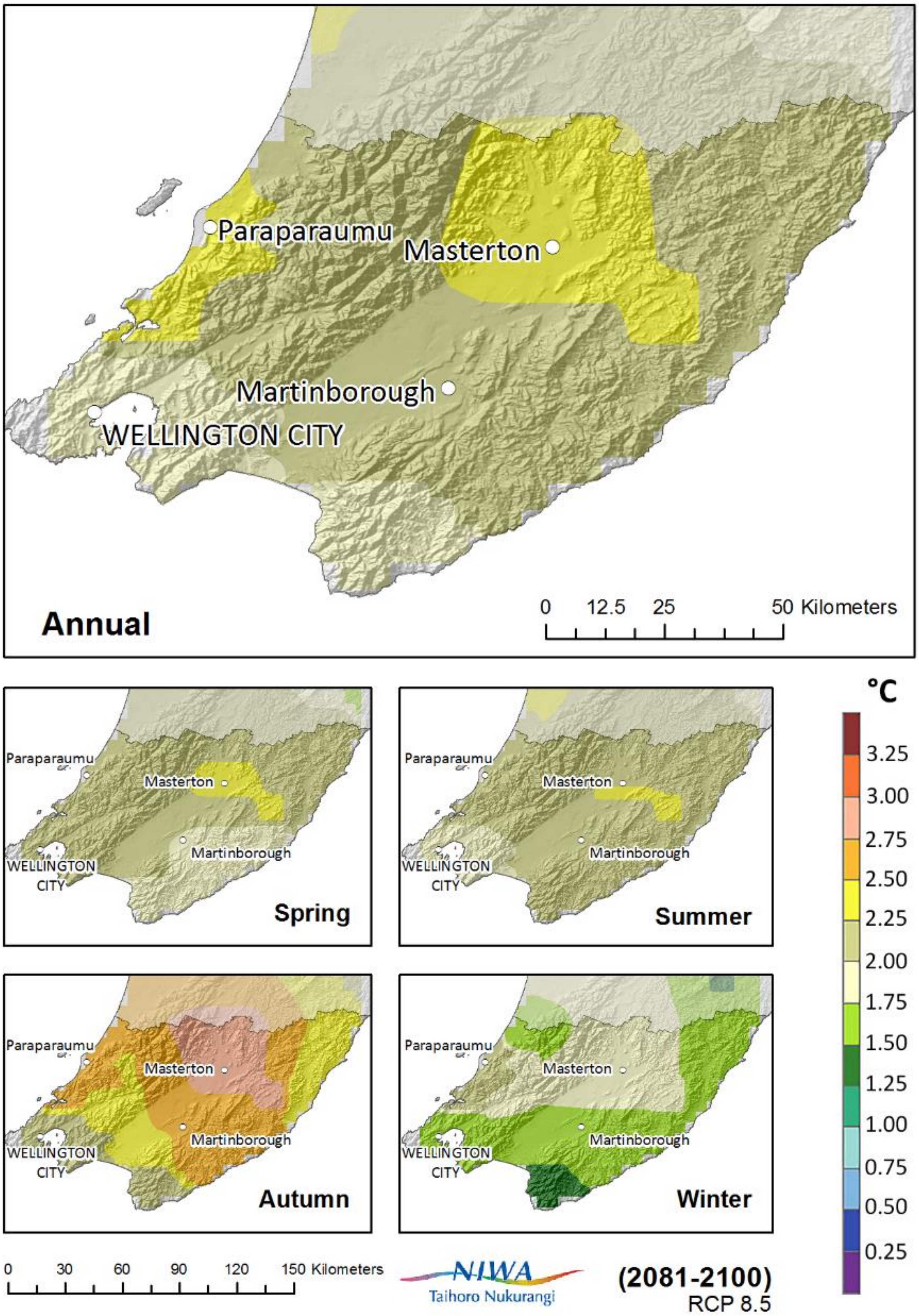

Figure 4-12: Projected annual and seasonal daily mean minimum temperature changes at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

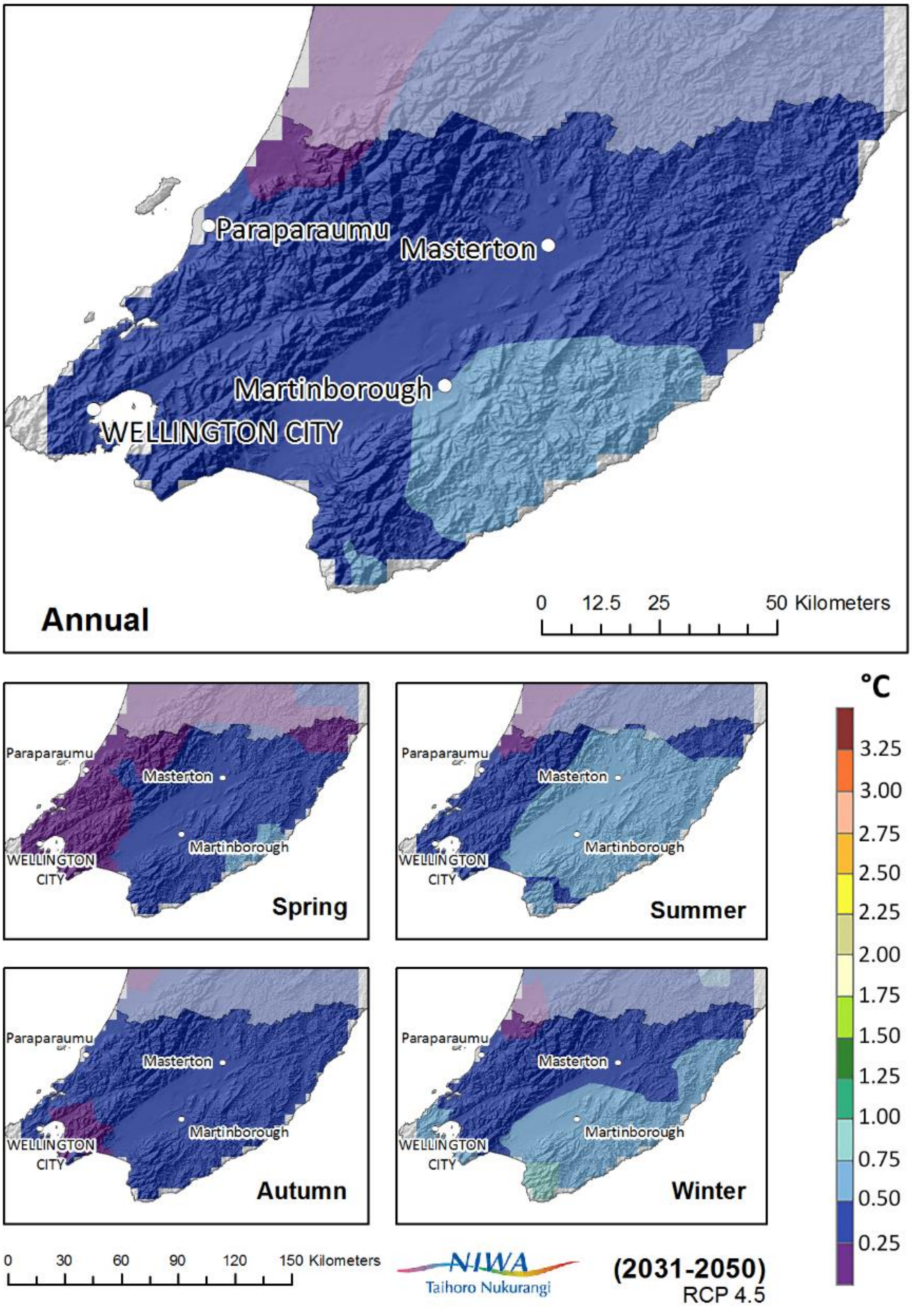

Figure 4-13: Projected annual and seasonal diurnal temperature range (Tmax minus Tmin) changes at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

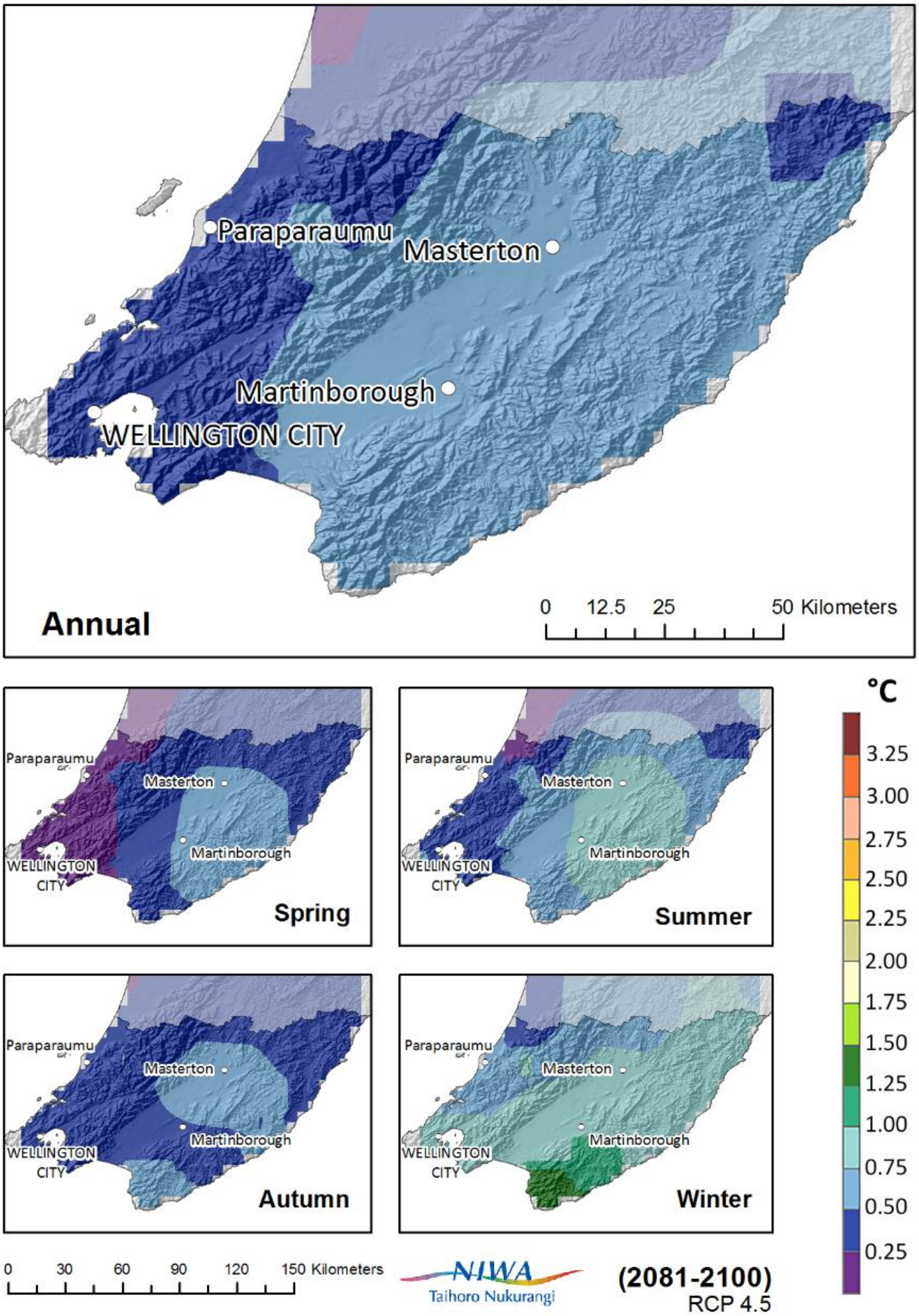

Figure 4-14: Projected annual and seasonal diurnal temperature range (Tmax minus Tmin) changes at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

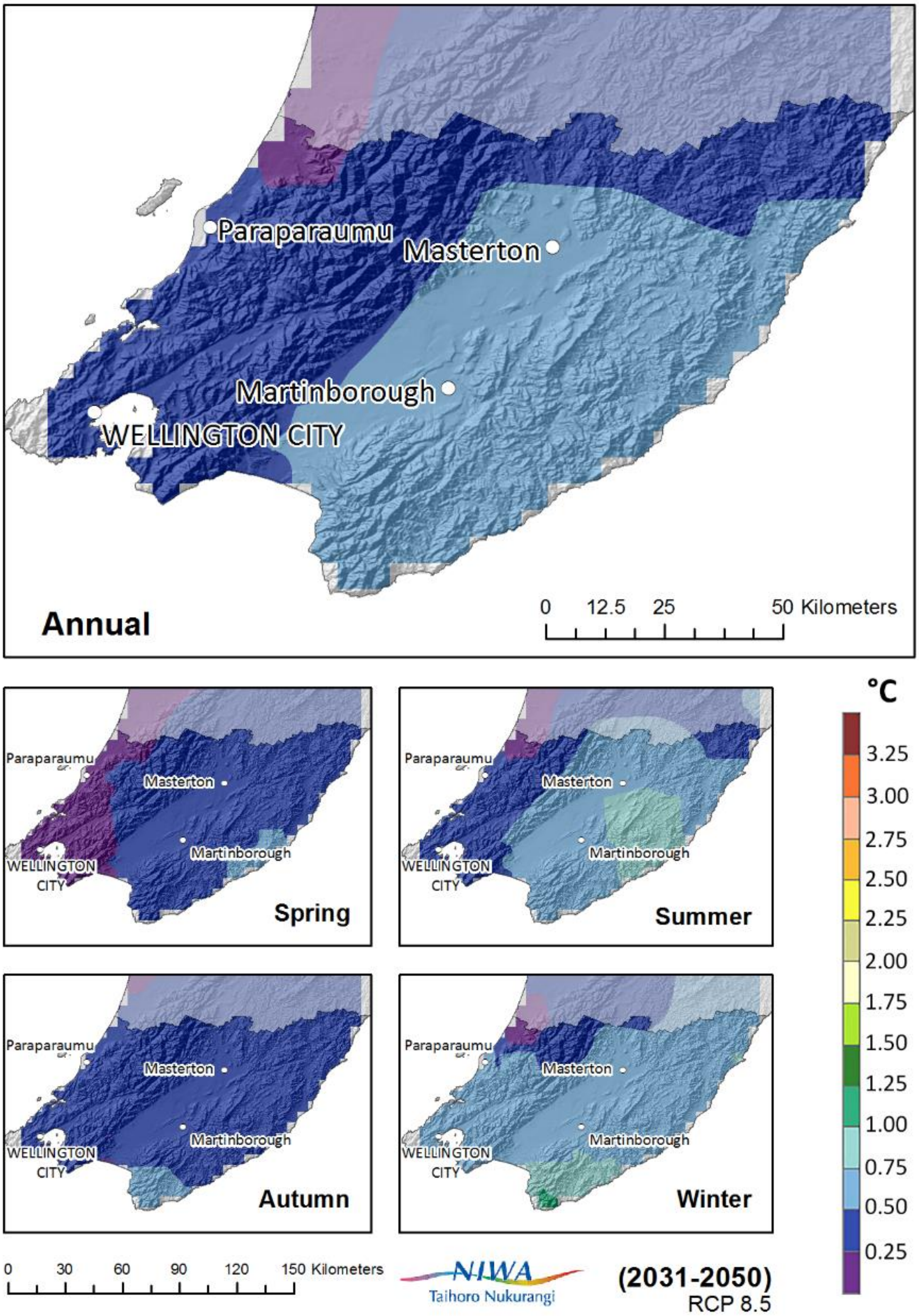

Figure 4-15: Projected annual and seasonal diurnal temperature range (Tmax minus Tmin) changes at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

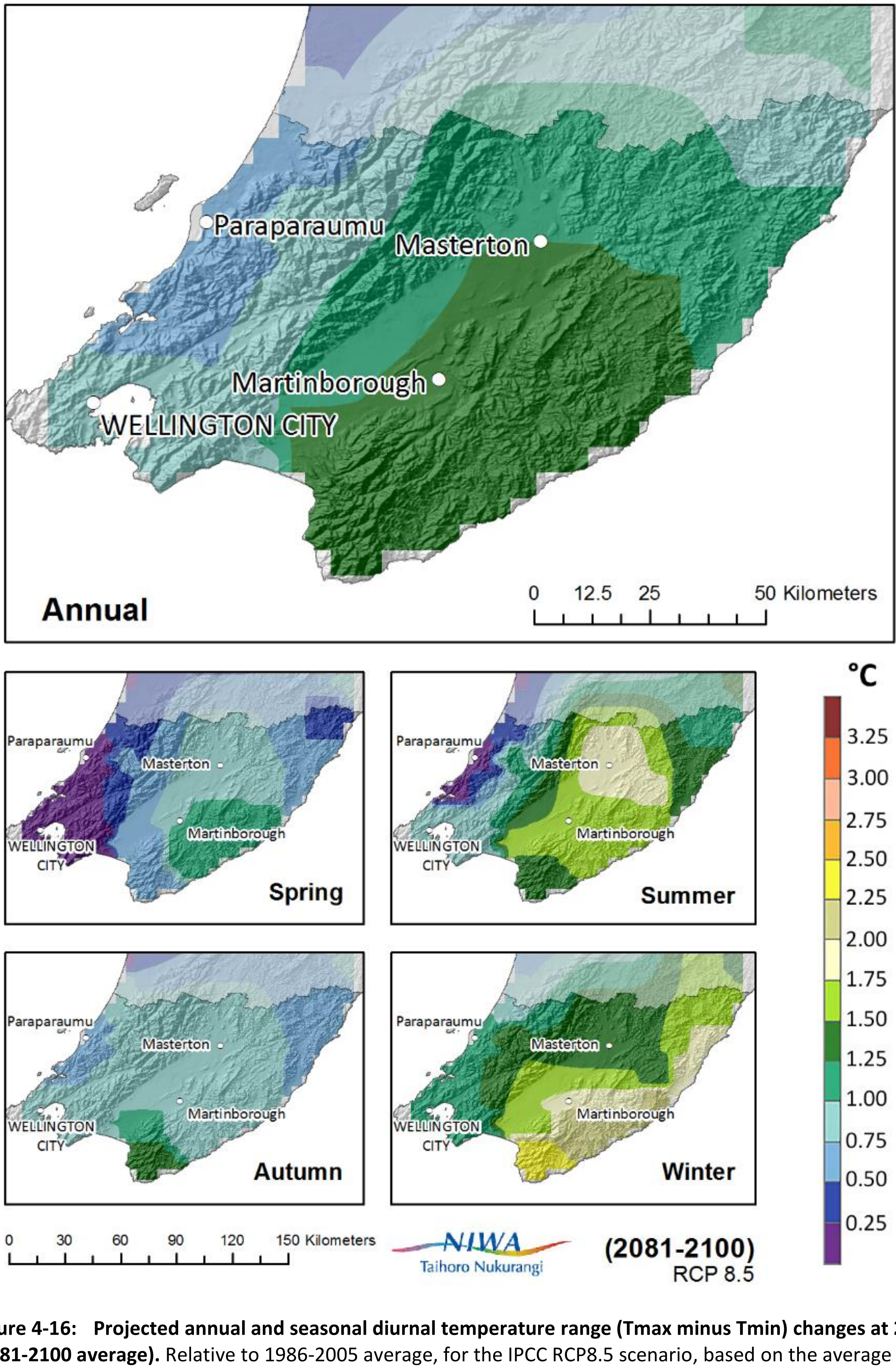

Figure 4-16: Projected annual and seasonal diurnal temperature range (Tmax minus Tmin) changes at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

4.1.3 Growing degree day projections

As discussed in Section 3.2.5, the calculation of growing degree days is useful to primary industry in terms of monitoring plant growth and planning harvests. Projections for growing degree days using base 10°C are presented in Figure 4-17. The future number of growing degree days has been calculated from dynamically downscaled daily temperature using NIWA's Regional Climate Model.

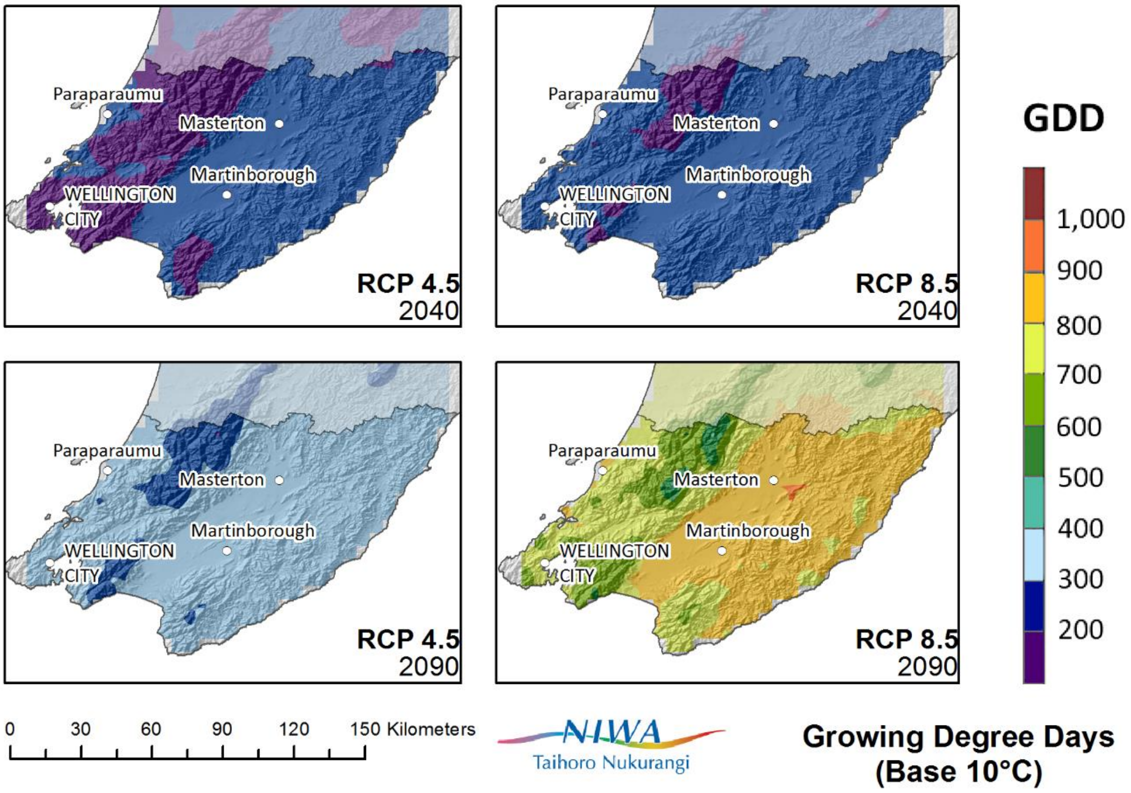

Figure 4-17: Projected increase in number of growing degree days per year (base 10°C) at 2040 & 2090 for RCP4.5 (left panels) and RCP8.5 (right panels), for the Wellington Region. Projected change in growing degree days is relative to 1995. Results are based on projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

By 2040, projections of growing degree days under both RCP4.5 and RCP8.5 (Figure 4-17) show the same pattern – an increase of up to 300 GDD across the region, with smaller increases in GDD projected for high elevation areas. By 2090, RCP4.5 shows an increase in GDD of 300-400 GDD in all areas except high elevations, where an increase of 200-300 GDD is expected. RCP8.5 shows an increase of 700-800 GDD for much of the western part of the Wellington Region, and 800-900 GDD for the eastern part of the region. Increases of 500-700 GDD are projected for higher elevations.

Model agreement is good for growing degree day projections as all models project an increase under both RCPs at both time periods.

4.1.4 Hot day and frost projections

As the seasonal mean temperature increases over time, we also expect to see changes in temperature extremes. In general, an increase in high temperature extremes, and a decrease in low temperature extremes is expected. Natural variability, of course, will continue to influence the climate of particular years. The specific timing of this variability cannot be predicted by the climate models due to the chaotic interactions that affect development of individual weather systems and larger-scale climate modes (such as El Niño events) (Mullan et al., 2016).

For this report, high temperature extremes (i.e. 'hot days') are considered as the number of days per year equal to or exceeding 25°C, and low temperature extremes (i.e. 'cold nights' or frosts) are considered as the number of nights per year equal to or below 0°C. These extremes were determined directly from the daily dynamically-downscaled maximum (for 'hot days') and minimum (for 'cold nights') temperature for each model by averaging the number of daily exceedances (greater than or equal to 25°C, or less than or equal to 0°C, for hot days and cold nights, respectively) for the selected RCP and time period over the modeled interval. Finally, the climate change signal was computed by averaging the change (with respect to the reference period) over the number of models (six).

Maps showing current spatial patterns of hot days and cold nights are shown in Figure 3-2 and Figure 3-3, respectively. The projected increase in the number of hot days per year at 2040 (2031-2050) and 2090 (2081-2100) relative to 1986-2005, for RCP4.5 and RCP8.5 is shown in Figure 4-18. The eastern part of the Wellington region, to the east of the Rimutaka and Tararua Ranges, is projected to experience a greater increase in hot days than western areas at all time slices and all RCPs.

At 2040, eastern areas are projected to experience increases in hot days by about 10-20 days per year for RCP4.5 and 10-30 for RCP8.5 (more hot days in the central Wairarapa under RCP8.5). For western areas, an increase of up to 10 hot days per year is projected.

At 2090 under RCP4.5, hot days are expected to increase by 30 days per year with some isolated patches around Masterton expecting 40 more hot days per year. Western areas are projected to experience mostly 5-10 more hot days per year, with some lower elevations in the Hutt Valley expecting up to 15 more hot days per year. Hot day numbers for high elevation areas are not expected to change much, with increases of less than five days per year.

Under RCP8.5 at 2090, large increases in the number of hot days across most of the Wellington Region are projected. For central Wairarapa, the number of hot days is projected to increase by around 70 days per year, with some areas near Masterton projecting an increase of up to 80 days per year. The eastern coastal margin is projected to experience 40-60 more hot days per year. For the western part of the region, lower elevations are projected to experience an increase in hot days of around 30-40 days, decreasing to five days per year for the highest elevations.

Model agreement is good for hot day projections as all models project an increase under both RCPs at both time periods.

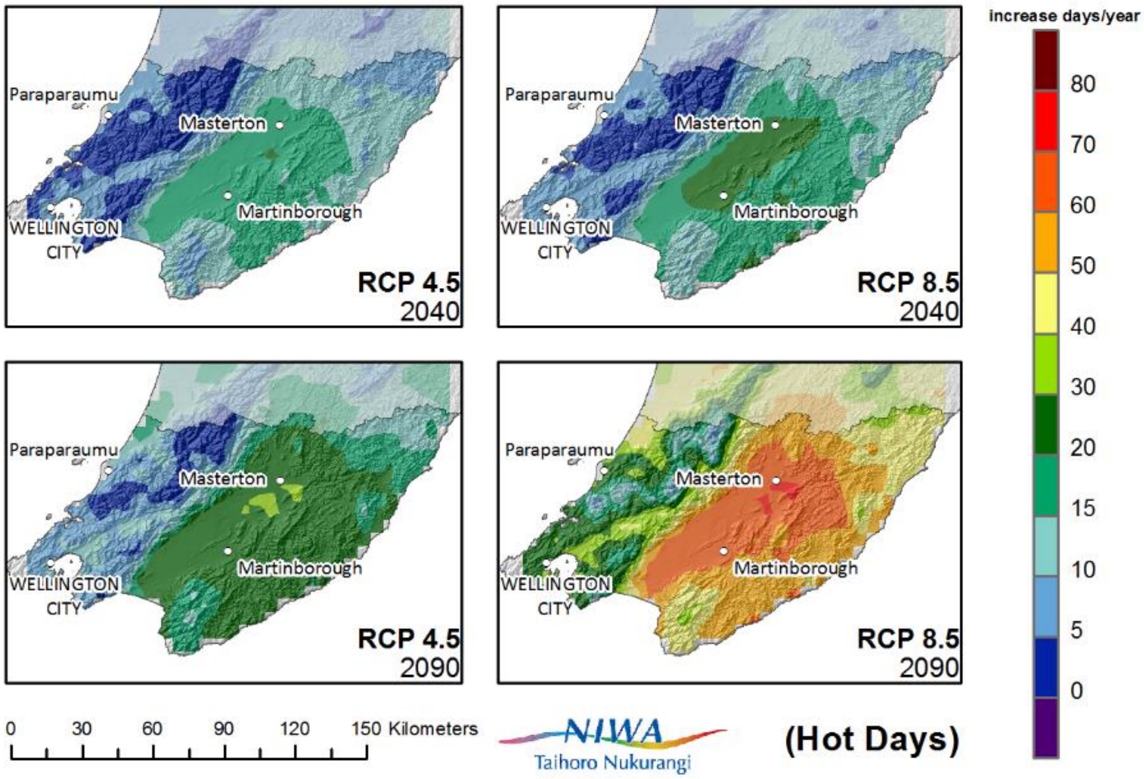

Figure 4-18: Projected increase in number of hot days per year (Tmax >25°C) at 2040 & 2090 for RCP4.5 (left panels) and RCP8.5 (right panels), for the Wellington Region. Projected change in hot days is relative to 1986-2005. The numbers on the scale refer to the *increase* in the number of hot days, e.g. the area around Masterton is projected to experience up to 80 more hot days per year by 2090 under RCP8.5 (red shades, lower right panel). Results are based on dynamically downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

The projected decrease in the number of cold nights (i.e. frosts) per year at 2040 (2031-2050) and 2090 (2081-2100) relative to 1995, for RCP4.5 and RCP8.5 is shown in Figure 4-19. Similar patterns are shown for changes in cold nights at 2040 under both RCP4.5 and RCP8.5. Most parts of the region outside the highest elevations of the Tararua Ranges are projected to experience a decrease of less than five cold nights per year (however, most of these areas currently observe less than five cold nights per year (Section 3.1) so the decline cannot be as much as in areas that currently observe more cold nights). Cold nights at high elevations are projected to decrease by up to 10 nights per year for most areas, with a very small area in the north of the Wellington Region that is expected to experience 15 fewer cold nights per year.

By 2090, the pattern for RCP4.5 is similar to 2040, except the areas with more than five fewer cold nights per year has spread to lower elevations, with 10 fewer cold nights experienced for most of the Tararua Ranges and small areas around Masterton and further east. Up to 20 fewer cold nights are projected for the highest elevations of the Tararua Ranges. Under RCP8.5 at 2090, far fewer cold nights are projected for much of the region. The highest elevations of the Tararua Ranges are expected to have up to 40 fewer cold nights per year, and lower elevations of the ranges expecting 15 fewer cold nights per year. The mountainous country in the eastern part of the region is likely to experience 10 fewer cold nights per year, as is much of the Kapiti Coast. The central Wairarapa around Masterton is projecting about 15 fewer cold nights per year.

Model agreement is good for frost projections as all models project a decrease under both RCPs at both time periods.

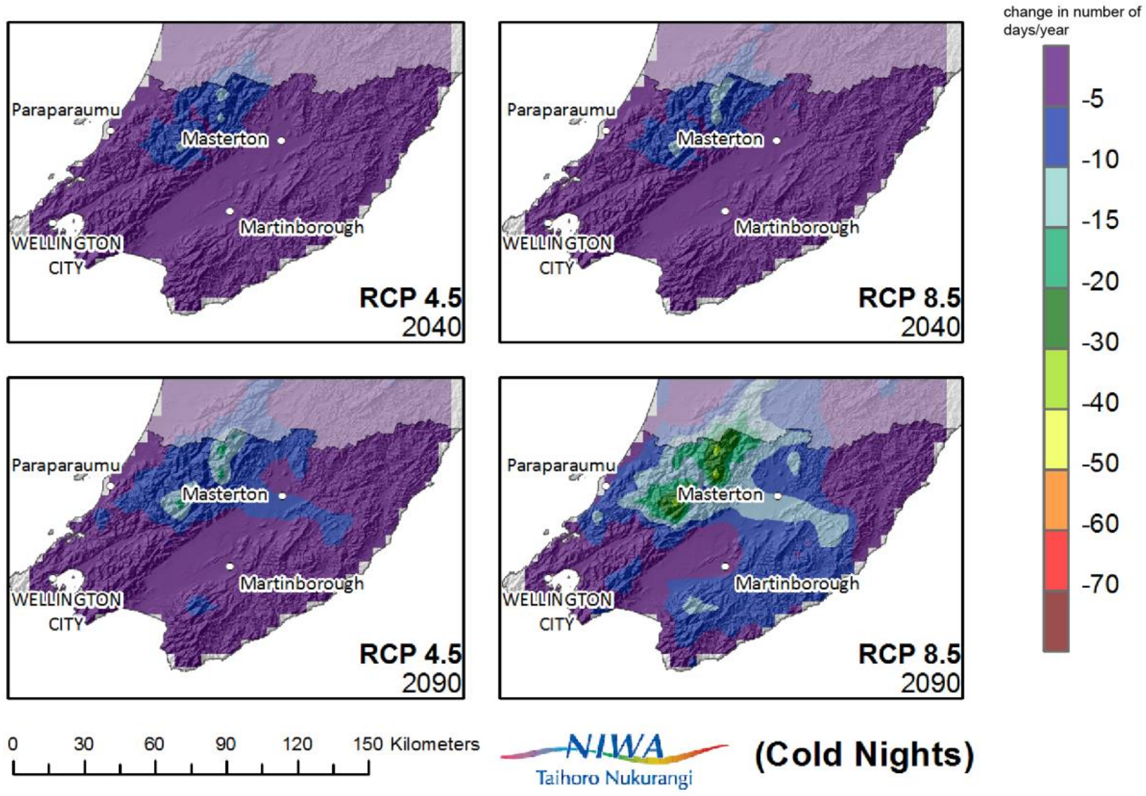

Figure 4-19: Projected decrease in number of cold nights (frosts) per year (Tmin <0°C) at 2040 & 2090 for RCP 4.5 (left panels) and RCP8.5 (right panels), for the Wellington Region. Projected change in cold nights is relative to 1995. The numbers on the scale refer to the *decrease* in the number of cold nights, e.g. parts of the Tararua Ranges are projected to experience up to 40 fewer cold nights per year by 2090 under RCP8.5 at 2090 (light green shades, lower right panel). Results are based on projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

4.2 Changes to precipitation

Precipitation projections are presented in this section. Variables covered include seasonal and annual precipitation (Section 4.2.1), number of rain days (> 1mm) (Section 4.2.2), number of heavy rain days (>25 mm) (Section 4.2.3), number of dry days (< 1mm) (Section 4.2.4), changes to snow (Section 4.2.5), and changes to extreme rainfall (Section 4.2.5).

4.2.1 Precipitation projections

The ensemble averages for dynamically downscaled projections, using NIWA's Regional Climate Model, for precipitation are presented in this section. Figure 4-20 and Figure 4-21 show the projected seasonal patterns of precipitation change over the Wellington Region at 2040 and 2090 for RCP4.5, and Figure 4-22 and Figure 4-23 show the same for RCP8.5.

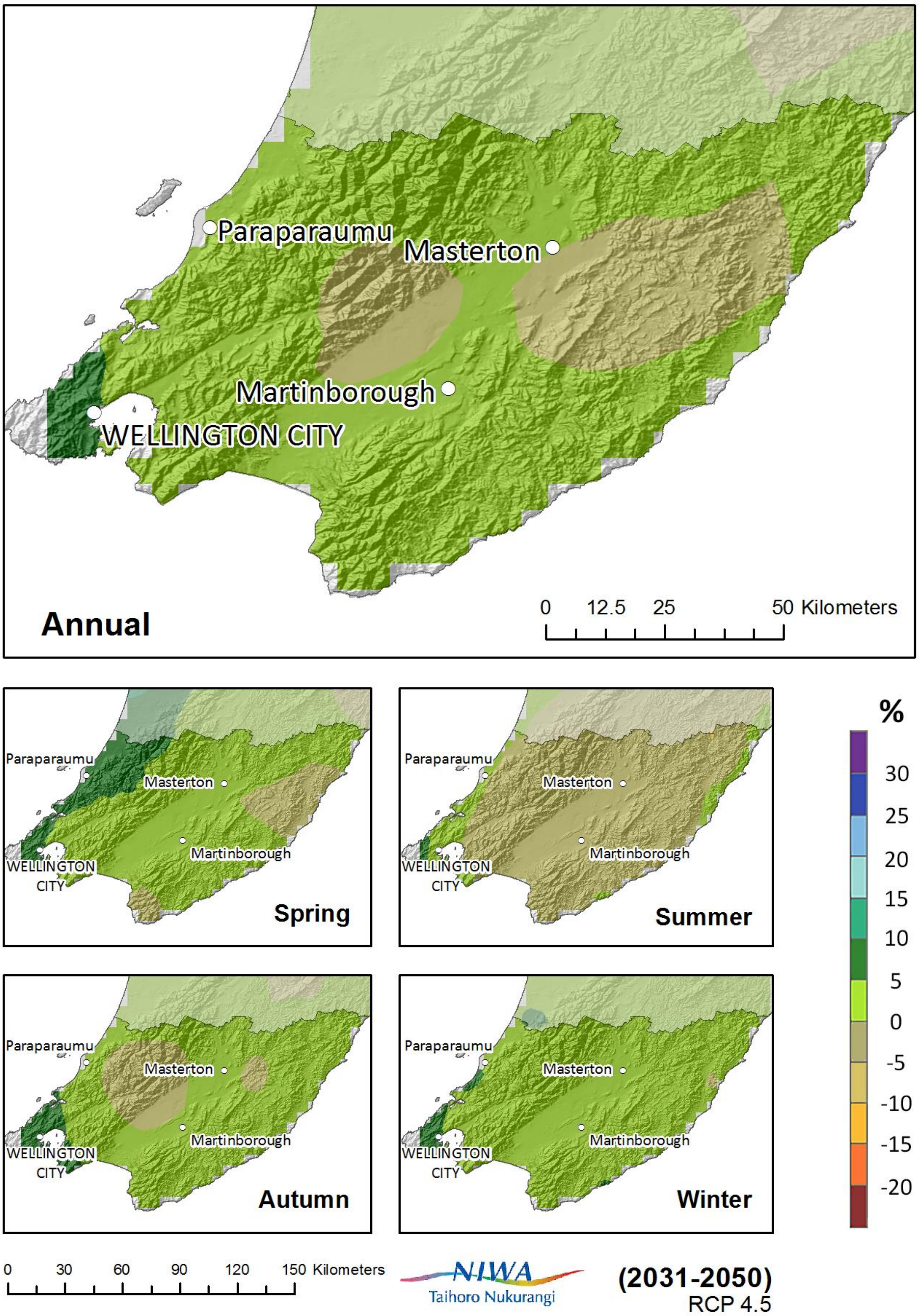

Figure 4-20: Projected annual and seasonal precipitation changes (in %) at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

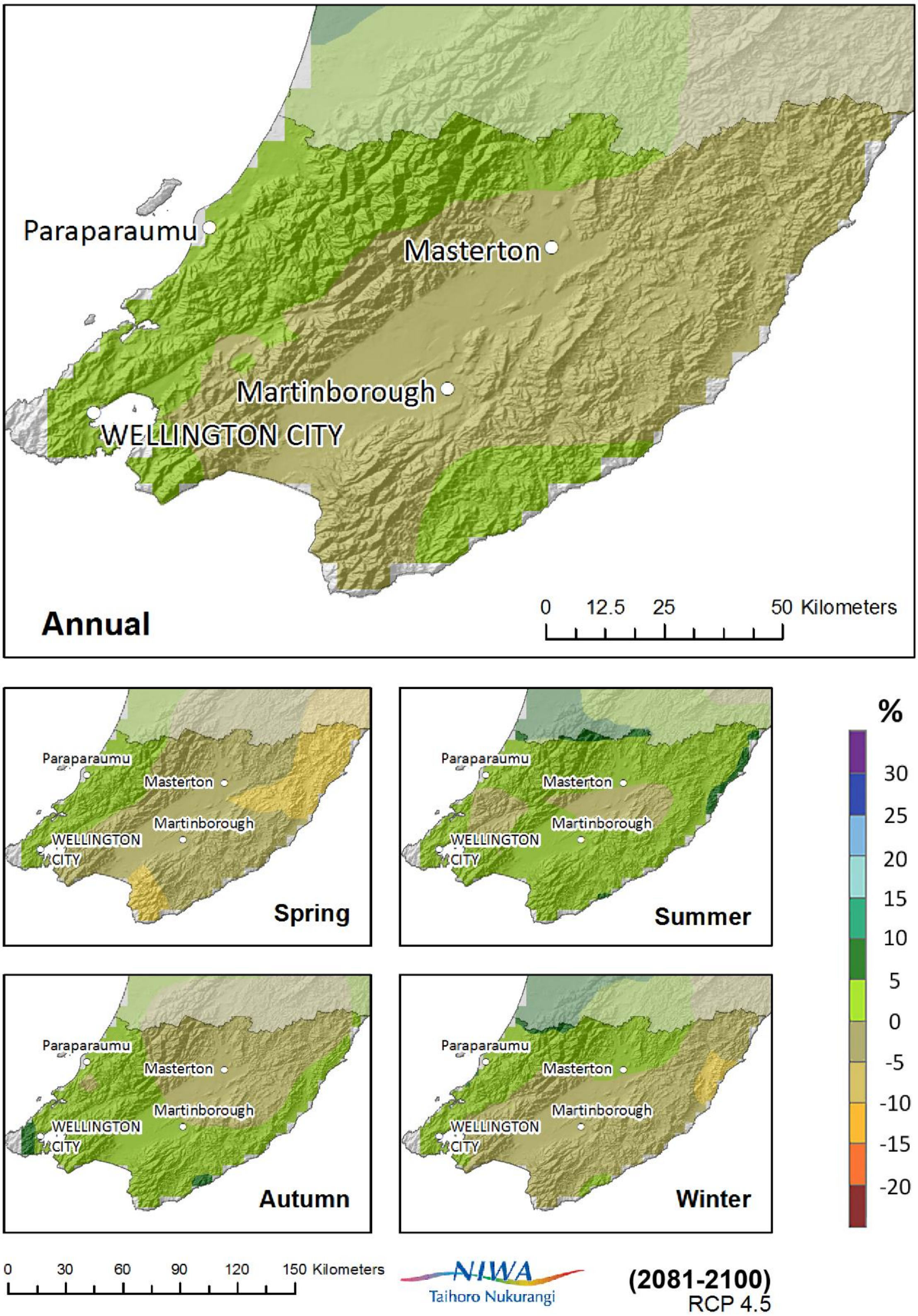

Figure 4-21: Projected annual and seasonal precipitation changes (in %) at 2090 (2081-2100 average). Relative to 1986-2005 average, for the RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

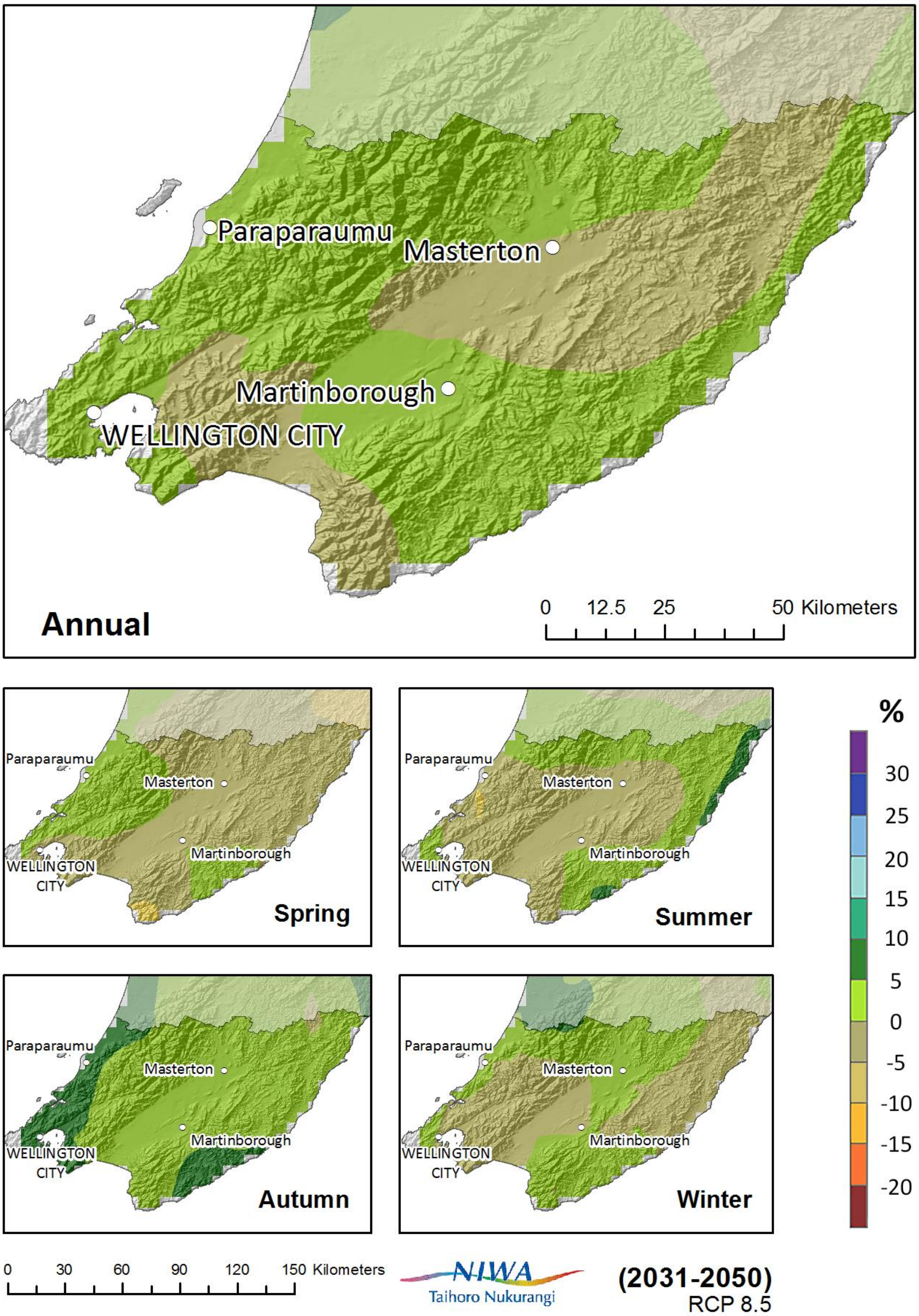

Figure 4-22: Projected annual and seasonal precipitation changes (in %) at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RC 8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

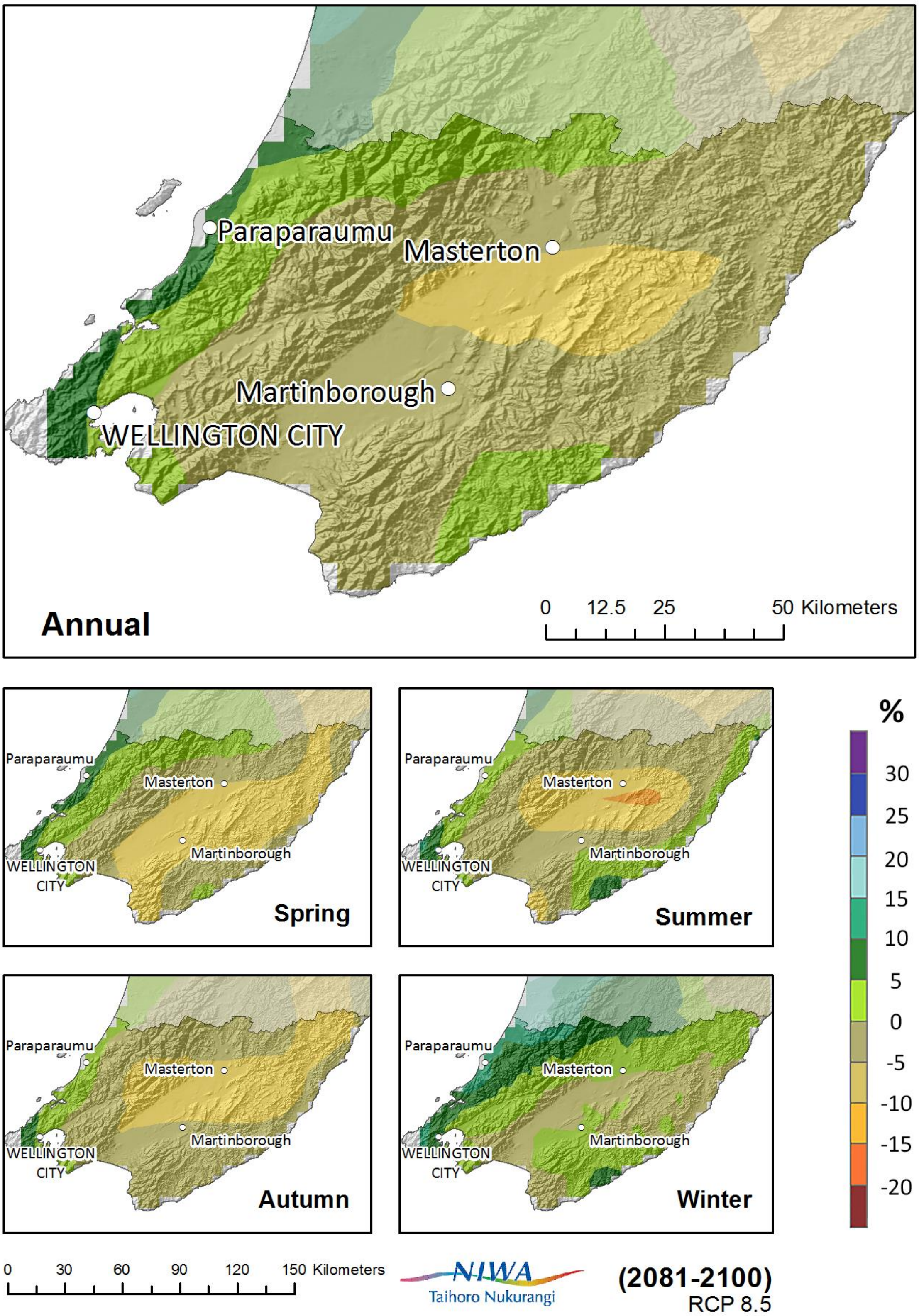

Figure 4-23: Projected annual and seasonal precipitation changes (in %) at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km. ©NIWA.

In general, rainfall is projected to increase in the west of the Wellington Region and decrease in the east of the region. Under RCP4.5 at 2040 (Figure 4-20), increases in annual rainfall of up to 5% are projected for most of the region. At the seasonal scale, summer exhibits a drying signal across most of the region, but only up to a 5% decrease in summer rainfall. Spring is expected to experience the largest increase in rainfall, with up to 10% more rainfall projected for western areas. For 2090 under RCP4.5 (Figure 4-21), a larger drying signal is observed in the eastern part of the region, with up to 10% less spring rainfall projected for eastern hill country areas and 5% less rainfall projected for the remaining area particularly in spring, winter, and at the annual scale. Up to 5% more rainfall is projected in the western region for all four seasons, at the annual scale, and for the majority of the region in summer.

Similar precipitation spatial patterns of change are seen for RCP8.5 at 2040 and 2090 as for RCP4.5, but these patterns are amplified relative to what is observed for RCP4.5. At 2040 (Figure 4-22), rainfall is projected to decrease in eastern parts of the region in spring, but only by up to 5%. Increases in rainfall are projected for the west and east coasts in autumn and for the east coast in summer (up to 10% increase). For 2090 (Figure 4-23), there is more of a drying signal across the eastern part of the region, with up to 15% less rainfall projected for part of the Wairarapa in summer, and extensive areas projecting up to 10% less rainfall in the east for spring, summer and autumn, and also at the annual scale. For all seasons, and also at the annual scale, rainfall is projected to increase in the west of the region by up to 10%. In winter, rainfall is projected to increase by up to 15% along the west coast.

Under RCP8.5 at 2090, model agreement is good for all seasons, but this agreement varies by area and by season. In summer, most models predict a decrease in precipitation. In autumn, most models predict a decrease in precipitation for the mountains. In winter, most models predict an increase in precipitation in the west, and in spring, most models predict a decrease in precipitation in the mountains and east. Model agreement is also good for autumn under RCP8.5 at 2040, and for summer and spring under RCP4.5 at 2040.

The full range of model-projected precipitation change (in %) is given for Paraparaumu and Masterton below, using statistical downscaling and dynamical downscaling methods (the maps in this report are generated from dynamically downscaled projections). Note that the projections for Wellington City are very similar to those for Paraparaumu. Model-projected changes are given for statistically downscaled projections 2031-2050 (2040) in Table 4-3 and for 2081-2100 (2090) in Table 4-4. Dynamically downscaled projections are given for 2040 in Table 4-5 and 2090 in Table 4-6. The precipitation changes are relative to the baseline period 1986-2005 (1995). Hence the projected changes at 2040 and 2090 should be thought of as 45-year and 95-year trends. The seasonal and annual ensemble average projection (the number outside the brackets) in Table 4-3 and Table 4-4 is the precipitation increase (in %) for the given locations for 2040 and 2090, respectively, averaged over all 23 models for RCP2.6, 37 models for RCP4.5, 18 models for RCP6.0, and 41 models for RCP8.5 analysed by NIWA. The bracketed numbers give the range (5^{th} and 95^{th} percentile) for each RCP for each season and the annual projection. For Table 4-5 and Table 4-6, the ensemble average projection is given outside the brackets (six models) and the bracketed numbers give the range (minimum and maximum) for each RCP for each season and the annual projection.

Table 4-3: Projected changes in seasonal and annual precipitation (in %) between 1986-2005 and 2031-2050 (2040) for selected locations within the Wellington Region, as derived from statistical downscaling. The changes are given for four RCPs (8.5, 6.0, 4.5 and 2.6), where the ensemble-average is taken over (41, 18, 37, 23) models respectively. The values in each column represent the ensemble average, and in brackets the range (5th percentile to 95th percentile) over all models within that ensemble. This table presents statistical downscaled projections. After Mullan et al. (2016).

Location	Summer	Autumn	Winter	Spring	Annual
Paraparaumu					
RCP8.5	0 (-8, 10)	1 (-6, 8)	6 (-4, 19)	1 (-10, 14)	2 (-3, 9)
RCP6.0	-1 (-10, 10)	2 (-6, 9)	6 (-6, 20)	0 (-9, 12)	2 (-4, 9)
RCP4.5	0 (-8, 9)	1 (-8, 9)	6 (-5, 15)	1 (-9, 11)	2 (-4, 8)
RCP2.6	0 (-6, 9)	2 (-6, 8)	4 (-8, 15)	1 (-8, 10)	2 (-3, 8)
Masterton					
RCP8.5	0 (-12, 7)	1 (-8, 8)	-2 (-11, 6)	-1 (-8, 8)	-1 (-6, 4)
RCP6.0	3 (-8, 18)	2 (-12, 10)	0 (-5, 8)	0 (-7, 10)	1 (-3, 6)
RCP4.5	1 (-8, 13)	1 (-8, 9)	-1 (-10, 10)	1 (-6, 10)	0 (-4, 6)
RCP2.6	2 (-6, 10)	0 (-6, 9)	0 (-8, 6)	0 (-7, 9)	0 (-3, 5)

Table 4-4: Projected changes in seasonal and annual precipitation (in %) between 1986-2005 and 2081-2100 (2090) for selected locations within the Wellington Region, as derived from statistical downscaling. The changes are given for four RCPs (8.5, 6.0, 4.5 and 2.6), where the ensemble-average is taken over (41, 18, 37, 23) models respectively. The values in each column represent the ensemble average, and in brackets the range (5 percentile to 95 percentile) over all models within that ensemble. This table presents statistical downscaled projections. After Mullan et al. (2016).

Location	Summer	Autumn	Winter	Spring	Annual
Paraparaumu					
RCP8.5	1 (-19, 19)	1 (-13, 12)	13 (-4, 29)	1 (-15, 14)	5 (-8, 12)
RCP6.0	1 (-23, 20)	2 (-10, 14)	11 (-5, 28)	3 (-11, 13)	5 (-9, 15)
RCP4.5	2 (-9, 14)	2 (-8, 7)	8 (-7, 21)	2 (-5, 13)	4 (-5, 11)
RCP2.6	2 (-7, 17)	3 (-6, 11)	5 (-4, 19)	3 (-7, 13)	3 (-2, 13)
Masterton					
RCP8.5	8 (-4, 28)	3 (-10, 12)	-7 (-24, 5)	-3 (-18, 10)	-1 (-8, 5)
RCP6.0	2 (-39, 16)	0 (-30, 8)	-4 (-31, 12)	-1 (-23, 11)	-1 (-30, 9)
RCP4.5	3 (-8, 13)	1 (-9, 10)	-2 (-14, 8)	0 (-7, 7)	0 (-5, 4)
RCP2.6	-1 (-11, 8)	1 (-6, 11)	1 (-5, 8)	2 (-5, 9)	1 (-6, 6)

For Paraparaumu, most precipitation change is expected to occur in winter, with a 6% increase projected under all RCPs except RCP2.6 at 2040 (Table 4-3) and a 13% increase projected under RCP8.5 at 2090 (Table 4-4). For the remaining seasons, the ensemble average change in precipitation is less than ±5%, with the model range (the 5th and 95th percentile values) varying between quite large (>10%) increases and decreases. Under RCP8.5 and RCP6.0 at 2090, annual precipitation is projected to increase by 5%.

For Masterton, minimal change in rainfall is projected to occur by 2040 compared with present (Table 4-3), as the ensemble averages are all close to zero. The 5th and 95th percentile values for model outputs have a large range. The ensemble averages are less than ±5% for most RCPs in most seasons at 2090. Nevertheless, the ensemble average for precipitation change is consistently negative for the three highest RCPs in winter. The only ensemble average changes greater than ±5% for Masterton are for RCP 8.5, which shows associated increases in summer rainfall of 8% and a decrease in winter rainfall of 7%.

Table 4-5: Projected changes in seasonal and annual precipitation (in %) between 1986-2005 and 2031-2050 (2040), for select locations within the Wellington Region, as derived from dynamical downscaling. The changes are given for four RCPs (8.5, 6.0, 4.5 and 2.6), where the ensemble-average is taken over six models. The values in each column represent the ensemble average, and in brackets the range (minimum and maximum) over all models within that ensemble. This table presents dynamical downscaled projections.

Location	Summer	Autumn	Winter	Spring	Annual
Paraparaumu					
RCP8.5	-3 (-12, 10)	6 (-1, 13)	0 (-9, 9)	4 (-4, 12)	2 (-4, 7)
RCP6.0	0 (-8, 9)	2 (-5, 10)	4 (-4, 16)	6 (-3, 13)	3 (2, 8)
RCP4.5	0 (-15, 23)	2 (-15, 17)	4 (-4, 12)	6 (-1, 11)	3 (-3, 10)
RCP2.6	3 (-1, 10)	3 (-6, 10)	2 (-15, 20)	4 (-14, 14)	3 (-1, 9)
Masterton					
RCP8.5	-4 (-17, 7)	2 (-9, 12)	0 (-4, 13)	-2 (-11, 7)	-1 (-8, 7)
RCP6.0	-1 (-9, 8)	0 (-7, 6)	1 (-6, 10)	0 (-11, 6)	0 (-4, 6)
RCP4.5	-5 (-16, 23)	1 (-11, 13)	2 (-6, 9)	0 (-9, 9)	0 (-6, 10)
RCP2.6	5 (-2, 14)	2 (-7, 15)	2 (-14, 12)	-2 (-12, 11)	2 (-3, 10)

Table 4-6: Projected changes in seasonal and annual precipitation (in %) between 1986-2005 and 2081-2100 (2090), for select locations within the Wellington Region, as derived from dynamical downscaling. The changes are given for four RCPs (8.5, 6.0, 4.5 and 2.6), where the ensemble-average is taken over six models. The values in each column represent the ensemble average, and in brackets the range (minimum and maximum) over all models within that ensemble. This table presents dynamical downscaled projections.

Location	Summer	Autumn	Winter	Spring	Annual
Paraparaumu					
RCP8.5	3 (-7, 23)	2 (-9, 10)	10 (1, 20)	6 (-6, 22)	5 (0, 11)
RCP6.0	0 (-12, 15)	3 (-8, 13)	7 (-3, 16)	3 (-14, 12)	3 (-3, 9)
RCP4.5	2 (-9, 15)	0 (-18, 10)	3 (-10, 22)	3 (-2, 11)	2 (-5, 12)
RCP2.6	0 (-16, 10)	0 (-11, 9)	1 (-7, 8)	8 (-4, 19)	2 (-1, 9)
Masterton					
RCP8.5	-10 (-19, 5)	-8 (-21, 4)	0 (-9, 6)	-7 (-13, -2)	-6 (-12, 0)
RCP6.0	-2 (-16, 3)	-4 (-13, 7)	0 (-10, 13)	-5 (-18, 1)	-3 (-9, 5)
RCP4.5	-1 (-10, 17)	-3 (-14, 12)	0 (-9, 10)	-5 (-9, 3)	-2 (-9, 7)
RCP2.6	1 (-14, 11)	1 (-9, 9)	3 (-6, 11)	0 (-6, 6)	1 (-4, 7)

The dynamical downscaled precipitation projections for Paraparaumu and Masterton in Table 4-5 and Table 4-6 show differences to the statistical downscaled projections in Table 4-3 and Table 4-4. At 2040 (Table 4-5), minimal change in mean precipitation is projected for Paraparaumu, with most RCPs and seasons expecting a ±5% change. Spring is the season with the most consistent increases in rainfall at 2040. For Masterton, change in rainfall is also ±5% for all RCPs and all seasons. At 2090 (Table 4-6), Paraparaumu is expected to experience increases in rainfall of up to 10% in winter under RCP 8.5. Masterton is expected to experience decreases in rainfall under most RCPs and seasons, and particularly in summer with a decrease in rainfall of 10% under RCP 8.5.

For both the statistical and downscaled precipitation projections, the model spread is generally large and often crosses zero, therefore the direction and magnitude of change for precipitation (increase or decrease) is uncertain.

4.2.2 Rain day projections

Projections of rain days (where daily rain >1 mm) are presented for 2040 and 2090, compared to 1995 under RCP4.5 and RCP8.5 in Figure 4-24 to Figure 4-27, based on dynamical downscaled models. The number of rain days is expected to decline across the Wellington Region under both RCP4.5 and RCP8.5 at 2040 and 2090. By 2040 for RCP4.5, summer, autumn and winter are expected to have up to five fewer rain days across the whole region, with up to 10 fewer rain days per year expected in parts of the Wairarapa (Figure 4-24). At 2090 under RCP4.5, all seasons show decreases in rain days of up to five days per season, which sums to between five and ten fewer rain days per year (Figure 4-25). This pattern is similar for RCP8.5 at 2040 (Figure 4-26), but at 2090 under RCP8.5 there are much more significant decreases, with 15-20 fewer rain days per year projected for the eastern Rimutaka and Tararua Ranges, as well as parts of the eastern Wairarapa hill country (Figure 4-27).

Model agreement is good for rain day projections as most models predict a decrease under both RCPs at both time periods.

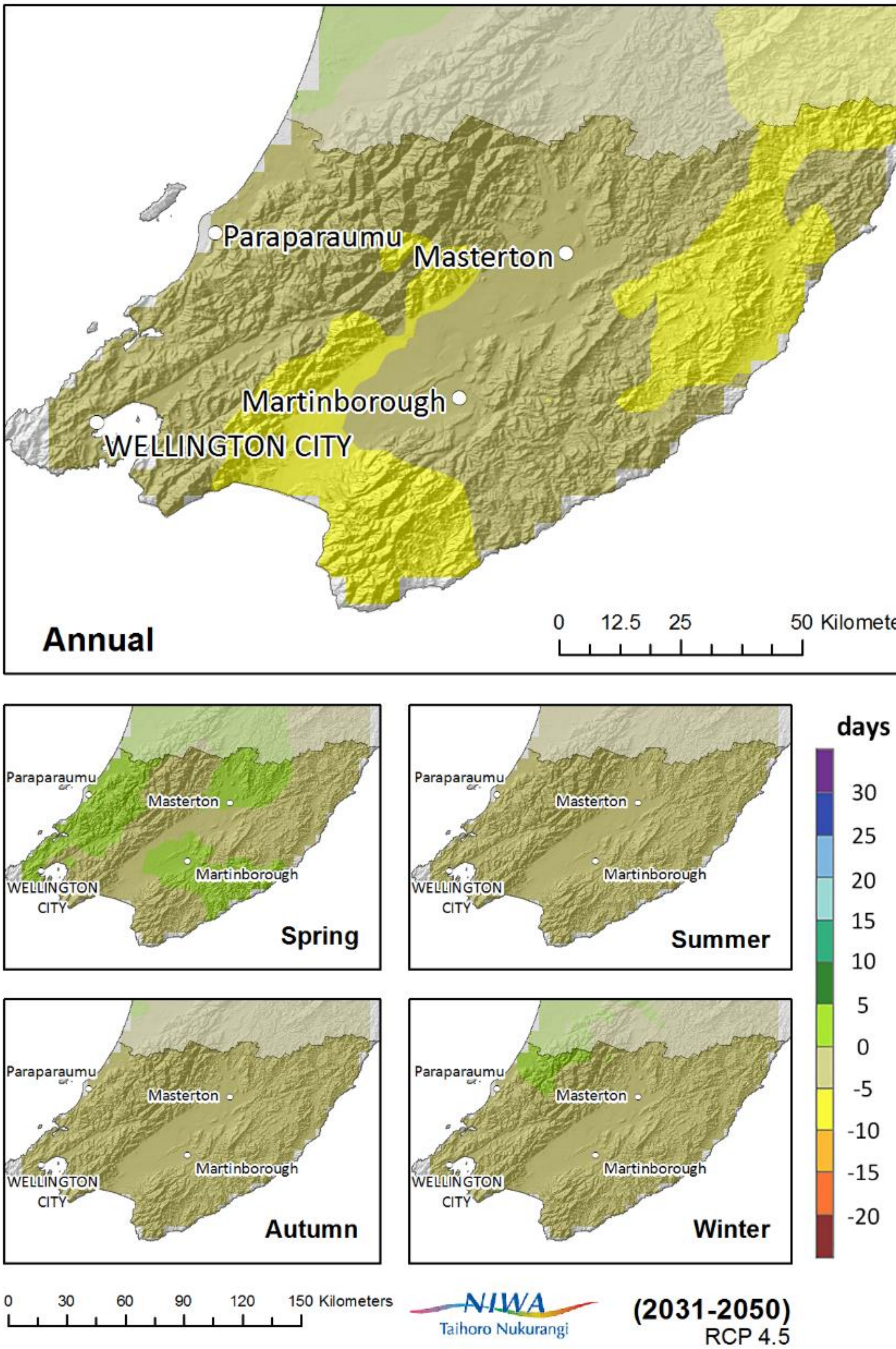

Figure 4-24: Projected annual and seasonal rain day changes (days where rain > 1 mm; in number of days) at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

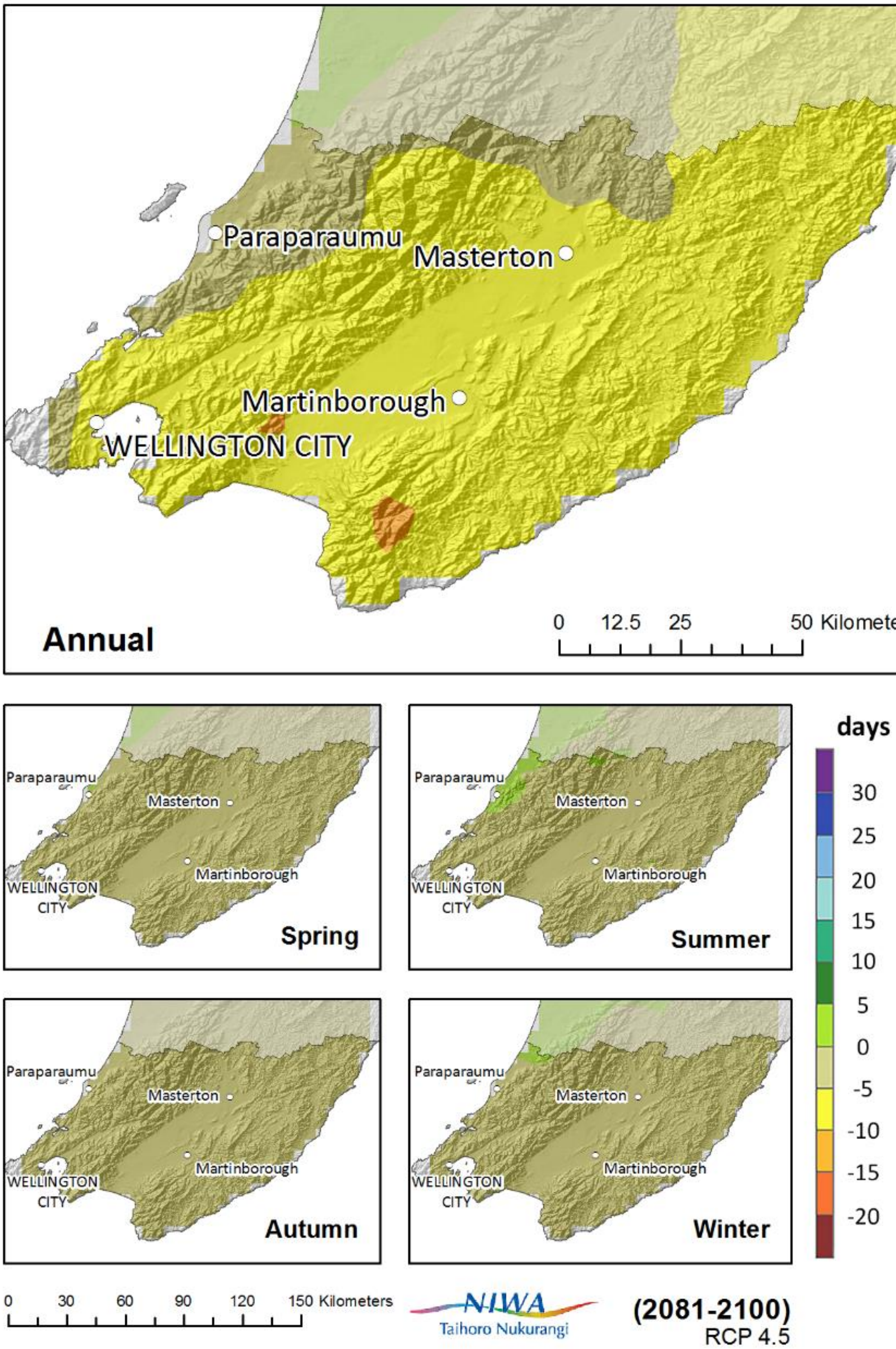

Figure 4-25: Projected annual and seasonal rain day changes (days where rain > 1 mm; in number of days) at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

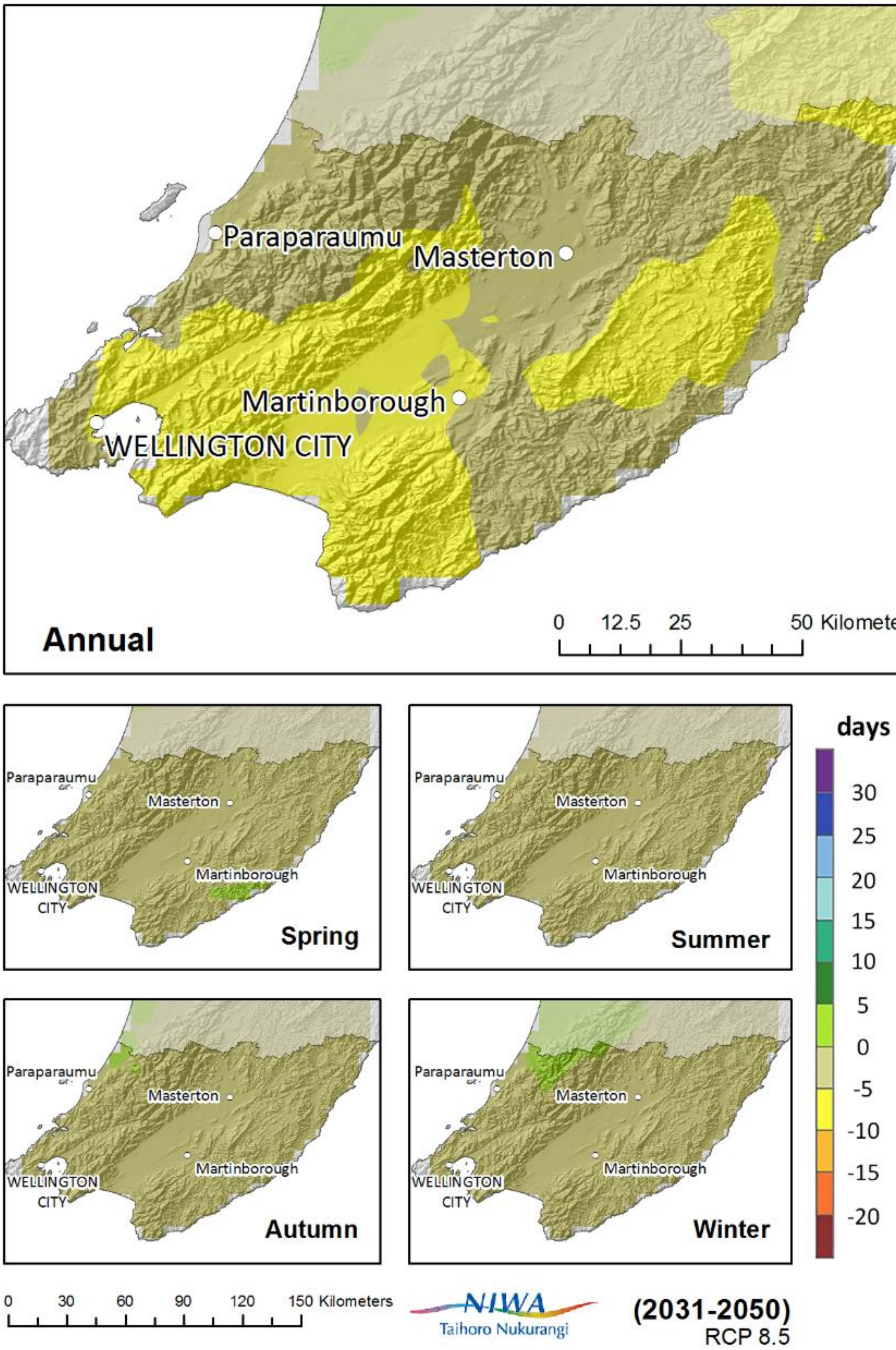

Figure 4-26: Projected annual and seasonal rain day changes (days where rain > 1 mm; in number of days) at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

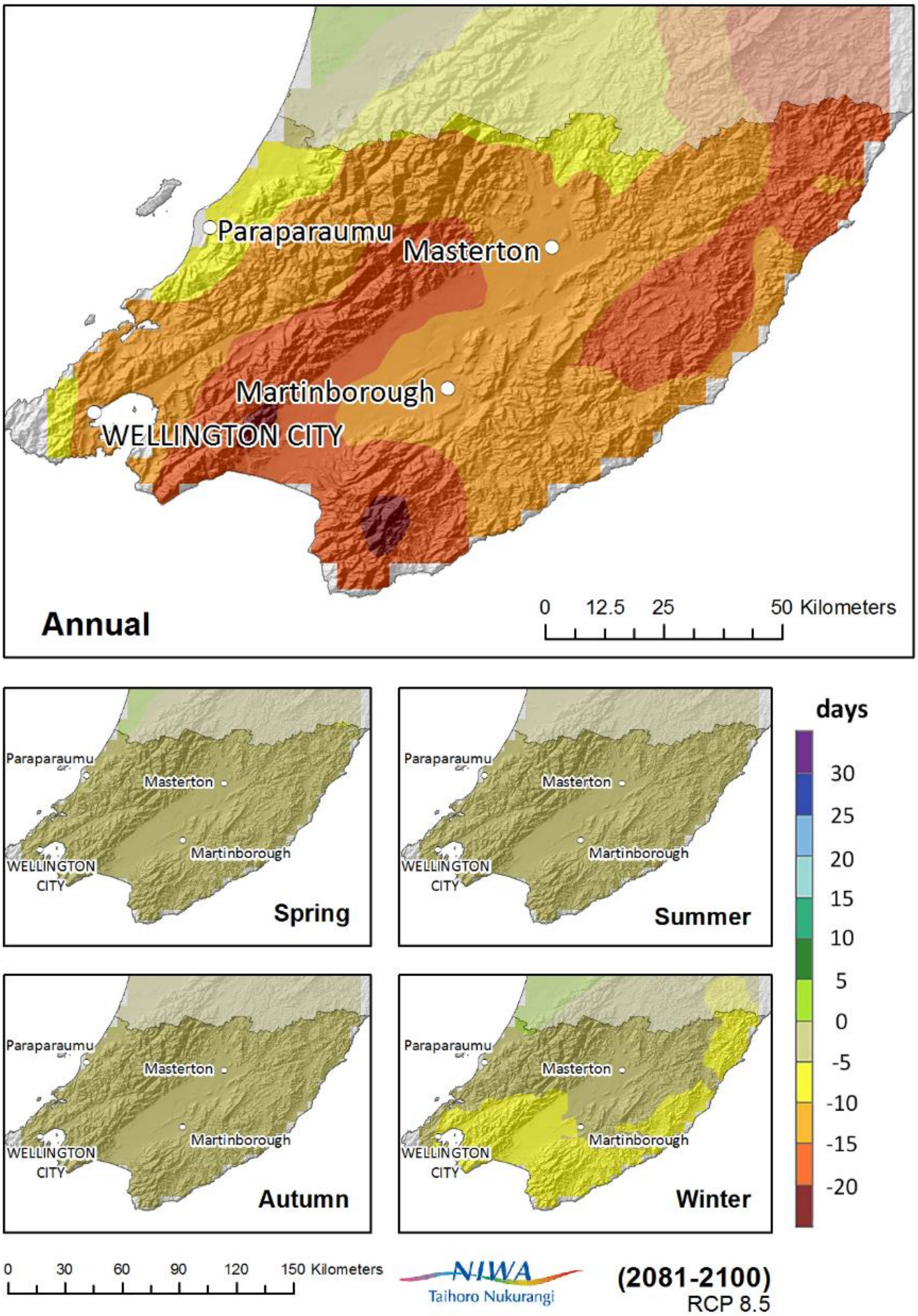

Figure 4-27: Projected annual and seasonal rain day changes (days where rain > 1 mm; in number of days) at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

4.2.3 Heavy rain day projections

Projections of heavy rain days (where daily rain >25 mm) are presented for 2040 and 2090 under RCP4.5 and RCP8.5 in Figure 4-28 to Figure 4-31, derived from dynamical downscaling. For 2040 under RCP4.5, increases of up to five heavy rain days are projected across most of the region at the annual scale and for winter, with small decreases of up to five days projected for central and eastern parts of the region in summer, spring and autumn (Figure 4-28). The pattern is similar for 2090 under RCP4.5, with small increases or decreases of five days projected for different parts of the region, but the number of days increases at the annual scale (Figure 4-29). For 2040 under RCP8.5, over half of the region is projected to experience up to five fewer heavy rain days in spring, but up to five more days for the year as a whole (Figure 4-30). For RCP8.5 at 2090, a small decrease in heavy rain days of up to five days is limited to the eastern Tararua and Rimutaka Ranges, with most of the rest of the region projecting five more heavy rain days per year or season (Figure 4-31).

Model agreement is good for heavy rain day projections under RCP8.5 at 2090 as most models predict an increase.

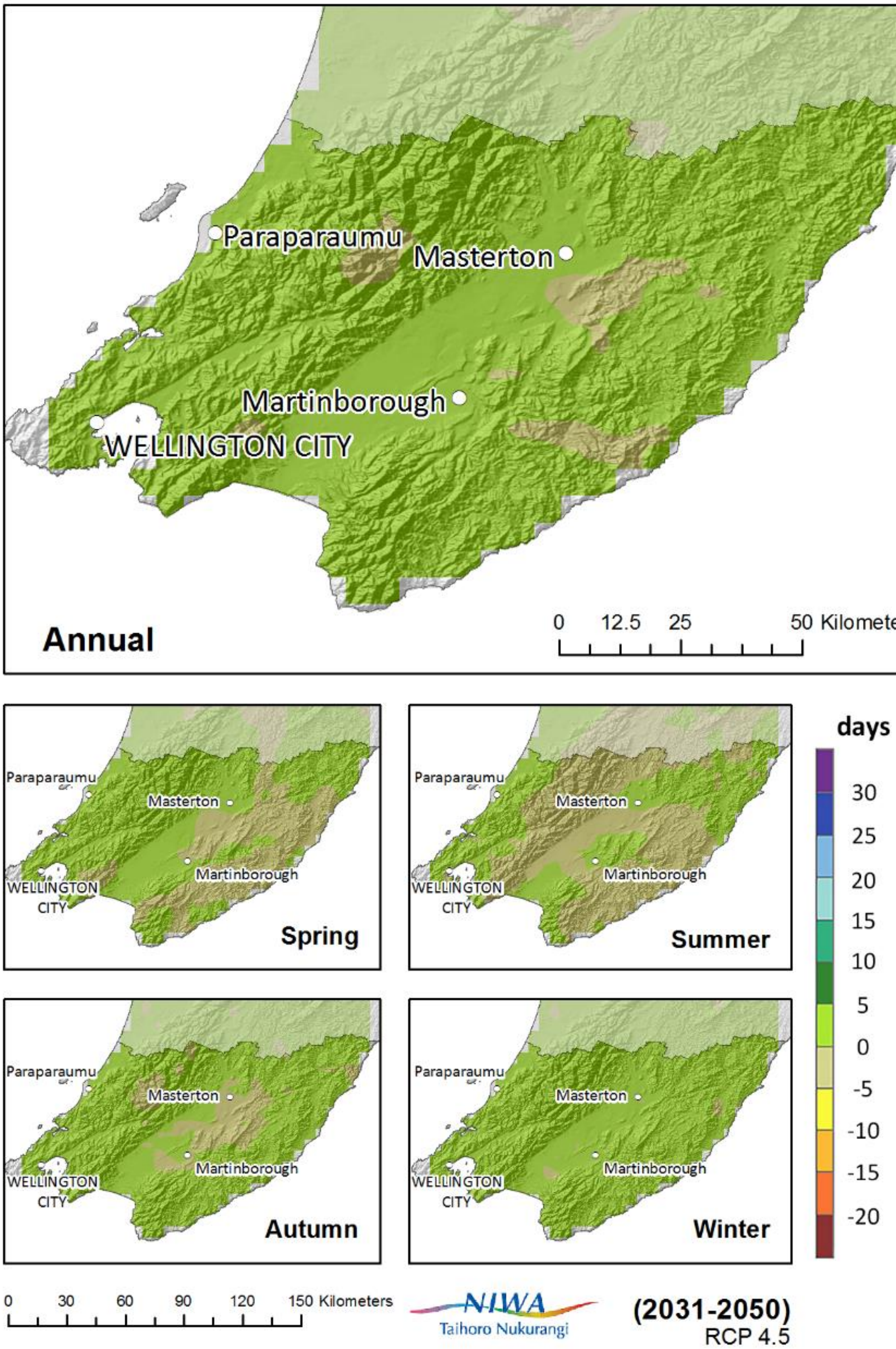

Figure 4-28: Projected annual and seasonal heavy rain day changes (days where rain > 25 mm; in number of days) at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

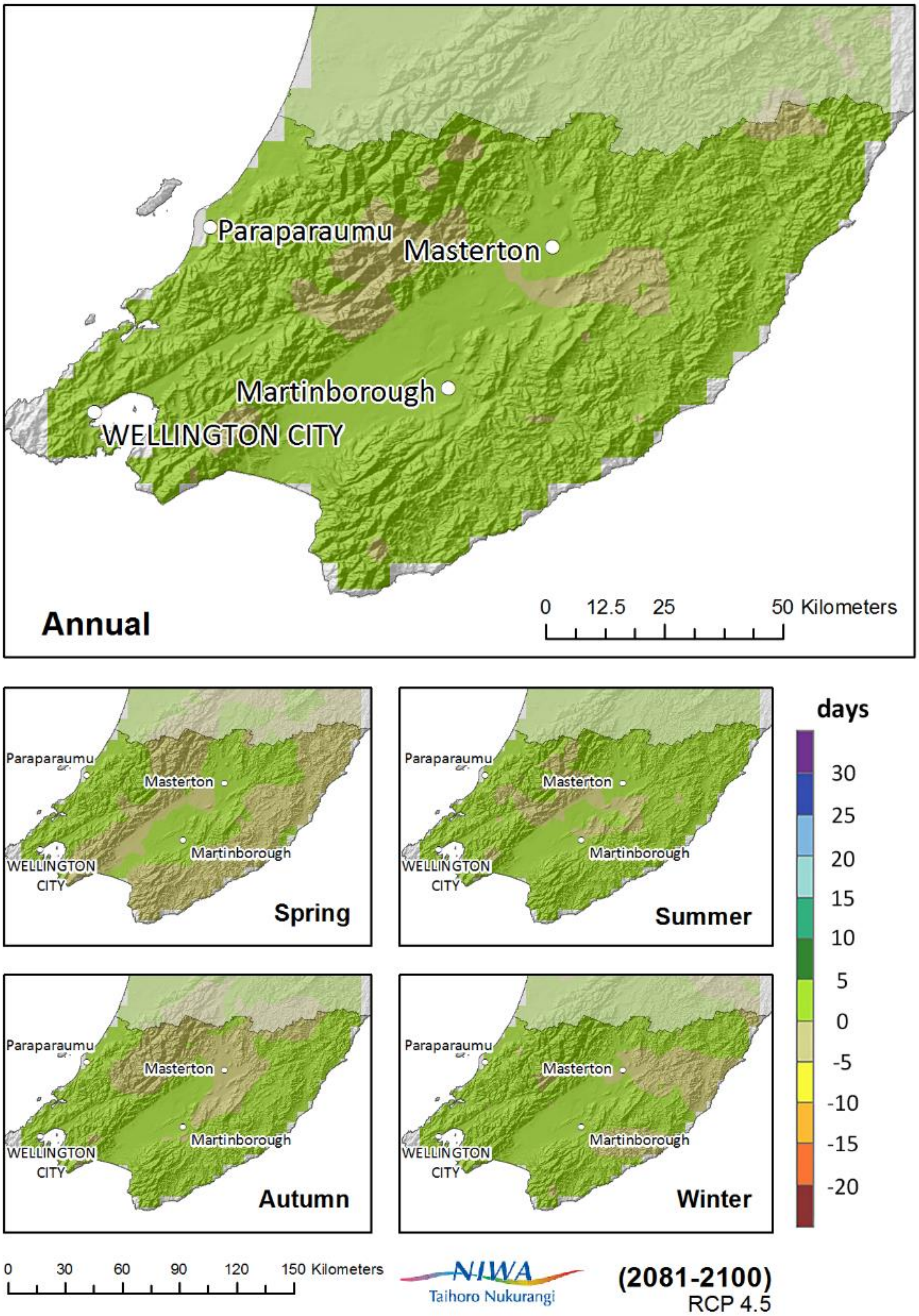

Figure 4-29: Projected annual and seasonal heavy rain day changes (days where rain > 25 mm; in number of days) at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP4.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

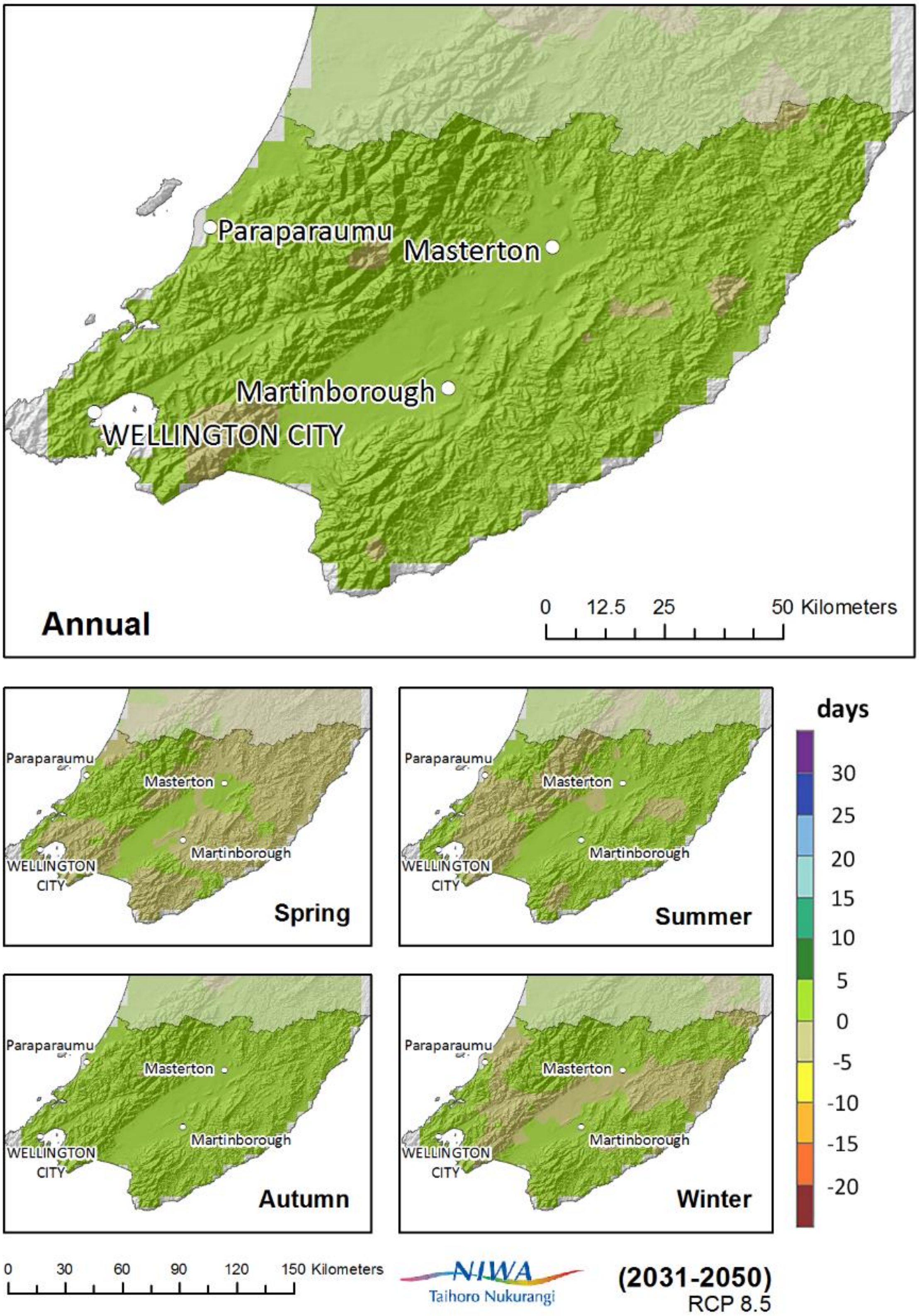

Figure 4-30: Projected annual and seasonal heavy rain day changes (days where rain > 25 mm; in number of days) at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

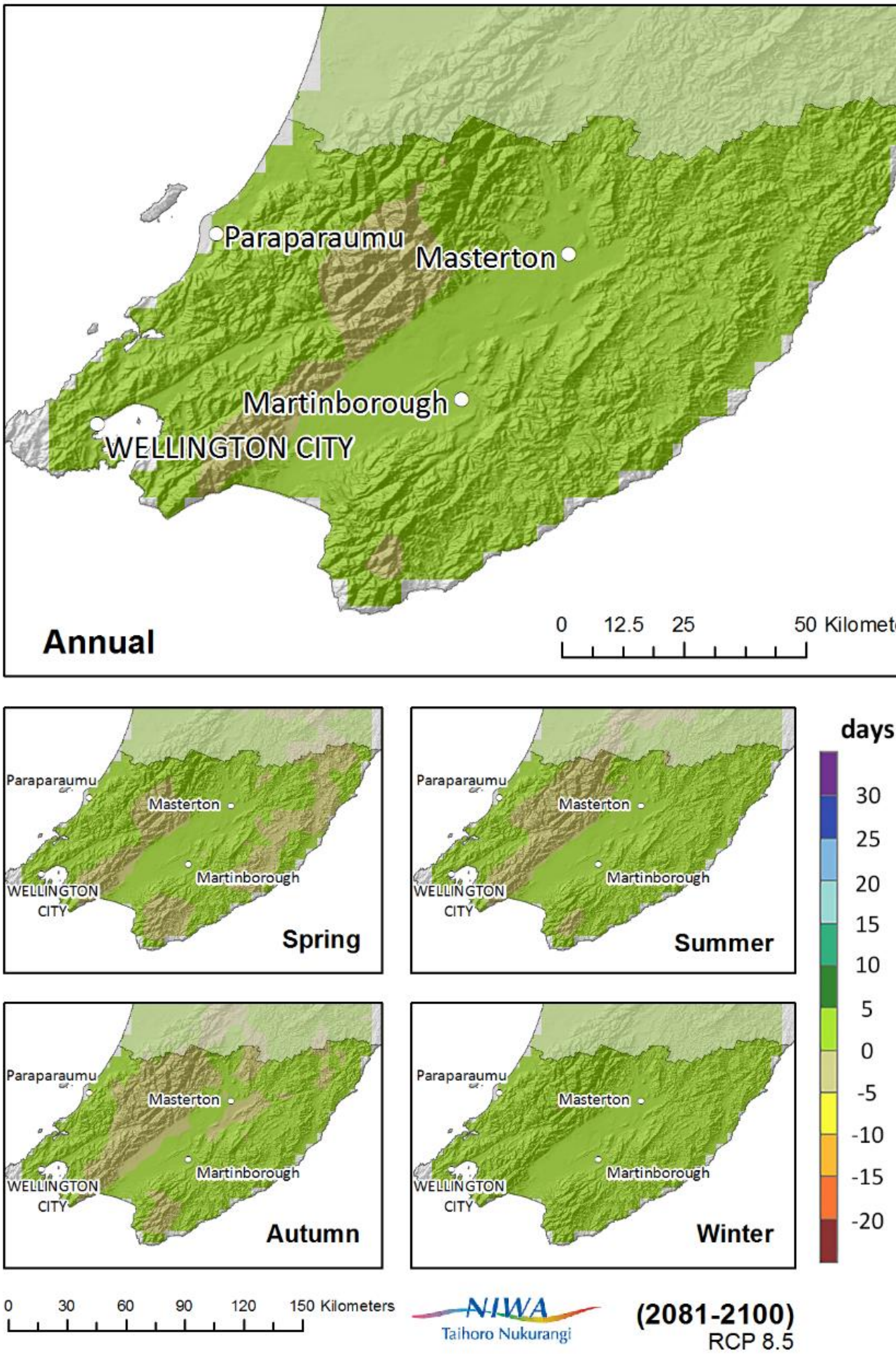

Figure 4-31: Projected annual and seasonal heavy rain day changes (days where rain > 25 mm; in number of days) at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP8.5 scenario, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

4.2.4 Dry day projections

Dry days are defined as days with rainfall less than 1 mm. The projected changes in dry days for the Wellington Region are presented for RCP4.5 and RCP8.5 at 2040 and 2090 in Figure 4-32 to Figure 4-35, derived from dynamical downscaled models. Under RCP4.5 at 2040, dry days increase to the east of the Tararua and Rimutaka Ranges, particularly in summer, and decrease along the west coast in spring (Figure 4-32). By 2090 under RCP4.5, over 12 more dry days are expected in the south Wairarapa region per year, and an increase in dry days is shown across the region at the annual scale except for isolated parts of the west coast (Figure 4-33). For 2040 under RCP8.5, dry days are projected to increase through the middle of the region, particularly in summer, and this is reflected at the annual scale (Figure 4-34). By 2090 under RCP8.5, over 12 more dry days are projected over virtually the entire Wellington Region, with the largest increase in dry days projected for winter (Figure 4-35).

Model agreement is good for dry day projections as most models predict an increase under both RCPs at both time periods.

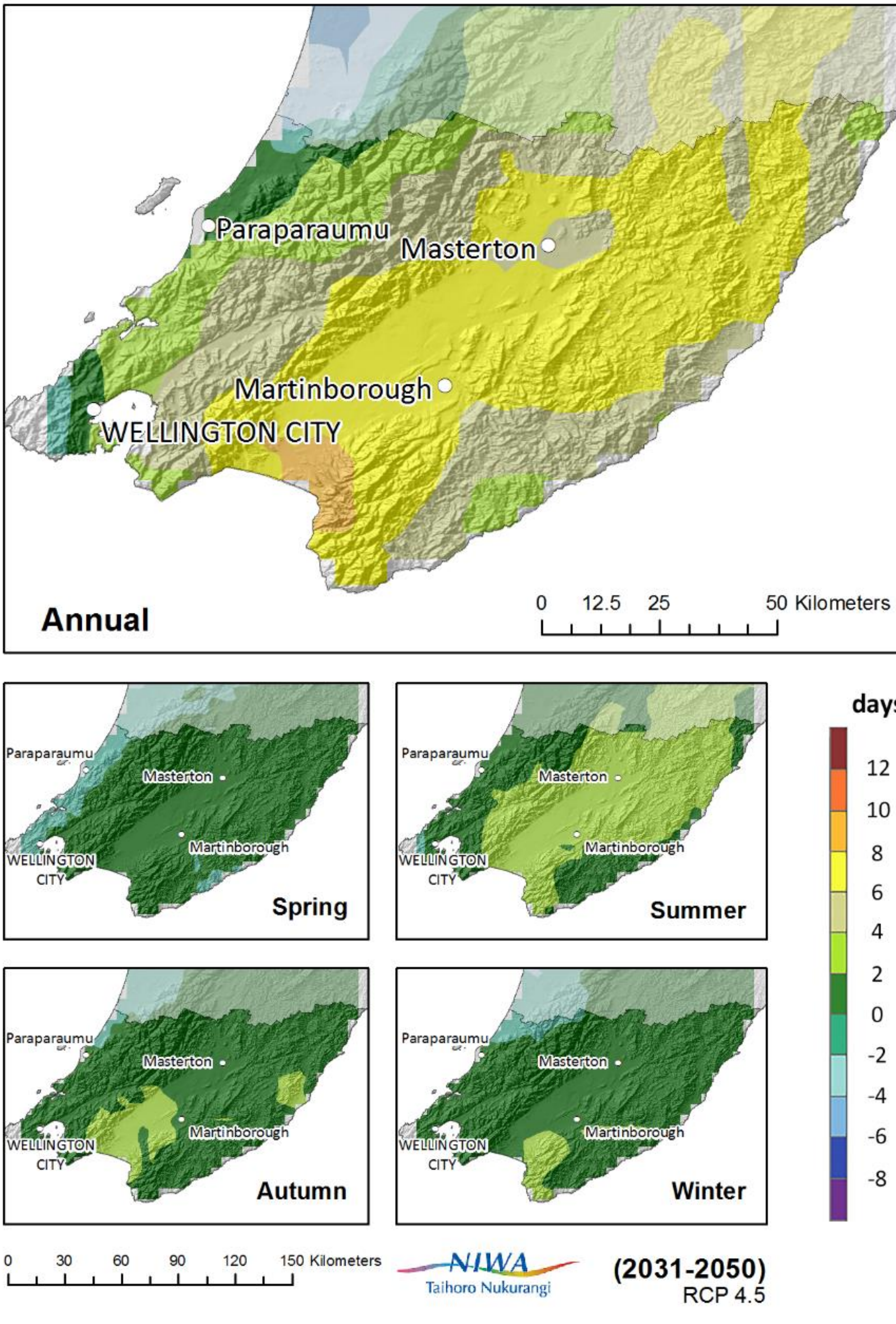

Figure 4-32: Projected change in number of dry days per year and season (precipitation <1mm/day) at 2040 for RCP4.5, for the Wellington Region. Projected change in dry days is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

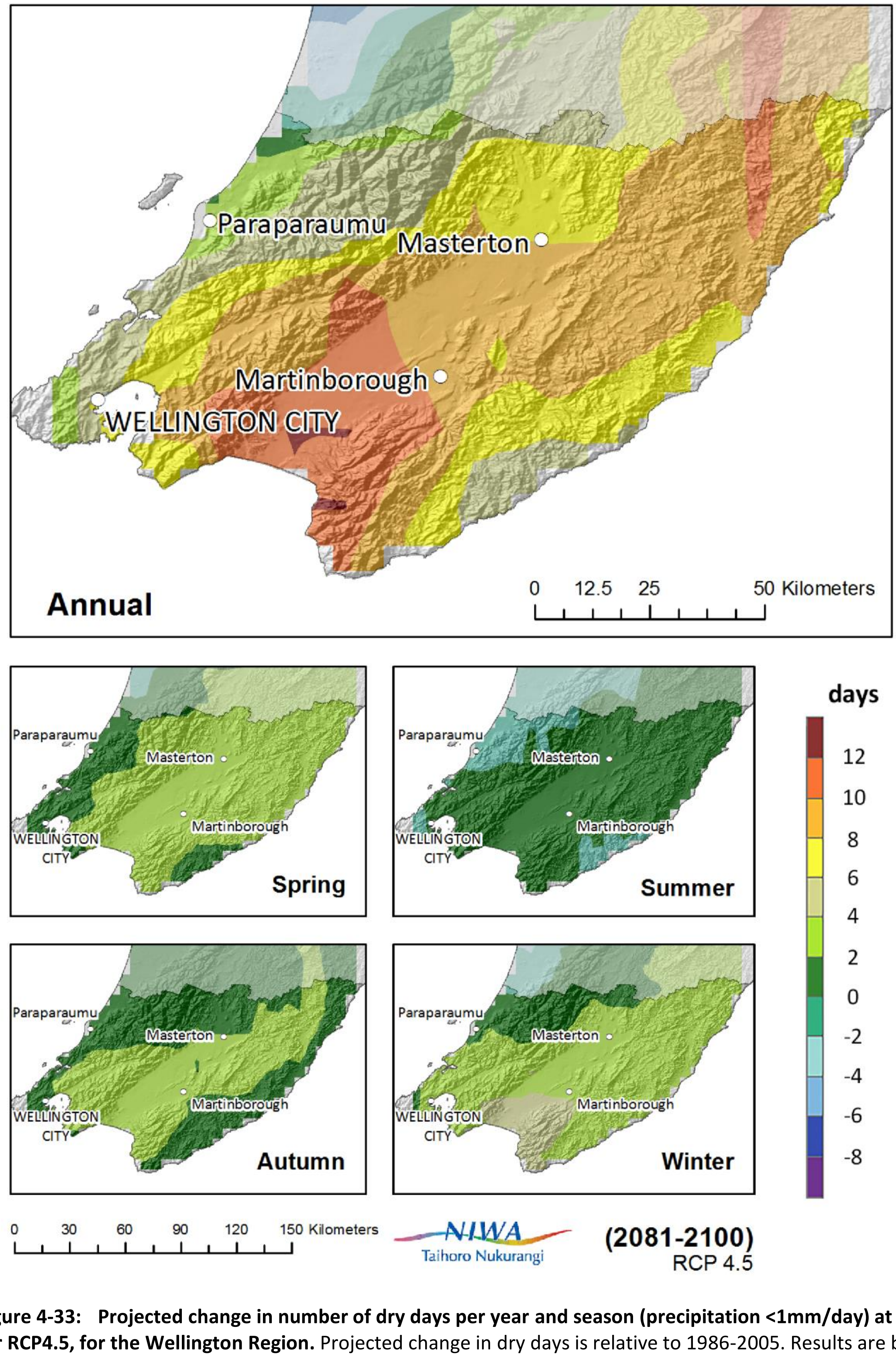

Figure 4-33: Projected change in number of dry days per year and season (precipitation <1mm/day) at 2090 for RCP4.5, for the Wellington Region. Projected change in dry days is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

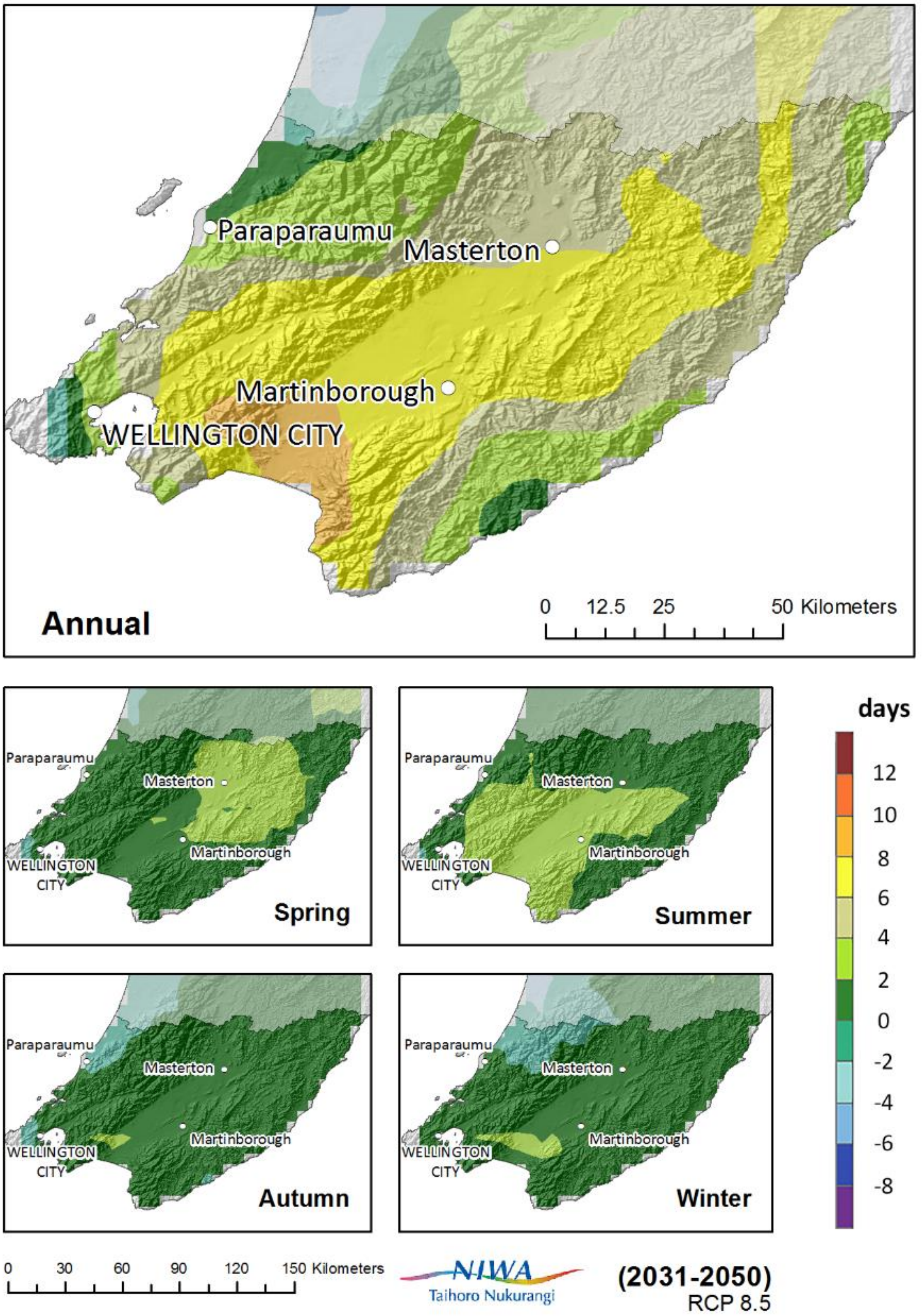

Figure 4-34: Projected change in number of dry days per year and season (precipitation <1mm/day) at 2040 for RCP8.5, for the Wellington Region. Projected change in dry days is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

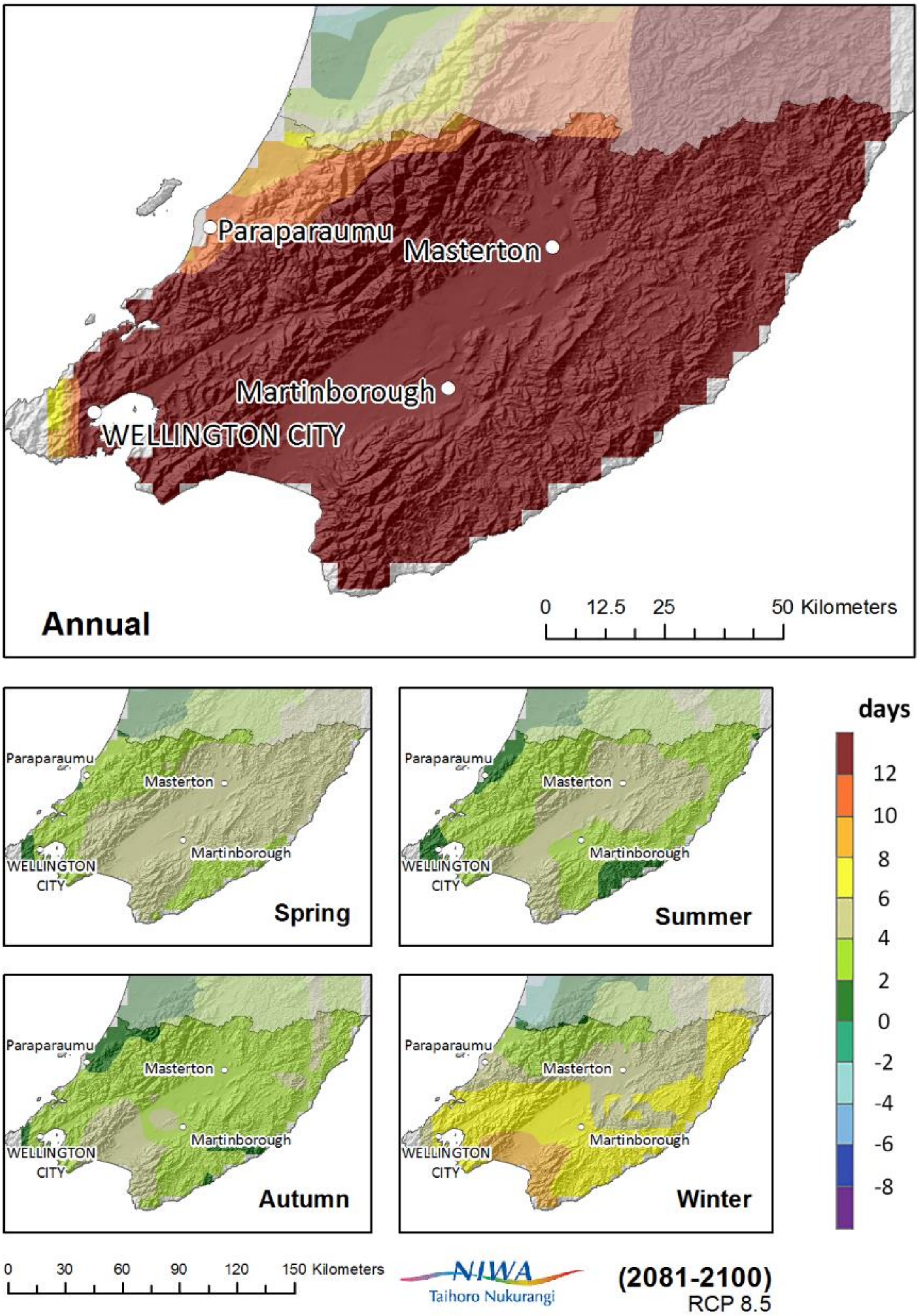

Figure 4-35: Projected change in number of dry days per year and season (precipitation <1mm/day) at 2090 for RCP8.5, for the Wellington Region. Projected change in dry days is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

4.2.5 Snow day projections

Changes in snow days have been estimated from the Regional Climate Model output. This was done by counting precipitation days where the mean temperature was below the freezing point. Modelled snow day frequency for 1986-2005 (current climatology) shows that the maximum amount of snow days experienced in the region is two days per year, in the highest elevations of the Tararua Ranges. This is likely underestimated due to the 5km x 5km grid cell resolution. Figure 4-36 shows the changes in 'snow days' calculated in this way for the Wellington Region, as a function of time period and RCP. The number of snow days per year essentially reduces everywhere, with the largest reduction in the highest elevations of the Tararua Ranges.

Model agreement is good for snow day projections as all models predict a decrease under both RCPs at both time periods.

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

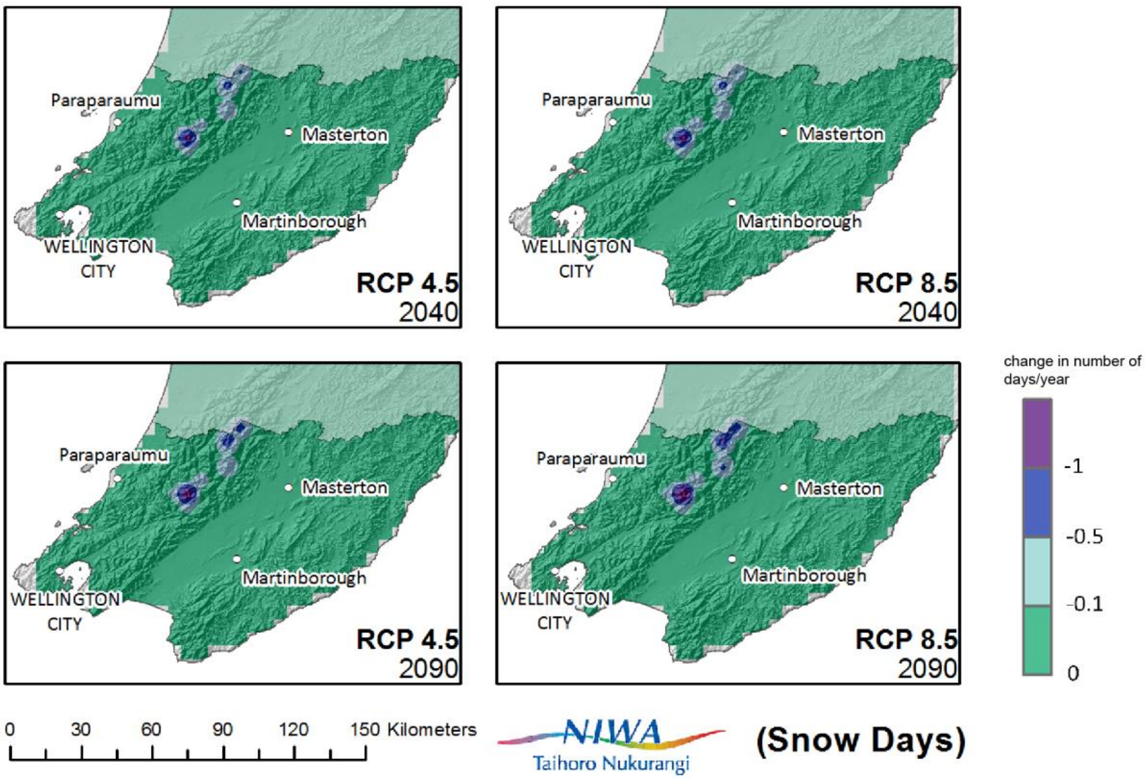

Figure 4-36: Projected changes in the annual number of 'snow days' (in days per year) for RCP4.5 (left panels) and RCP8.5 (right panels) at 2040 and 2090. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km.

4.2.6 Extreme rainfall

A warmer atmosphere can hold more moisture, so there is potential for heavier extreme rainfall with global increases in temperatures under climate change. In its Fifth Assessment Report, the IPCC concluded that the frequency of heavy precipitation events is "very likely" to increase over most mid-latitude land areas (this includes New Zealand) (IPCC, 2013, Table SPM.1). Given the mountainous nature of New Zealand, spatial patterns of changes in rainfall extremes are expected to depend on changes in atmospheric circulation and storm tracks.

NIWA produced guidance on changes in heavy rainfall to be used for "screening assessments"[4] in New Zealand, for the 2008 update to the Local Government Guidance manual (Ministry for the Environment, 2008a). The manual recommends use of a geographically uniform relationship between projected changes in temperature and changes in extreme rainfall return period statistics. An overview of the process for producing heavy rainfall statistics for screening analyses, with detailed examples of its application for two locations in the Wellington Region, is provided here (Wellington City and Masterton). This method uses augmentation amounts for various rainfall return intervals and durations set out in Table 4-7, which is a reproduction of Table 5.2 of the revised Guidance Manual (Ministry for the Environment, 2008a). The recommendation in the Local Government Guidance manual is that if a screening analysis using statistics produced through this process indicates changes in heavy rainfall could lead to problems for a particular asset or activity, then further guidance should be sought from a science provider for a more detailed risk analysis.

Table 4-8 to Table 4-11 provide current rainfall depth-duration-frequency statistics for Wellington (Kelburn), as well as statistics for screening studies under mid-range and high-end temperature scenarios for 2100. Table 4-12 to Table 4-15 show the same information for Masterton.

Table 4-7: Augmentation factors (percentage increases per degree of warming) used in deriving changes in extreme rainfall for preliminary scenario studies, based on NIWA's regional climate model.

	ARI						
Duration	**2 yrs**	**5 yrs**	**10 yrs**	**20 yrs**	**30 yrs**	**50 yrs**	**100 yrs**
< 10 minutes	8.0	8.0	8.0	8.0	8.0	8.0	8.0
10 minutes	8.0	8.0	8.0	8.0	8.0	8.0	8.0
30 minutes	7.2	7.4	7.6	7.8	8.0	8.0	8.0
60 minutes	6.7	7.1	7.4	7.7	8.0	8.0	8.0
2 hours	6.2	6.7	7.2	7.6	8.0	8.0	8.0
3 hours	5.9	6.5	7.0	7.5	8.0	8.0	8.0
6 hours	5.3	6.1	6.8	7.4	8.0	8.0	8.0
12 hours	4.8	5.8	6.5	7.3	8.0	8.0	8.0
24 hours	4.3	5.4	6.3	7.2	8.0	8.0	8.0
48 hours	3.8	5.0	6.1	7.1	7.8	8.0	8.0
72 hours	3.5	4.8	5.9	7.0	7.7	8.0	8.0

Note: This table recommends *percentage* adjustments to apply to extreme rainfall per 1°C of warming, for a range of average recurrence intervals (ARIs). The percentage changes are mid-range estimates per 1°C and should be used only in a screening assessment. The entries in this table for a duration of 24 hours are based on results from a regional climate model driven for the A2 SRES emissions scenario. The entries for 10-minute duration are based on the theoretical increase in the amount of water held in the

[4] "Screening" describes an initial assessment step to consider whether potential impacts of climate change on a particular function or item of infrastructure are likely to be material.

atmosphere for a 1°C increase in temperature (8%). Entries for other durations are based on logarithmic (in time) interpolation between the 10-minute and 24-hour rates. After Ministry for the Environment (2008a).

Table 4-8: Current rainfall depth-duration-frequency statistics for Wellington (Kelburn) from HIRDS V3. Numbers in the body of the table are in mm.

ARI (years)	Duration									
	10m	**20m**	**30m**	**60m**	**2h**	**6h**	**12h**	**24h**	**48h**	**72h**
2	6.6	9.7	12.2	17.8	24.4	40.2	55	75.3	90.6	100.9
5	8.4	12.4	15.5	22.8	31	50.4	68.6	93.3	112.2	125
10	9.9	14.5	18.2	26.7	36.2	58.6	79.3	107.5	129.3	144.1
20	11.6	17	21.3	31.2	42.1	67.6	91.3	123.1	148.1	165
30	12.6	18.6	23.2	34.1	45.9	73.5	98.9	133.1	160.2	178.5
50	14.1	20.7	26	38.1	51.1	81.5	109.4	146.8	176.6	196.8
100	16.4	24.1	30.1	44.2	59.2	93.7	125.3	167.5	201.5	224.5

Table 4-9: Projected rainfall depth-duration-frequency statistics for Wellington (Kelburn) in 2100, for a low-range temperature scenario (1°C warming), from HIRDS V3.

ARI (years)	Duration									
	10m	**20m**	**30m**	**60m**	**2h**	**6h**	**12h**	**24h**	**48h**	**72h**
2	7.1	10.4	13.1	19	25.9	42.3	57.6	78.5	94	104.4
5	9.1	13.4	16.6	24.4	33.1	53.5	72.6	98.3	117.8	131
10	10.7	15.6	19.6	28.7	38.8	62.6	84.5	114.3	137.2	152.6
20	12.5	18.4	23	33.6	45.3	72.6	98	132	158.6	176.6
30	13.6	20.1	25.1	36.8	49.6	79.4	106.8	143.7	172.7	192.2
50	15.2	22.4	28.1	41.1	55.2	88	118.2	158.5	190.7	212.5
100	17.7	26	32.5	47.7	63.9	101.2	135.3	180.9	217.6	242.5

Table 4-10: Projected rainfall depth-duration-frequency statistics for Wellington (Kelburn) in 2100 for a mid-range temperature scenario (2°C warming), from HIRDS V3.

ARI (years)	Duration									
	10m	20m	30m	60m	2h	6h	12h	24h	48h	72h
2	7.7	11.2	14	20.2	27.4	44.5	60.3	81.8	97.5	108
5	9.7	14.3	17.8	26	35.2	56.5	76.6	103.4	123.4	137
10	11.5	16.8	21	30.7	41.4	66.6	89.6	121	145.1	161.1
20	13.5	19.7	24.6	36	48.5	77.6	104.6	140.8	169.1	188.1
30	14.6	21.6	26.9	39.6	53.2	85.3	114.7	154.4	185.2	206
50	16.4	24	30.2	44.2	59.3	94.5	126.9	170.3	204.9	228.3
100	19	28	34.9	51.3	68.7	108.7	145.3	194.3	233.7	260.4

Table 4-11: Projected rainfall depth-duration-frequency statistics for Wellington (Kelburn) in 2100, for a higher-end temperature scenario (3°C warming), from HIRDS V3.

ARI (years)	Duration									
	10m	20m	30m	60m	2h	6h	12h	24h	48h	72h
2	8.2	11.9	14.8	21.4	28.9	46.6	62.9	85	100.9	111.5
5	10.4	15.3	18.9	27.7	37.2	59.6	80.5	108.4	129	143
10	12.3	17.9	22.3	32.6	44	70.6	94.8	127.8	153	169.6
20	14.4	21.1	26.3	38.4	51.7	82.6	111.3	149.7	179.6	199.7
30	15.6	23.1	28.8	42.3	56.9	91.1	122.6	165	197.7	219.7
50	17.5	25.7	32.2	47.2	63.4	101.1	135.7	182	219	244
100	20.3	29.9	37.3	54.8	73.4	116.2	155.4	207.7	249.9	278.4

Table 4-12: Current rainfall depth-duration-frequency statistics for Masterton from HIRDS V3. Numbers in the body of the table are in mm.

ARI (years)	Duration									
	10m	20m	30m	60m	2h	6h	12h	24h	48h	72h
2	6	8.5	10.4	14.6	20.5	34.9	48.9	68.5	83.5	93.8
5	8.1	11.4	13.9	19.6	27	45	62.2	85.9	104.7	117.6
10	9.8	13.8	16.8	23.7	32.4	53.3	72.9	99.7	121.6	136.6
20	11.8	16.6	20.3	28.5	38.7	62.6	84.9	115.1	140.4	157.7
30	13.1	18.5	22.5	31.7	42.8	68.7	92.7	125	152.5	171.3
50	15	21.1	25.7	36.2	48.6	77.2	103.5	138.6	169.1	189.9
100	17.9	25.2	30.8	43.4	57.6	90.3	120	159.3	194.3	218.3

Table 4-13: Projected rainfall depth-duration-frequency statistics for Masterton in 2100, for a low-range temperature scenario (1°C warming), from HIRDS V3.

ARI (years)	Duration									
	10m	**20m**	**30m**	**60m**	**2h**	**6h**	**12h**	**24h**	**48h**	**72h**
2	6.5	9.2	11.1	15.6	21.8	36.7	51.2	71.4	86.7	97.1
5	8.7	12.3	14.9	21	28.8	47.7	65.8	90.5	109.9	123.2
10	10.6	14.9	18.1	25.5	34.7	56.9	77.6	106	129	144.7
20	12.7	17.9	21.9	30.7	41.6	67.2	91.1	123.4	150.4	168.7
30	14.1	20	24.3	34.2	46.2	74.2	100.1	135	164.4	184.5
50	16.2	22.8	27.8	39.1	52.5	83.4	111.8	149.7	182.6	205.1
100	19.3	27.2	33.3	46.9	62.2	97.5	129.6	172	209.8	235.8

Table 4-14: Projected rainfall depth-duration-frequency statistics for Masterton in 2100 for a mid-range temperature scenario (2°C warming), from HIRDS V3.

ARI (years)	Duration									
	10m	**20m**	**30m**	**60m**	**2h**	**6h**	**12h**	**24h**	**48h**	**72h**
2	7	9.8	11.9	16.6	23	38.6	53.6	74.4	89.8	100.4
5	9.4	13.2	16	22.4	30.6	50.5	69.4	95.2	115.2	128.9
10	11.4	16	19.4	27.2	37.1	60.5	82.4	112.3	136.4	152.7
20	13.7	19.3	23.5	32.9	44.6	71.9	97.3	131.7	160.3	179.8
30	15.2	21.5	26.1	36.8	49.6	79.7	107.5	145	176.3	197.7
50	17.4	24.5	29.8	42	56.4	89.6	120.1	160.8	196.2	220.3
100	20.8	29.2	35.7	50.3	66.8	104.7	139.2	184.8	225.4	253.2

Table 4-15: Projected rainfall depth-duration-frequency statistics for Masterton in 2100, for a higher-end temperature scenario (3°C warming), from HIRDS V3.

ARI (years)	Duration									
	10m	**20m**	**30m**	**60m**	**2h**	**6h**	**12h**	**24h**	**48h**	**72h**
2	7.4	10.5	12.6	17.5	24.3	40.4	55.9	77.3	93	103.6
5	10	14	17	23.8	32.4	53.2	73	99.8	120.4	134.5
10	12.2	17	20.6	29	39.4	64.2	87.1	118.5	143.9	160.8
20	14.6	20.6	25.1	35.1	47.5	76.5	103.5	140	170.3	190.8
30	16.2	22.9	27.9	39.3	53.1	85.2	114.9	155	188.2	210.9
50	18.6	26.2	31.9	44.9	60.3	95.7	128.3	171.9	209.7	235.5
100	22.2	31.2	38.2	53.8	71.4	112	148.8	197.5	240.9	270.7

Projected rainfall depth-duration-frequency tables for other locations in the Greater Wellington can be produced using HIRDS (High Intensity Rainfall Design System) software package (www.hirds.niwa.co.nz) and the process is described in the revised Local Government Guidance Manual (Ministry for the Environment, 2008a). Note that a significant update to HIRDS is currently underway (to be completed in late 2017).

Changes in the magnitude of extreme precipitation across the Wellington Region have been dynamically downscaled using NIWA's Regional Climate Model in Figure 4-37. The magnitude of extreme precipitation, as quantified by the changes in the 99th percentile of the daily precipitation distribution (i.e. the top 1% of rain days[5]), shows increases across the region (no part of the region projects decreases in extreme rainfall). The most increases in 99th percentile daily precipitation are generally around Wellington city, as well as in the coastal areas of the region.

Under RCP4.5 at 2040, most areas are expected to receive a 5% increase in extreme daily precipitation, with some western and southern parts of the region experiencing up to a 10% and 15% increase in extreme daily precipitation around Wellington City. By 2090 under RCP4.5, more high elevation areas are likely to receive up to 10% more extreme precipitation and east coast areas may receive up to 15% more extreme precipitation.

Under RCP8.5 at 2040, there is a relatively even split between areas that are expecting up to 5% increase in extreme daily precipitation and those that are expecting up to a 10% increase. However, by 2090, most areas are likely to receive at least a 10-15% increase in extreme daily precipitation, with some coastal areas (especially around Wellington City) projected to receive more than a 25% increase in extreme precipitation.

Model agreement is good across both RCPs and both time periods. For RCP4.5, most models predict extreme daily rain to increase in the west and the mountains. For RCP8.5, all models predict increasing extreme rainfall throughout the region.

This preliminary analysis suggests that some regional variation may be expected in future return periods of extreme rainfall. This is an advance on Ministry for the Environment (2008a), where a spatially constant factor was applied to changes in rainfall return periods as temperatures increase.

As a cautionary aside, the climate models being used do not have the resolution to realistically simulate tropical cyclones, so extreme rainfall from these phenomena are likely to be underestimated in our results.

[5] Note that the 99th percentile is a relatively low threshold for engineering purposes (see Ministry for the Environment, 2008a, Chapter 5.2). We would expect that, on average, approximately one day per year would exceed this threshold.

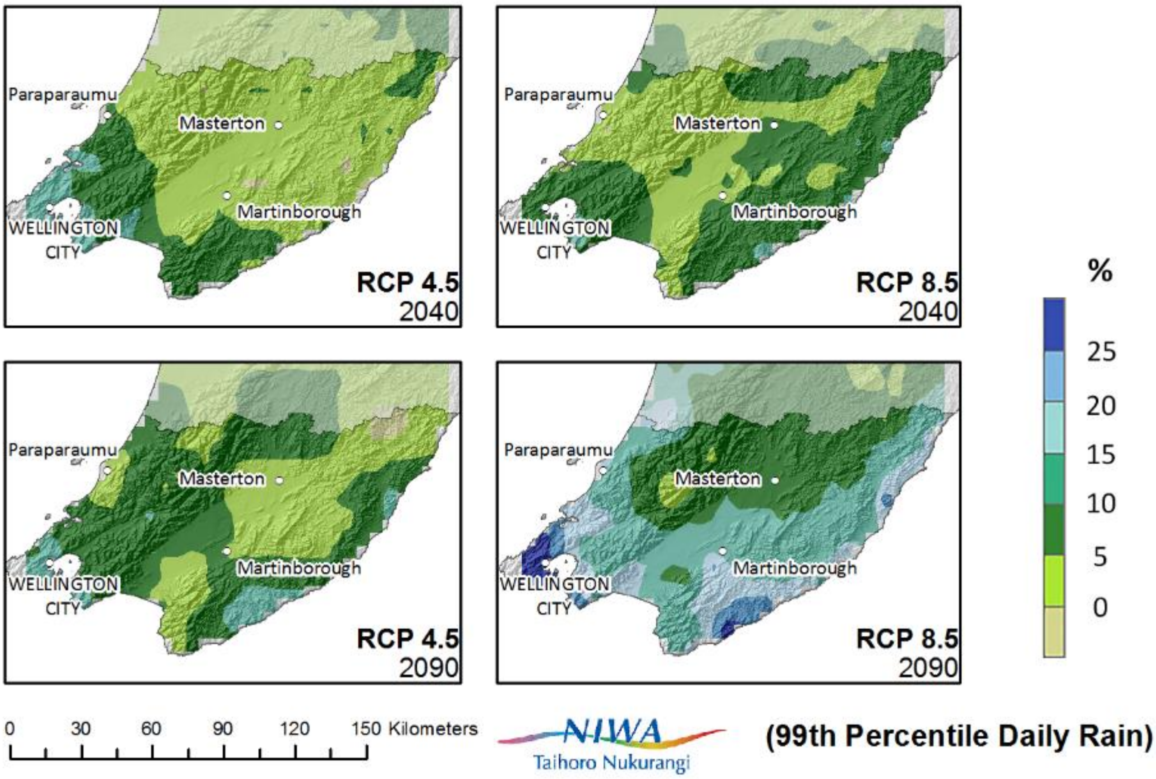

Figure 4-37: Change in the magnitude of the 99th percentile of daily precipitation (in %) for RCP4.5 and RCP8.5, at 2040 and 2090. Projected change in 99^{th} percentile of daily precipitation is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

4.3 Temperature and precipitation projection comparisons within RCPs

The average picture of projected temperature and rainfall changes in the tables and maps in Sections 4.1 and 4.2 obscures significant variations between the individual models run under each RCP on the projected seasonal changes. Figure 4-38 and Figure 4-39 show seasonal temperature projections from all the models individually averaged over the Wellington Region for 2040 and 2090, respectively. The coloured vertical bars, and inset stars, show the individual models, so the complete range is displayed (unlike Table 4-1, Table 4-3 and Table 4-4, where the 5th to 95th percentile range has been calculated). Figure 4-38 and Figure 4-39 show an excellent way of not only demonstrating the difference with season and RCP, but also the range of model sensitivity. The black stars within each vertical bar represent the results of the six Regional Climate Model (RCM) simulations; the RCM projections tend to be in the lower half of the statistically-downscaled results, owing to the bias-correction applied to the raw RCM output.

For 2040 (Figure 4-38), all four RCPs project quite similar changes on average for the region (model-average warming – the black horizontal line on the bars – is within about 0.5°C). The models for RCP 8.5 have the greatest spread, particularly in summer and secondly for winter (the red bar). For 2090 (Figure 4-39), the model spread is much larger, with the models for summer for RCP 8.5 spread across 3.5°C of warming. However, the models all agree on the direction of change (i.e. warming), although some models project temperatures very close to 0°C change under RCP2.6 (the blue bar) for summer.

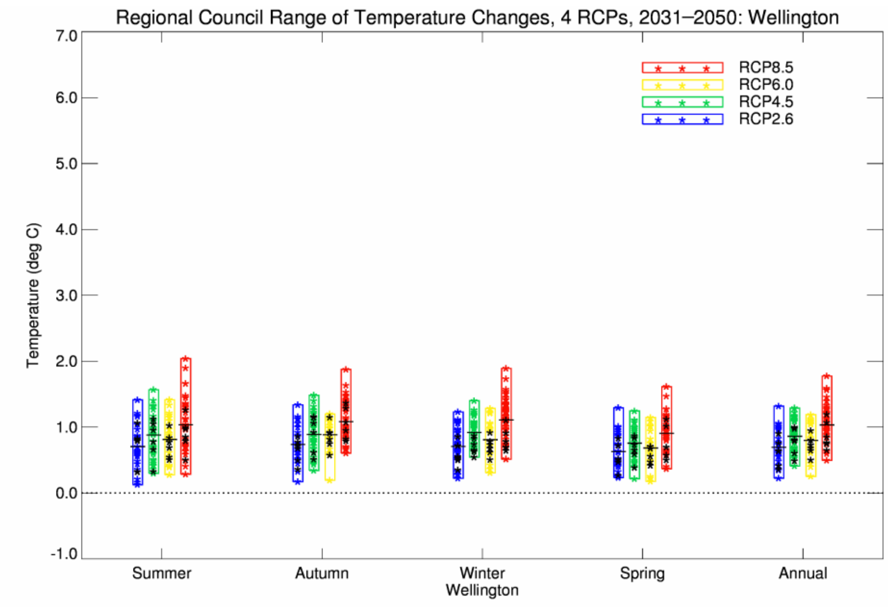

Figure 4-38: Projected seasonal temperature changes by 2040 (2031-2050) averaged over the Wellington Region, for the four RCPs. The vertical coloured bars show the range over all climate models used, and coloured stars the projected changes for each model individually (results from statistical downscaling). The black stars represent the 6-model dynamical downscaling changes. The short horizontal line is the model-average warming over all statistical and dynamical models. Blue = RCP2.6, 23 models; green = RCP4.5, 37 models; yellow = RCP6.0, 18 models; red = RCP8.5, 41 models. © NIWA.

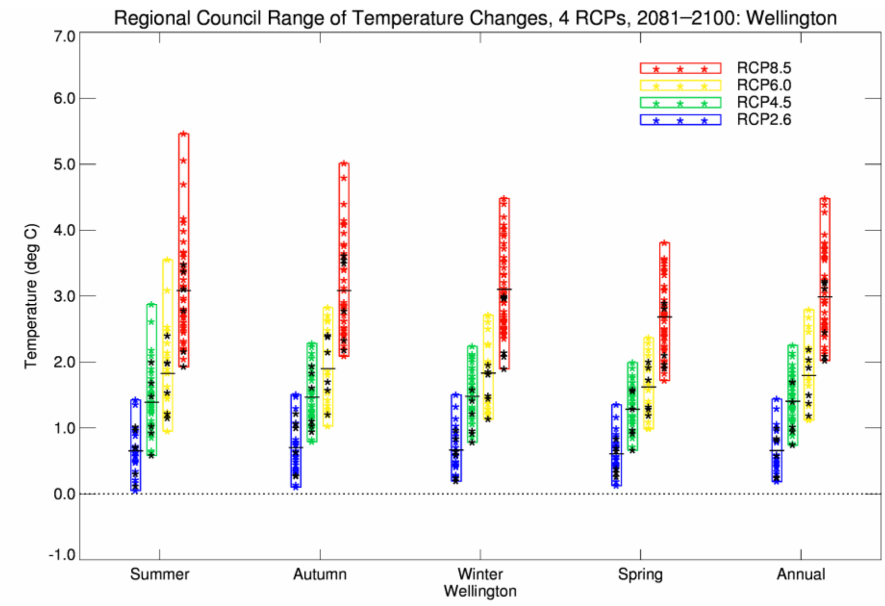

Figure 4-39: Projected seasonal temperature changes by 2090 (2081-2100) averaged over the Wellington Region, for the four RCPs. The vertical coloured bars show the range over all climate models used, and coloured stars the projected changes for each model individually (results from statistical downscaling). The black stars represent the 6-model dynamical downscaling changes. The short horizontal line is the model-average warming over all statistical and dynamical models. Blue = RCP2.6, 23 models; green = RCP4.5, 37 models; yellow = RCP6.0, 18 models; red = RCP8.5, 41 models. © NIWA.

Figure 4-40 and Figure 4-41 show seasonal rainfall projections from all the models individually for two grid points from the Wellington Region (Paraparaumu and Masterton) for 2040 and 2090, respectively. Note that Wellington city was also plotted but showed no difference to the Paraparaumu figure, so has been excluded here. In general, there is no agreement between the models as to the direction of projected rainfall changes, as identified in Table 4-3 to Table 4-6 for the different RCPs. For all regions, the model-average rainfall projections for summer, autumn and spring 2040 are close to zero, but larger positive changes are projected for winter for Paraparaumu (Figure 4-40 top). Masterton shows model-average projections are close to zero for all seasons (Figure 4-40 bottom). The spread of the models under each RCP is quite large; outputs are spread across approximately -10% to +20% precipitation change for winter for Paraparaumu and -20% to +15% precipitation change for summer for Masterton, at 2040. For 2090 (Figure 4-41), the model spread under each RCP is much larger than in Figure 4-40. For both Paraparaumu, summer and winter have the greatest spread, and for Masterton, summer has the greatest model spread.

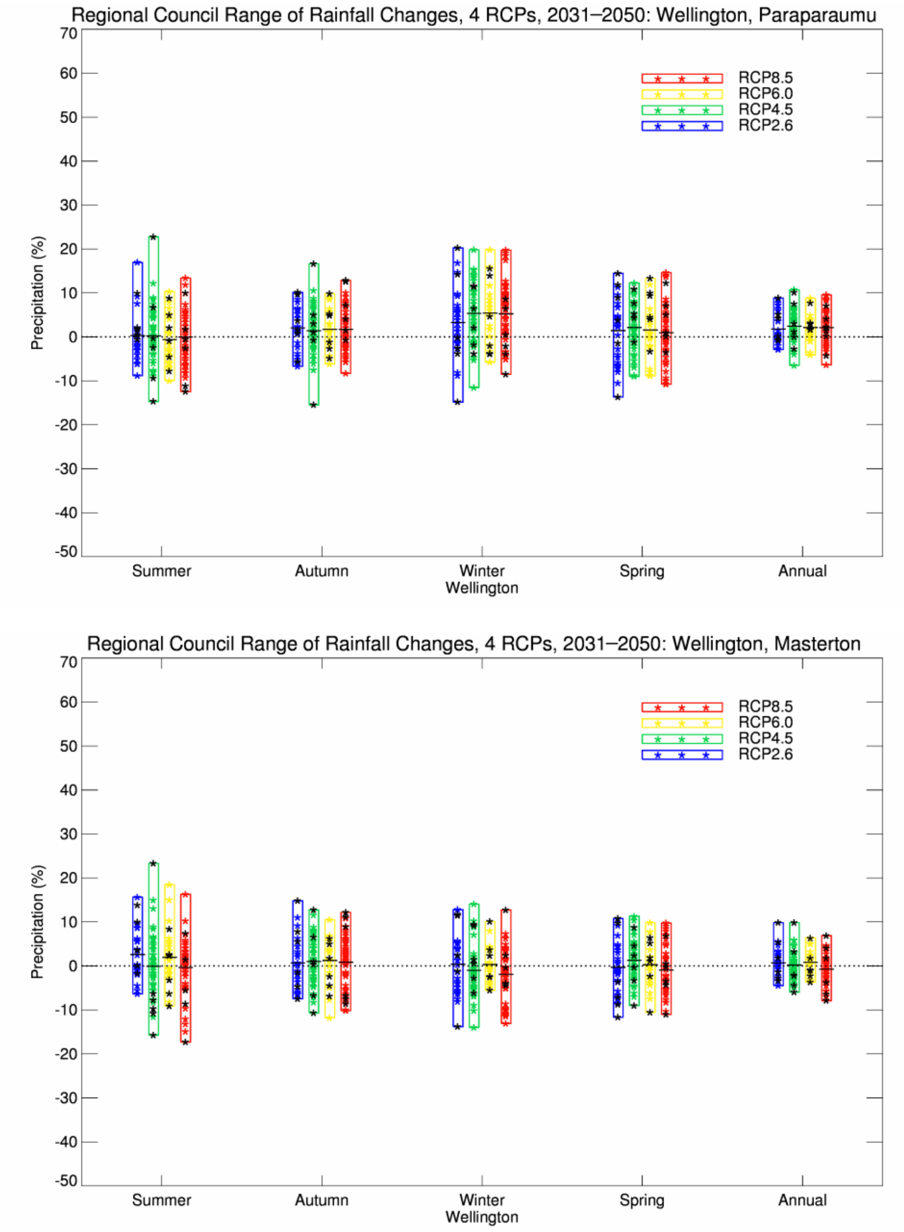

Figure 4-40: Projected seasonal rainfall changes by 2040 (2031-2050) for Paraparaumu and Masterton, respectively, for the four RCPs. The vertical coloured bars show the range over all climate models used, and coloured stars the projected changes for each model individually (results from statistical downscaling). The black stars represent the 6-model dynamical downscaling changes. The short horizontal line is the model-average rainfall over all statistical and dynamical models. Blue = RCP2.6, 23 models; green = RCP4.5, 37 models; yellow = RCP6.0, 18 models; red = RCP8.5, 41 models. © NIWA.

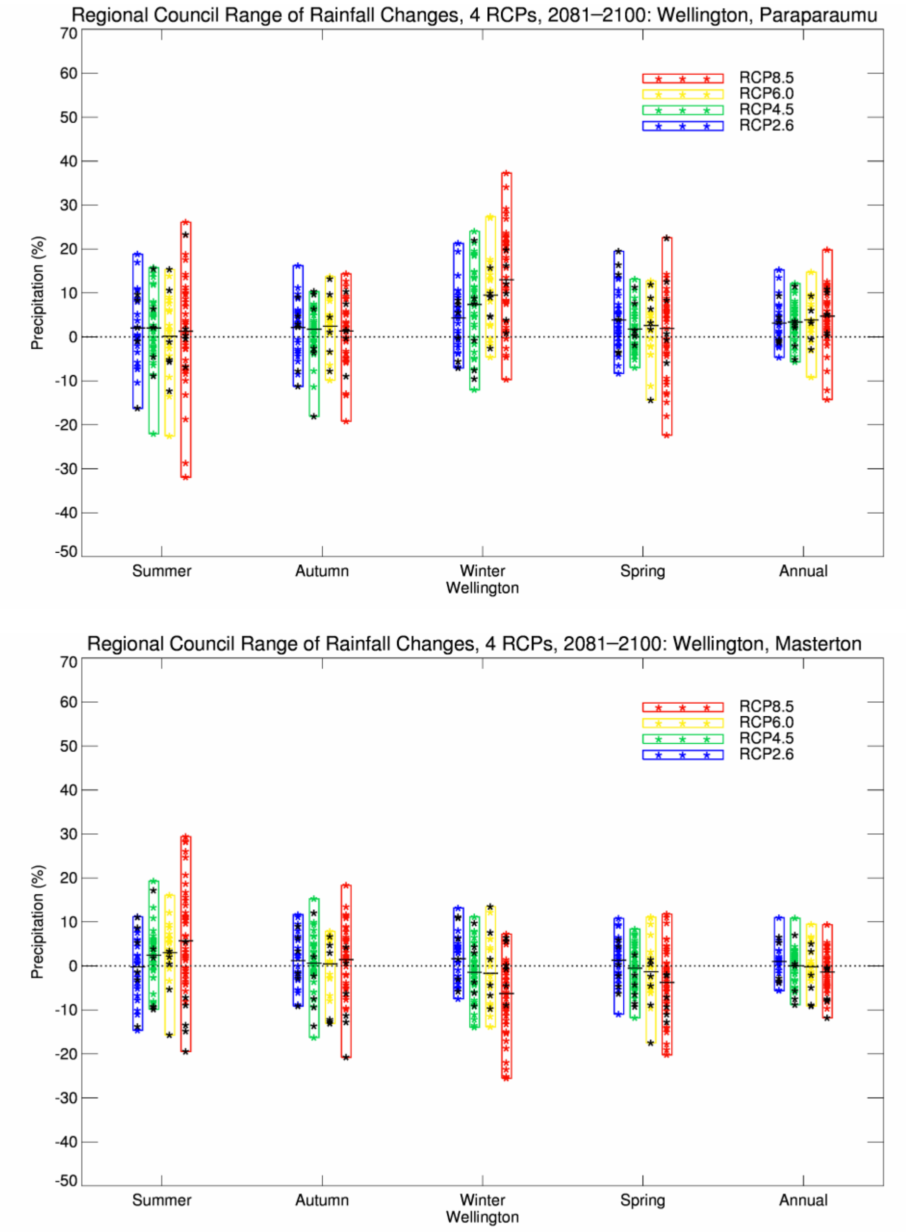

Figure 4-41: Projected seasonal rainfall changes by 2090 (2081-2100) for Paraparaumu and Masterton, respectively, for the four RCPs. The vertical coloured bars show the range over all climate models used, and coloured stars the projected changes for each model individually (results from statistical downscaling). The black stars represent the 6-model dynamical downscaling changes. The short horizontal line is the model-average rainfall over all statistical and dynamical models. Blue = RCP2.6, 23 models; green = RCP4.5, 37 models; yellow = RCP6.0, 18 models; red = RCP8.5, 41 models. © NIWA.

Note that Figure 4-40 and Figure 4-41 show the model variability at two grid points only (Paraparaumu and Masterton), rather than a regional average (as was done for temperature). This is because the projected changes for rainfall vary greatly over the region.

4.4 Changes to evaporation, soil moisture and climatic drought

The increase in frequency and intensity of climatic droughts in a changing climate is of deep concern for the New Zealand society and economy, not the least for the stakeholders of the primary sector. Drought intensity is affected by increasing temperature which in turn increases moisture loss through higher evapotranspiration rates, and also by the lack of sufficient moderate intensity precipitation required to recharge aquifers and replenish soil moisture.

Potential evapotranspiration deficit (PED) is the cumulative difference between potential evapotranspiration (PET) and rainfall from 1 July of a calendar year to 30 June of the next year, 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 rainfall needed in order to keep pastures growing at optimum levels. An increase in PED of 30 mm or more corresponds to an extra week of reduced grass growth.

A regional map of projected changes in potential evapotranspiration deficit is presented in Figure 4-42. The maps are plotted with an annual accumulated PED anomaly with respect to the historical annual average. The historical record of PED in select locations within the Wellington Region can be seen in Section 3.2.3.

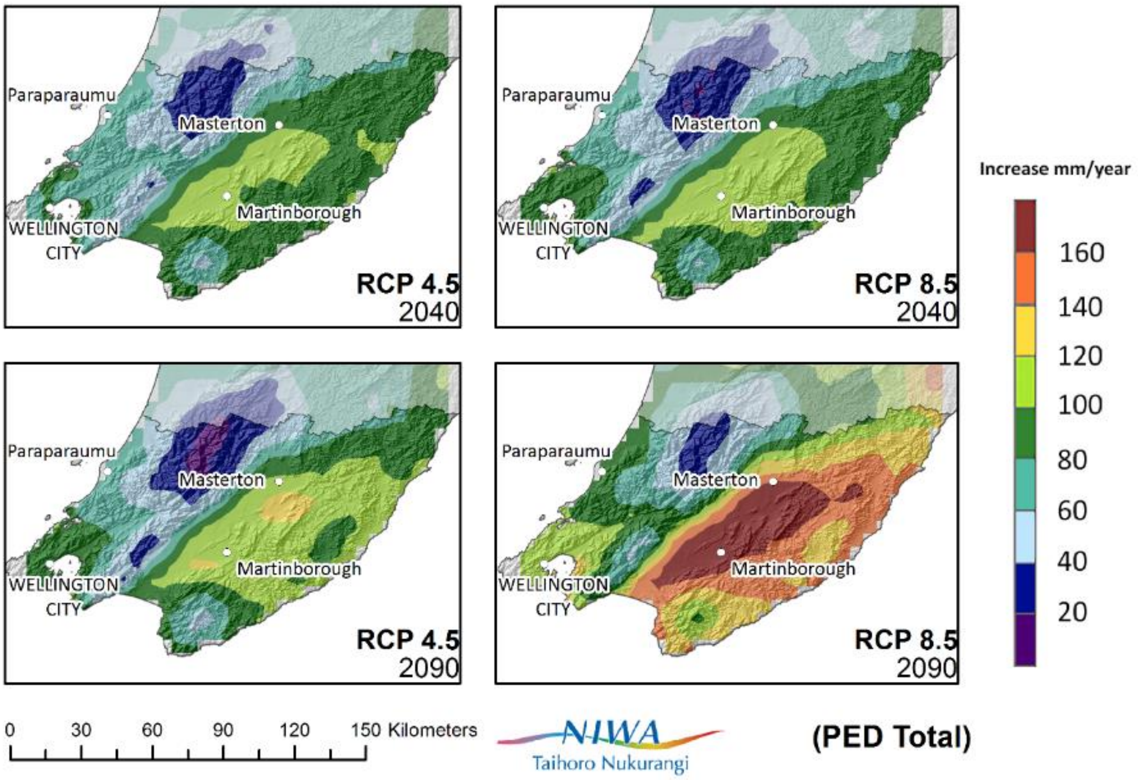

Figure 4-42: Projected changes in Potential Evapotranspiration Deficit (PED, in mm accumulation over the July-June 'hydrologic year') for the Wellington Region, for RCP4.5 and RCP8.5, at 2040 and 2090. Projected change in PED is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

As shown by Figure 4-42, projected PED varies across the Wellington Region. Generally, smaller increases in PED are projected for high elevations of the Tararua and Rimutaka Ranges, as well as the western parts of the region, and larger increases in PED are projected for the inland Wairarapa region. By 2090 under RCP8.5, increases in PED of over 160 mm/year are projected for the area between Masterton and Martinborough, and further southwest of Martinborough. This indicates that the Wairarapa is likely to become more drought prone in the future.

Model agreement is good for PED projections as all models predict an increase under both RCPs at both time periods.

A NIWA study published in 2011 (Clark et al., 2011) used downscaled climate model results from the IPCC Fourth Assessment Report to examine how the frequency of very dry conditions could change over the 21st century. Three major global greenhouse gas emissions scenarios were used (B1, A1B, and A2), and the final estimates of climatic drought probability were derived from a nationally comprehensive soil moisture indicator.

The study established distinct regional differences across New Zealand in changes to climatic drought vulnerability projected under future climate change, with an increase in climatic drought on the east coast of the North and South Islands being the most plausible and consistent outcome. This is consistent with previous studies on climate change impacts on climatic drought in a New Zealand context (e.g. Mullan et al., 2005). The study concluded that climatic drought risk is expected to increase during this century in all areas that are currently drought prone, under both the 'low-medium' and 'medium-high' scenarios. The 'drought risk' was analysed in terms of soil moisture levels – drought initiation occurs when soil moisture falls below the historically established 10th percentile for the given time of year for a period greater than one month, and drought termination occurs when soil moisture is above the 10th percentile for one month.

During this century, evidence for increased climatic drought duration is apparent for Canterbury, Hawke's Bay, Gisborne, and Northland (Clark et al., 2011). For the Canterbury Plains, even very mild future climate changes are expected to shift this area towards a more drought prone setting. No significant change in drought exposure is expected for the West Coast region.

Under the mid-range emissions scenario, the projected increase in drought duration from 1980-99 levels is about 5% for western areas of the Wellington Region and 7% for the Wairarapa for 2030-2050 and 10% for the whole region except the Tararua Ranges for 2070-2090 (Figure 4-43). There is no change to drought duration for the Tararua Ranges. This can be interpreted as: for a site that is currently in drought 10% of the time in the Wairarapa, in 2030-2050 it is likely that this same location will be in drought 17% of the time (i.e. an additional 7%), and in 2070-2090 that location is likely to be in drought 20% of the time (an additional 10%). Note that these results are based on the IPCC's Fourth Assessment Report and will be updated in due course to reflect the IPCC's Fifth Assessment Report.

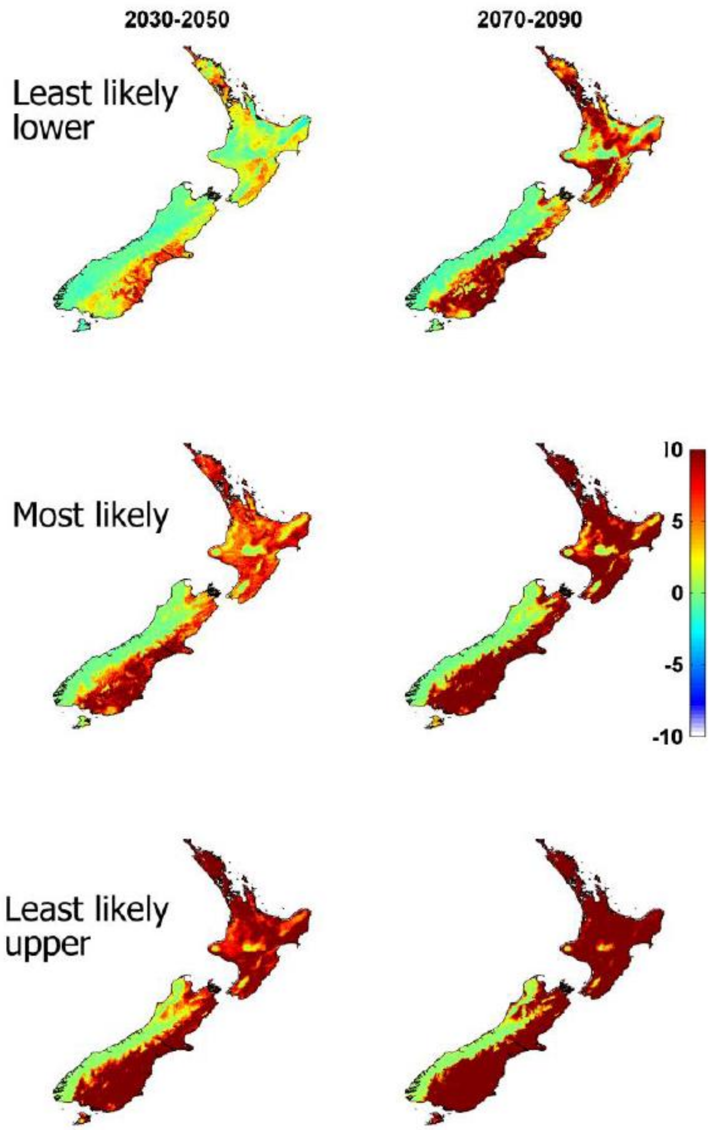

Figure 4-43: Projected increase in percentage of time spent in climatic drought from 1980-99 levels for the A1B emissions scenario based on IPCC AR4. Results summarise 19 global climate models. After Clark et al. (2011).

4.5 Changes to air pressure, wind and storms

4.5.1 Air pressure

Mean sea-level pressure projections have been derived from the Regional Climate Model (RCM) simulations by Mullan et al. (2016). The RCM simulations provide much more information about potential future weather than is readily available from statistical downscaling. In all cases, there is a maximum of six models available for analysis for each RCP and time period.

The key projected changes in mean sea-level pressure (MSLP) and mean winds are as follows (more detail can be found in Mullan et al. (2016)):

- MSLP tends to increase in summer (December–January–February (DJF)), 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–July–August (JJA)), especially over and south of the South Island, resulting in stronger westerlies over central New Zealand (including Wellington). This is consistent with the model projections of increased precipitation on the West Coast in this season.
- 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 similar to those of summer (i.e., more anticyclonic), and for spring changes to be similar to those of winter (lower pressures south of the South Island, and stronger mean westerly winds over southern parts of the country).

4.5.2 Changes to mean wind speed

There is no change projected for annual and seasonal mean wind speed compared with present, for the Wellington Region. The dynamically downscaled projections were analysed and the maximum change under all RCPs and all time periods was an increase in mean wind speed of 0.6 m/s. Therefore, these data were not mapped.

4.5.3 Changes to windy days

A 'windy day' was considered to have a daily mean wind speed of 10 m/s or more. The annual and seasonal change in the number of windy days for the Wellington Region was calculated from the dynamically downscaled projections using NIWA's Regional Climate Model, for 2040 and 2090 under RCP4.5 and RCP8.5. Model data for 1986-2005 (current climatology) shows that there is a gradient across the region in terms of windy days, with the west coast, Wellington city, the Hutt Valley and the southern Rimutaka Ranges observing up to 18 windy days per year during the historical period, to most of the inland Wairarapa observing about 14 windy days per year.

The number of windy days per year is expected to increase across the whole Wellington Region at both time periods for both scenarios. The south of the region is expected to have the largest increase in windy days, with up to six more windy days per year under both scenarios at 2040 and 2090, and over 10 more windy days per year under RCP8.5 at 2090 for some parts of the region. This is about 50% more windy days than at present by 2090 under RCP8.5. Most of the region is expected to experience increases of over six windy days per year at 2090 under RCP8.5.

Model agreement is good for winter and spring under RCP8.5 at 2090, as most models predict an increase in windy days across the region. Model agreement is also good for winter under RCP4.5 at 2040 and 2090.

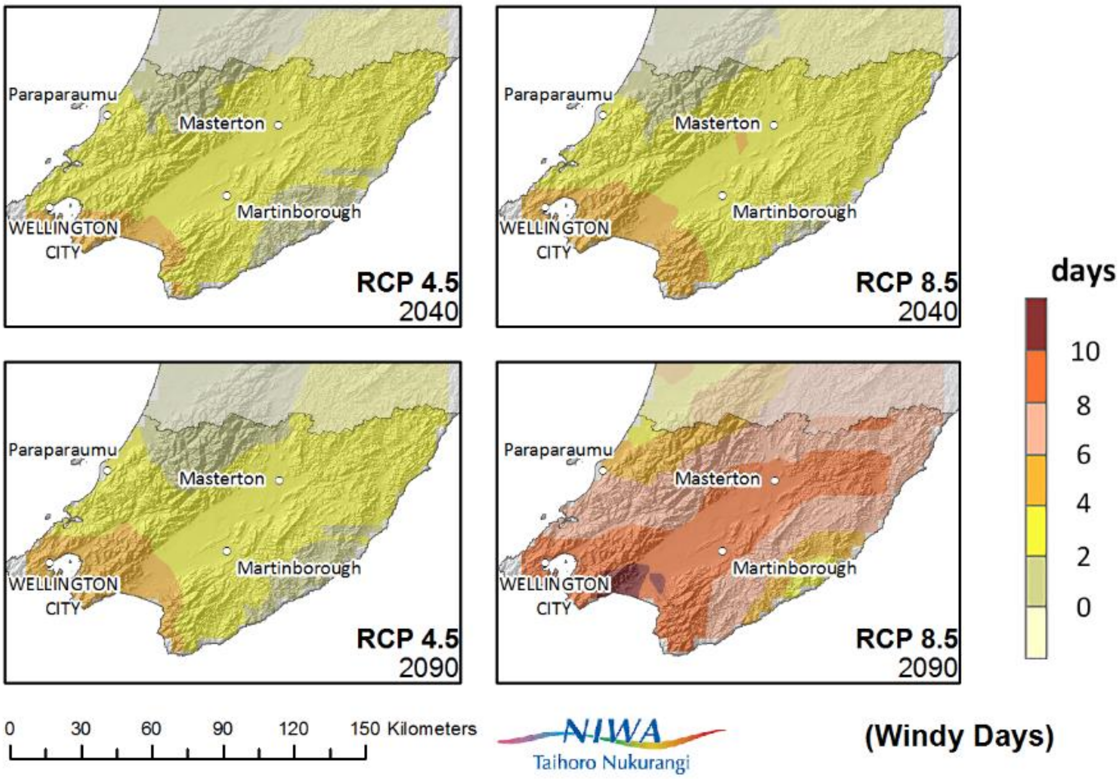

Figure 4-44: Change in the annual number of windy days (>10m/s), for RCP4.5 and RCP8.5 at 2040 and 2090. Projected change in the number of windy days is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

4.5.4 Extreme wind

The 99th percentile of daily-mean wind speed was evaluated over the historical 1986-2005 period at each VCSN grid-point in the downscaled (but not bias-corrected) regional model output data, by Mullan et al. (2016). Figure 4-45 maps how the 99th percentiles at 2040 and 2090 differ from the current climate for RCP4.5 and RCP8.5.

Relatively small increases in extreme daily winds are projected in Figure 4-45 for the Wellington Region. The greatest increases are projected for eastern parts of the Wairarapa hill country for 2090 under RCP8.5, where a 3-4% increase in the 99th percentile of daily mean wind speeds is projected.

Model agreement is good under RCP8.5 at 2090, RCP8.5 at 2040 and RCP4.5 at 2090, as most models predict an increase in extreme daily wind across the region.

No seasonal breakdown of extremes is given, but it is expected that the higher winds are primarily due to the increased westerly pressure gradient in winter and spring. Very localised extreme winds from more vigorous summer convection are also potentially a problem in the future, but such events are not resolved by the regional model being used here.

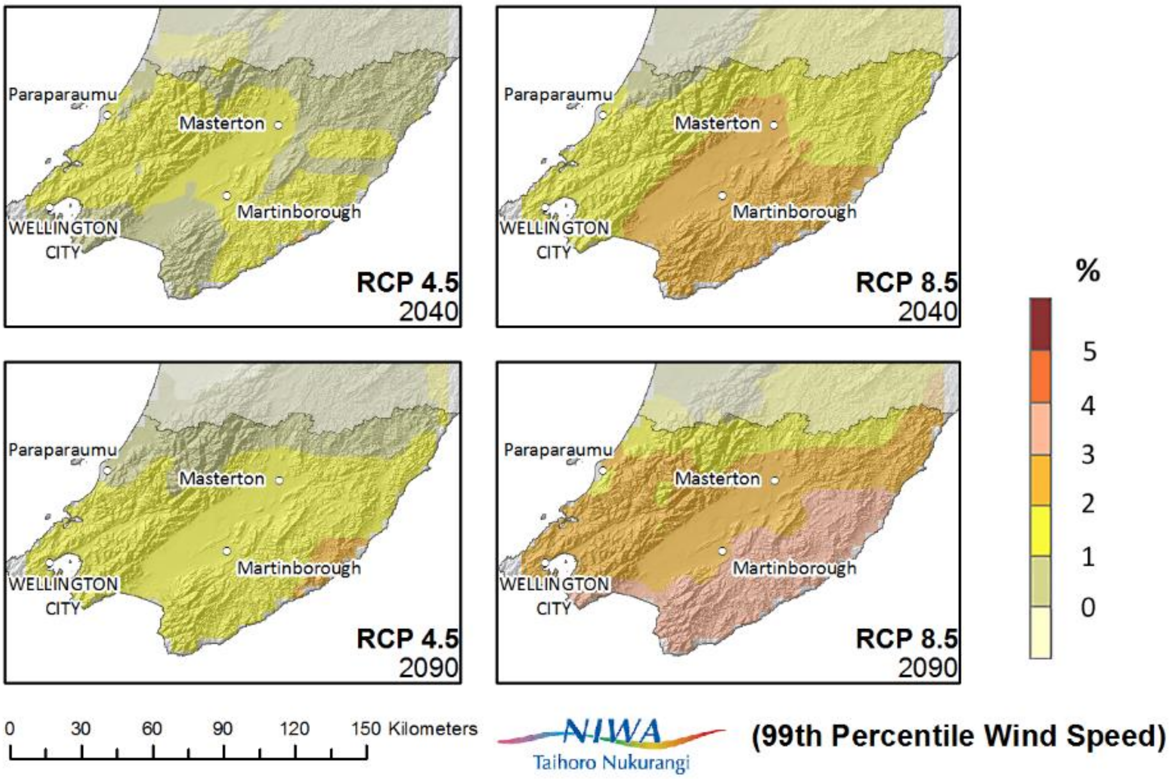

Figure 4-45: Change in the magnitude of the 99th percentile of daily-mean wind speed, for RCP4.5 and RCP8.5 at 2040 and 2090. Projected change in 99th percentile of daily mean wind speed is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

4.5.5 Storms

Tropical and ex-tropical cyclones

Across the world, it is considered likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged over the 21st century, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and rain rates (IPCC, 2013). The influence of future climate change on tropical cyclones is likely to vary by region, but there is low confidence in region-specific projections. The frequency of some storms will more likely than not increase in some basins. More extreme precipitation near the centres of tropical cyclones making landfall is projected in some regions including Australia and many Pacific Islands – this is important as tropical cyclones generated in these areas may affect New Zealand.

The Wellington Region is sometimes adversely affected by cyclones of tropical origin. These storms, which bring heavy rain and strong winds to northern parts of New Zealand, are usually weaker by the time they affect the Wellington Region. However, occasionally they retain characteristics which have the potential to cause flooding, generate primary and secondary wind damage to vegetation and infrastructure, and higher-than-normal wave heights and coastal storm surges. Approximately two ex-tropical cyclones come within 550 km of the Wellington Region every three years (estimated using the SPEAr-TC database, Diamond et al. (2012)).

Overall, there is significant uncertainty surrounding projections of tropical cyclones into the future. It is likely that storms making landfall will be stronger and cause more damage. However, the IPCC

(2013) projections are for tropical cyclones – storms that are in the tropics and thus at their full strength, not ex-tropical cyclones that have undergone extratropical transition where they begin to lose their strength, as they do upon their southwards path where they may influence New Zealand. Therefore, the frequency with which ex-tropical cyclones and other tropical depressions may reach the Wellington Region in the future is uncertain.

Extra-tropical cyclones

The IPCC comments that the global number of extra-tropical cyclones (the low pressure systems that affect New Zealand every few days, with origins outside of the tropics) is unlikely to decrease by more than a few per cent, and future changes in storms are likely to be small compared to natural inter-annual variability. This statement applies globally, and regionally-specific changes can be quite different. The storm track response to global warming is more consistent between AR5 models (and between AR4 and AR5 models) in the Southern Hemisphere than in the Northern Hemisphere. Extratropical storm tracks will tend to shift poleward by several degrees (Figure 4-46), but the reduction in storm frequency is only a few per cent.

The mid-latitude jet associated with the storm tracks (usually situated well south of New Zealand) is projected to increase in strength (Barnes and Polvani, 2013). The pattern of variability of the Southern Hemisphere jet is also predicted to change based on an analysis of CMIP5 models (Barnes and Polvani, 2013). Less north-south vacillation of the jet is expected in the future, but with more pulsing in intensity (with the opposite behaviour in the Northern Hemisphere jet). Just what this means for New Zealand is unclear, however, and further analysis of regional consequences is needed.

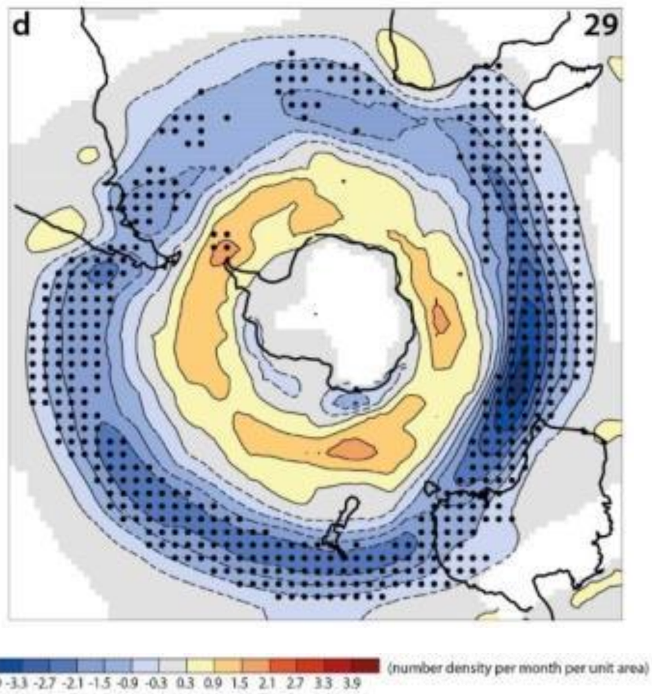

Figure 4-46: Change in winter Southern Hemisphere storm track between 1986–2005 and 2081–2100, under RCP8.5, from a 29-member CMIP5 multi-model ensemble. Blue shading indicates a decrease, and yellow-orange shading an increase in the number of storm ’centres’. Stippling is added where 90 per cent of the models agree on the sign of the change. Reproduced from IPCC AR5 Figure 12.20(d), which gives further detail on the figure and underlying analysis.

One regional study analysed the IPCC Fourth Assessment projections of “East Coast Lows”, low pressure systems which develop in the Tasman Sea off the east coast of Australia, usually in the winter season, and can have serious consequences with extreme rainfall, winds and waves (Dowdy et al. (2013). Such lows then generally move south-eastwards and affect New Zealand. Dowdy et al. (2013) found that such lows reduced in frequency by 30% (mainly in winter) between the late 20th century and the late 21st century.

Information on possible changes to New Zealand storminess and extremes can be found in Mullan et al. (2011) (based on AR4 global models). Evidence is presented that suggests some increase in storm intensity, small-scale wind extremes and thunderstorms is likely to occur in the New Zealand region, especially for the Wellington region and the South Island. For summer, slightly fewer extreme winds are projected for the Wellington Region. For winter, slightly more extreme winds are projected for this region.

4.6 Changes to solar radiation

Projections of solar radiation were calculated for the Wellington Region using NIWA's Regional Climate Model. Figure 4-47 shows summer and winter 1986–2005 climatologies of solar radiation from the NIWA VCSN data sets. Solar radiation is typically three to four times higher in summer than in winter. The geographic distribution depends not only on astronomical factors but also local rainfall (and cloudiness) patterns. Average solar radiation ranges from 6-7 MJ m^2/day in winter to 21-23 MJ m^2/day in summer for the Wellington Region.

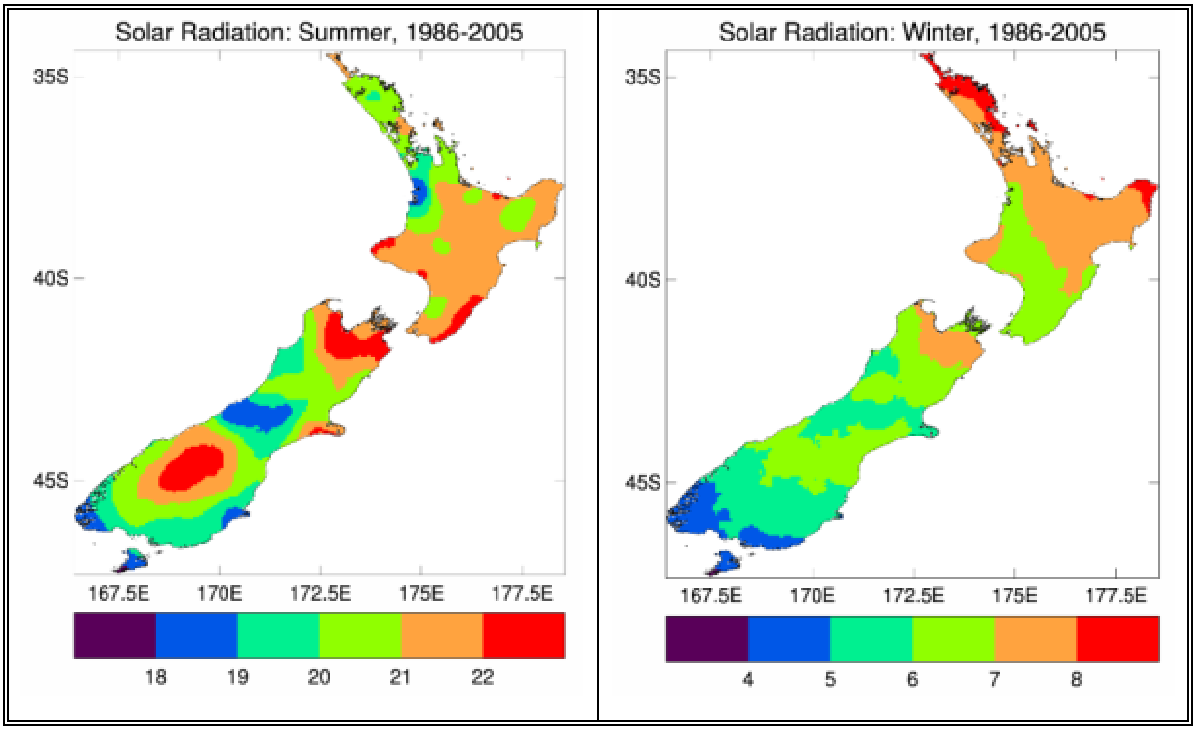

Figure 4-47: Summer (left) and winter (right) seasonal-average solar radiation (MJ m^2 / day), calculated from VCSN data over the 1986–2005 baseline period. Note that the contour intervals for solar radiation are very different between the summer and winter seasons.

Figure 4-48 to Figure 4-51 show maps of changes in incident total solar radiation (direct plus diffuse) at the surface for 2040 and 2090 under RCP4.5 and RCP8.5. The changes are with respect to the model 1986–2005 climatology, followed by averaging over up to six available RCM simulations for each RCP. Note that these data have not been bias-corrected as has been done for temperature and precipitation. Changes to solar radiation are consistent with increases and decreases in rainfall (and therefore cloudiness) for the Wellington Region.

At the annual timescale, there is minimal change for RCP4.5 at 2040 (Figure 4-48) and 2090 (Figure 4-49), and for RCP8.5 at 2040 (Figure 4-50) (± 1% change). For RCP8.5 at 2090 however, central parts of the region are projected to experience up to 2% increase in solar radiation at the annual scale (Figure 4-51).

However, at the seasonal scale, more increases in solar radiation are generally observed for spring, with up to 3-4% increase in solar radiation (mainly in the northern part of the Wellington Region) under RCP4.5 at 2090 and RCP8.5 at 2040 and 2090. Increases in solar radiation are also evident in northern inland areas for summer at 2040 under RCP4.5 and 2090 under RCP8.5. Some decreases (up to 4%) in solar radiation are evident in summer under RCP4.5 at 2090 and RCP8.5 at 2040 and 2090, particularly for eastern coastal areas.

Model agreement is good for spring under RCP8.5 at 2090 across the region, as most models predict an increase in solar radiation.

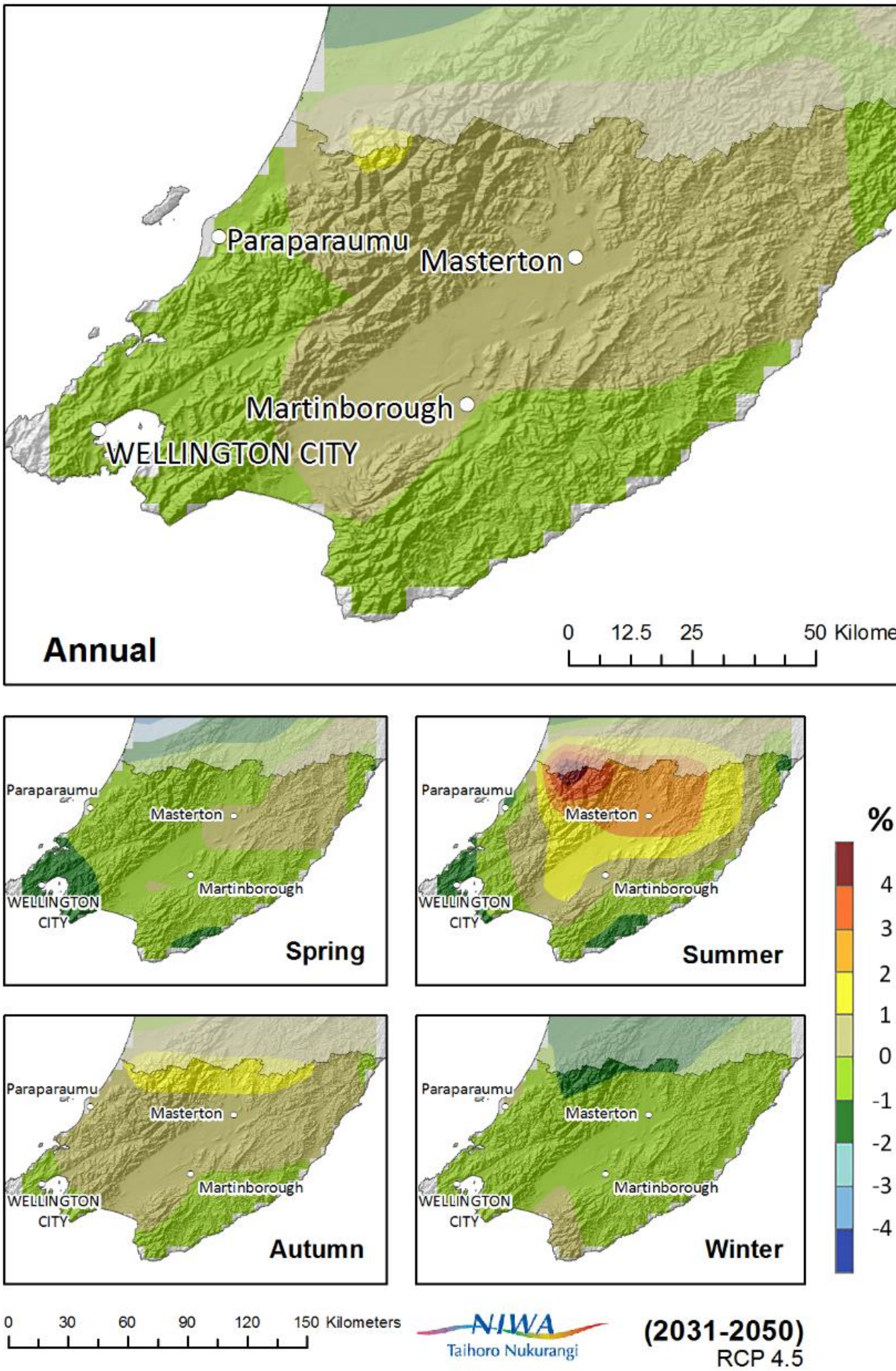

Figure 4-48: Projected change in annual and seasonal solar radiation (in %) at 2040 for RCP4.5, for the Wellington Region. Projected change in solar radiation is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

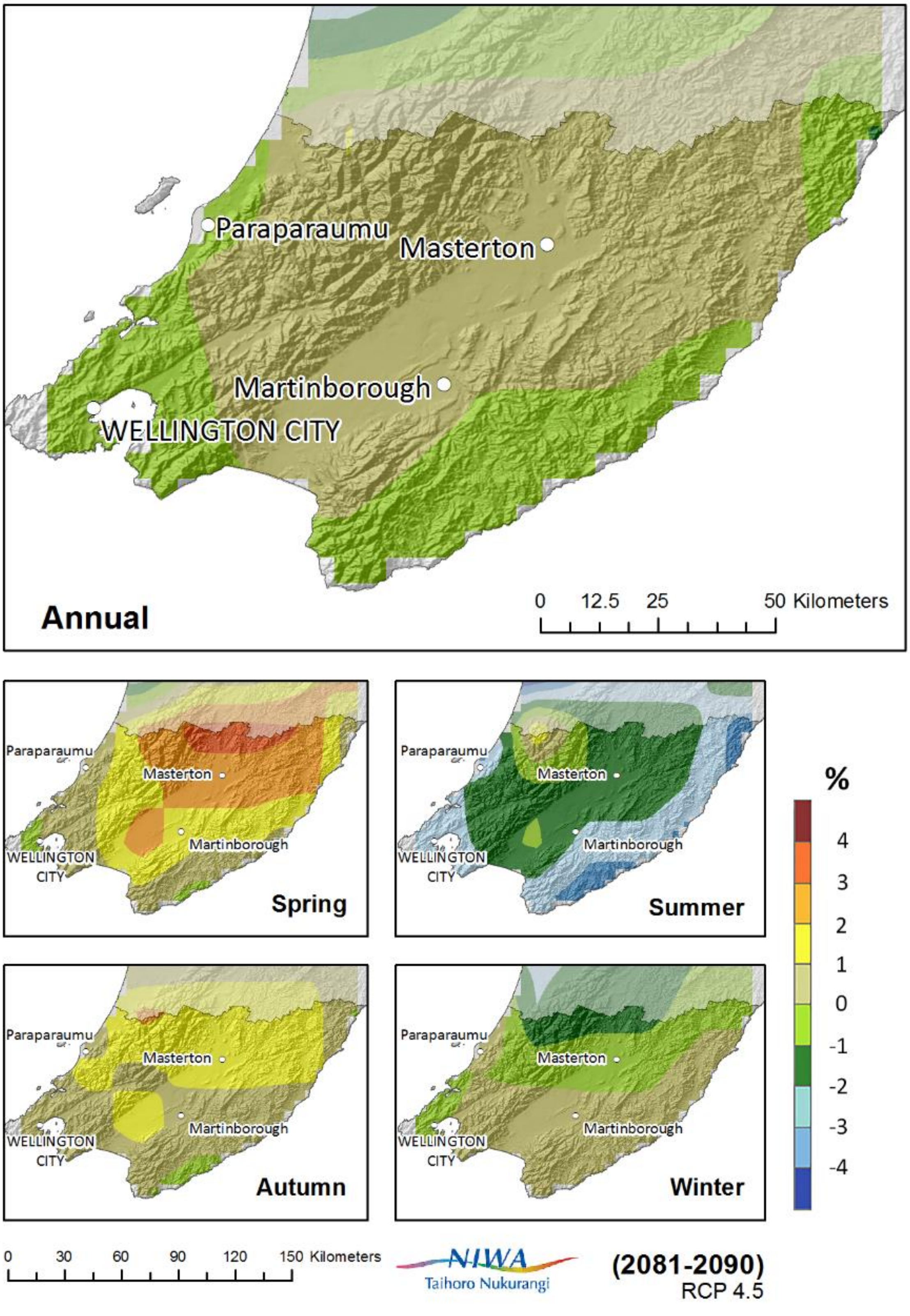

Figure 4-49: Projected change in annual and seasonal solar radiation (in %) at 2090 for RCP4.5, for the Wellington Region. Projected change in solar radiation is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

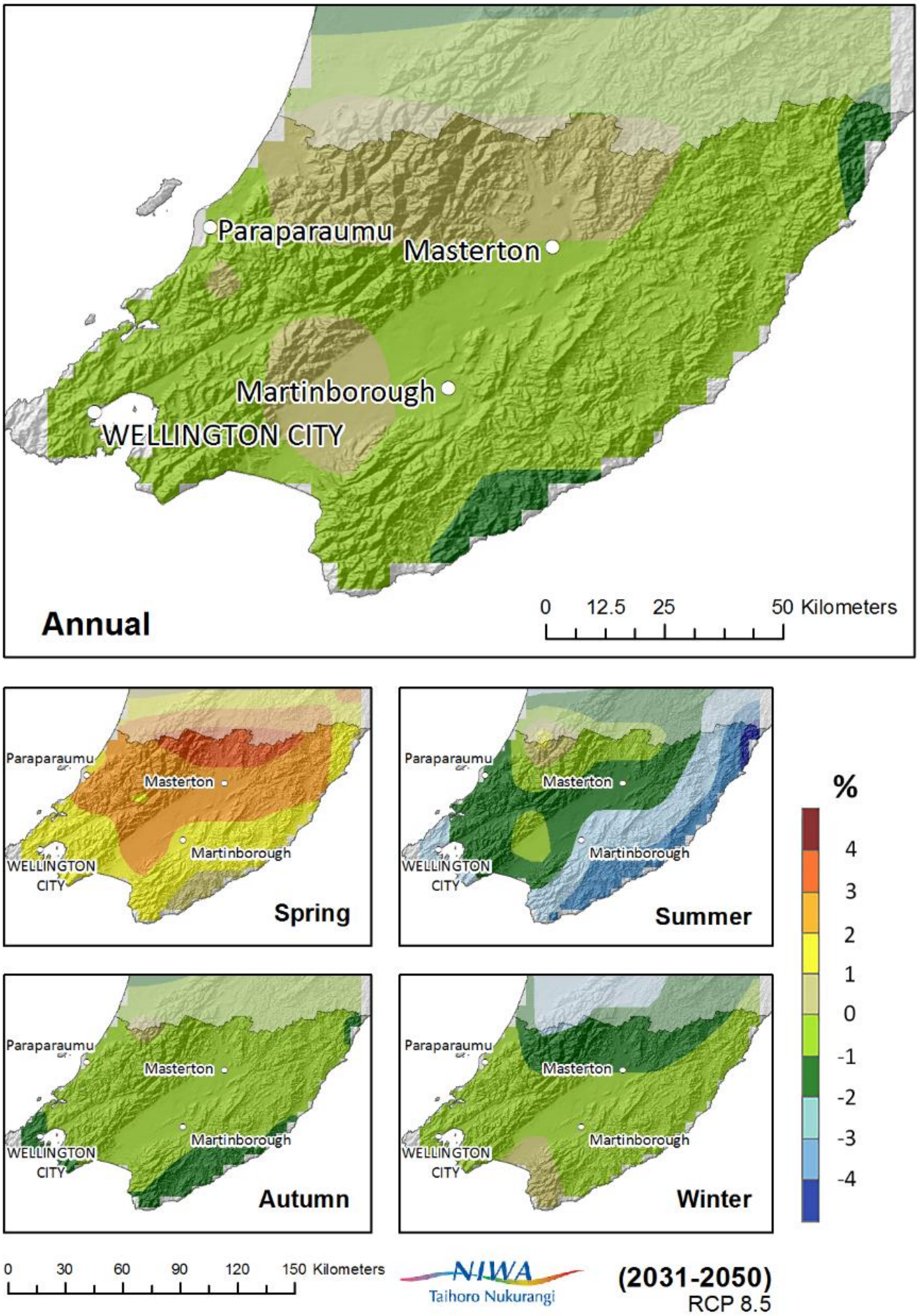

Figure 4-50: Projected change in annual and seasonal solar radiation (in %) at 2040 for RCP8.5, for the Wellington Region. Projected change in solar radiation is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

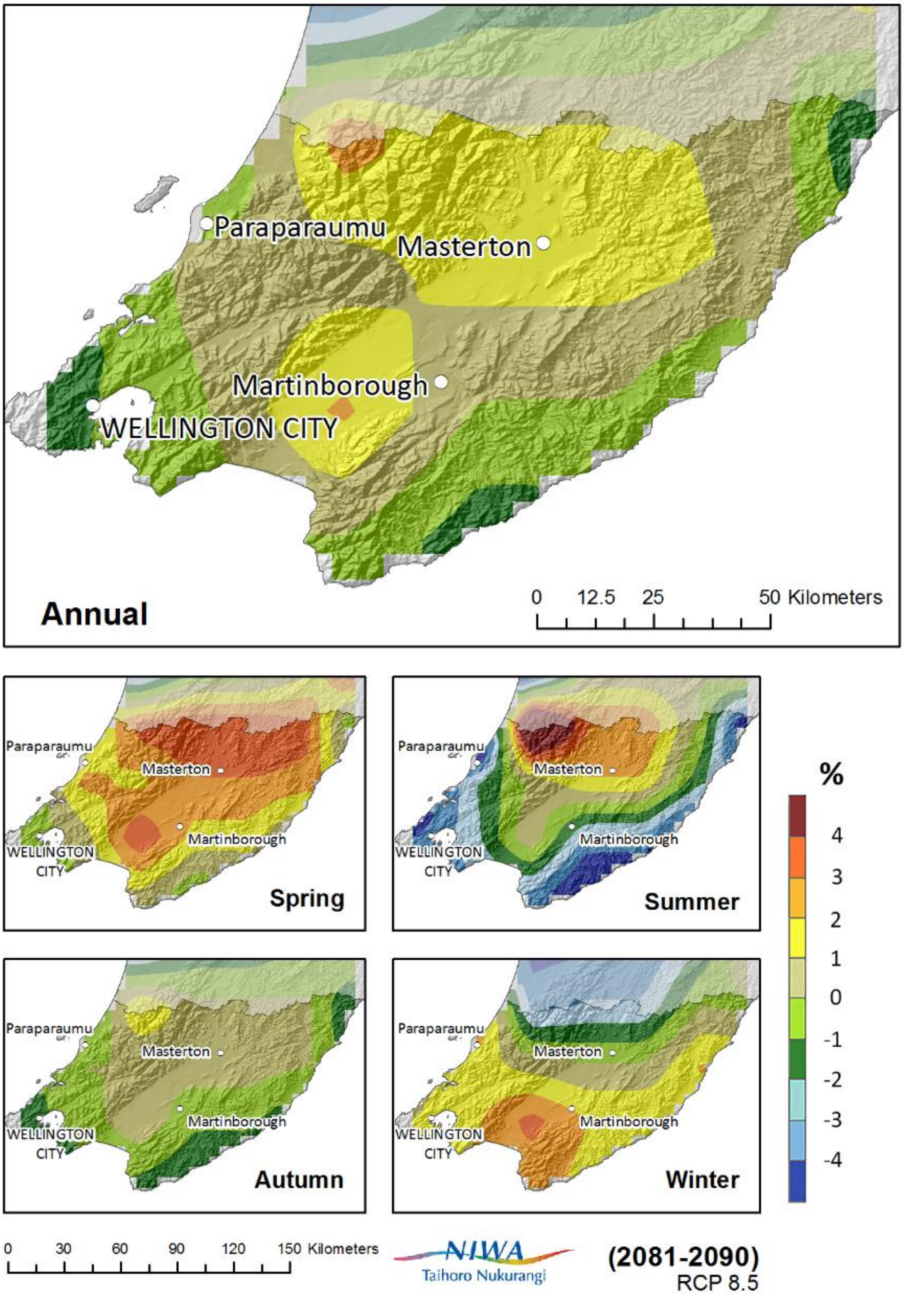

Figure 4-51: Projected change in annual and seasonal solar radiation (in %) at 2090 for RCP8.5, for the Wellington Region. Projected change in solar radiation is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

4.7 Changes to relative humidity

Changes to daily mean relative humidity are presented in Figure 4-52 to Figure 4-55 for RCP4.5 and RCP8.5 at 2040 and 2090. These projections have been dynamically downscaled using NIWA's Regional Climate Model.

For most parts of the Wellington Region, relative humidity is projected to slightly decline into the future, under both scenarios at both time periods, and at the annual and seasonal timescales. The only parts of the region to undergo (very small) increases of up to 1% are around the southern coast and Wellington City. The largest change is projected for RCP8.5 at 2090 (Figure 4-55), where annual average relative humidity is projected to decline by 2% for inland parts of the region, and spring and winter are projected to experience decreases of up to 3% for inland parts of the region. Most other time periods and RCPs project only a 1-2% decline in relative humidity.

Model agreement is good for winter and spring under RCP8.5 at 2090 across the region, as all models predict a decrease in relative humidity. Model agreement is also good for spring under RCP8.5 at 2040 across the region.

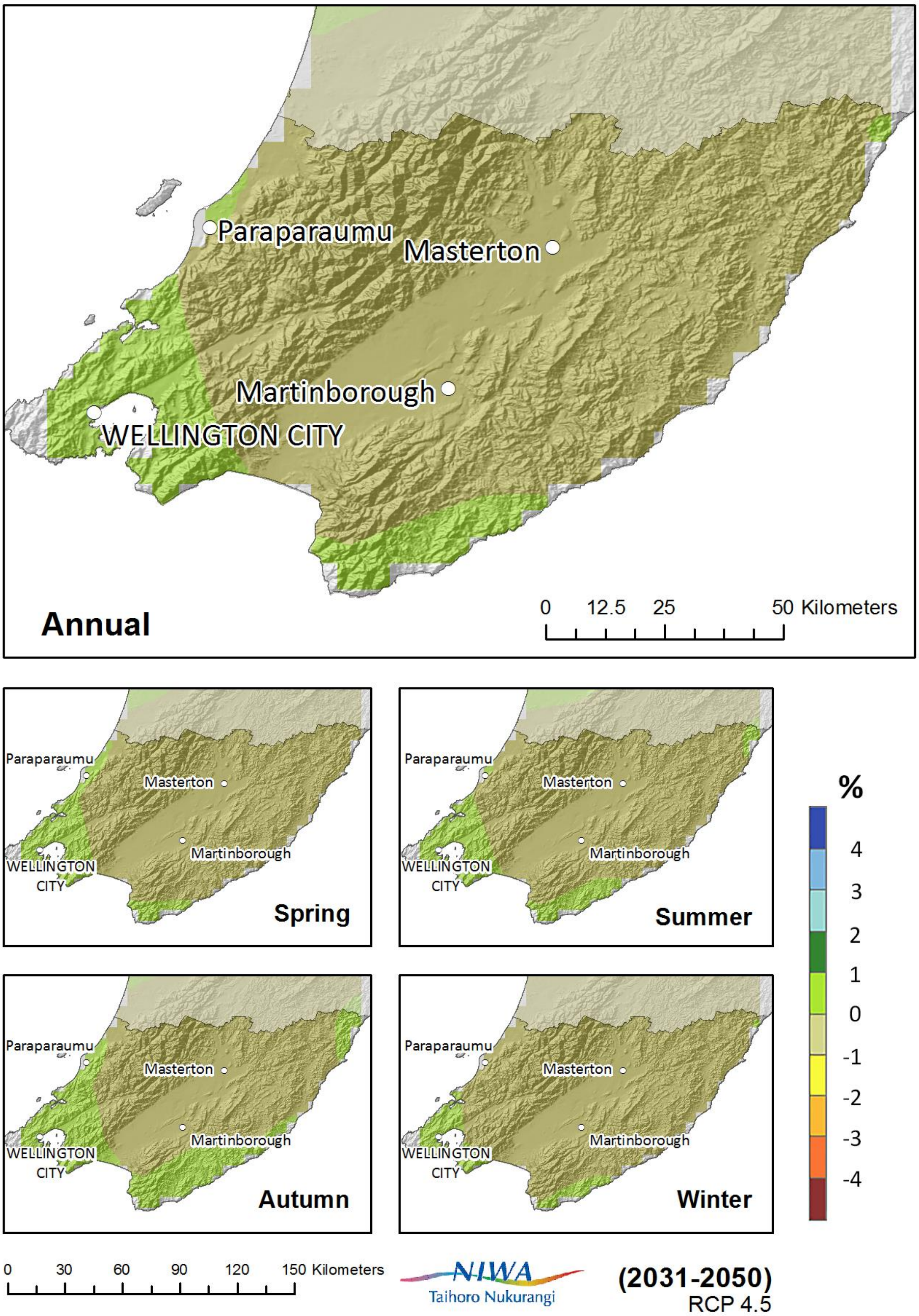

Figure 4-52: Projected change in annual and seasonal relative humidity (change in relative humidity, which is measured in %) at 2040 for RCP4.5, for the Wellington Region. Projected change in relative humidity is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

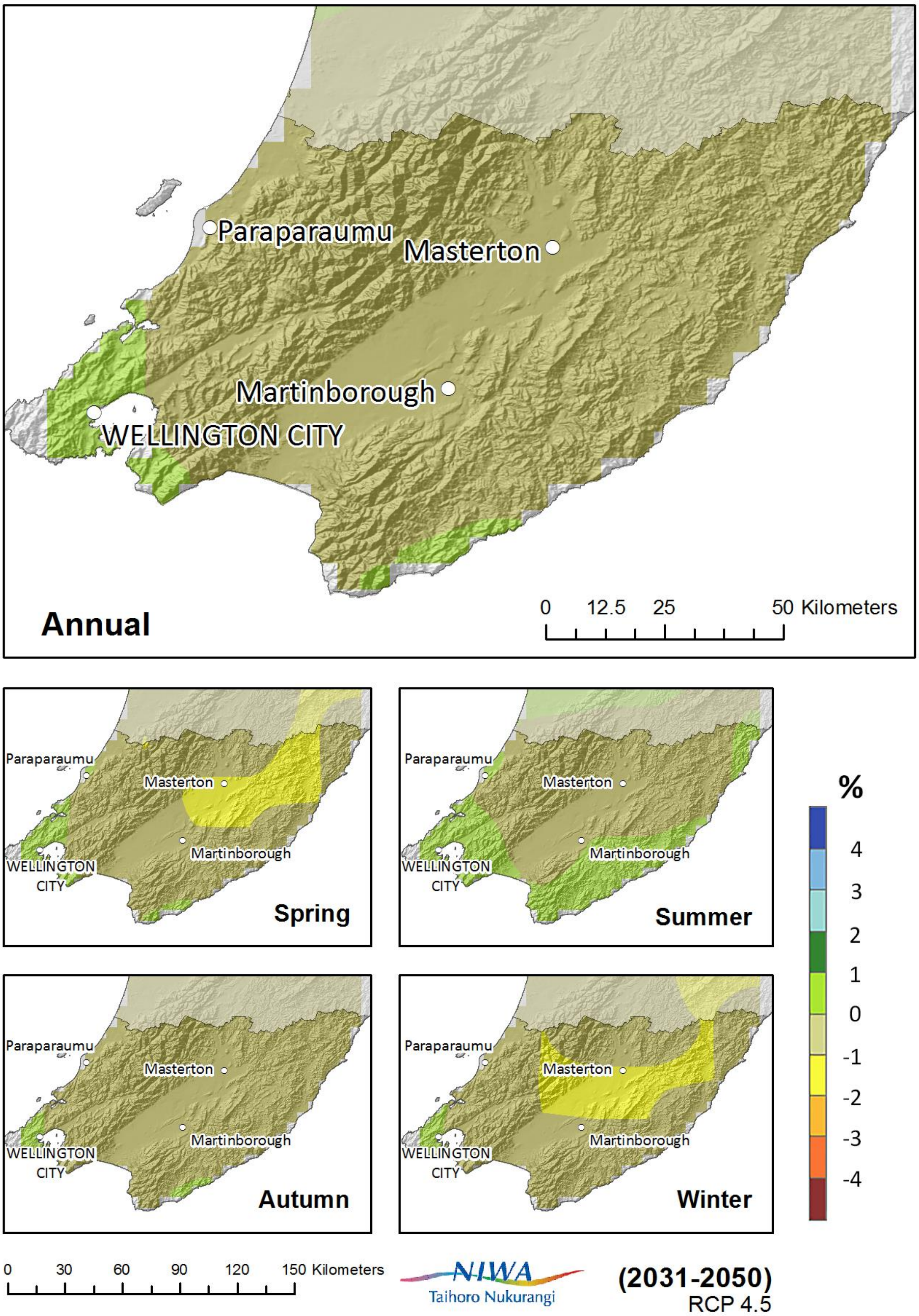

Figure 4-53: Projected change in annual and seasonal relative humidity (change in relative humidity, which is measured in %) at 2090 for RCP4.5, for the Wellington Region. Projected change in relative humidity is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

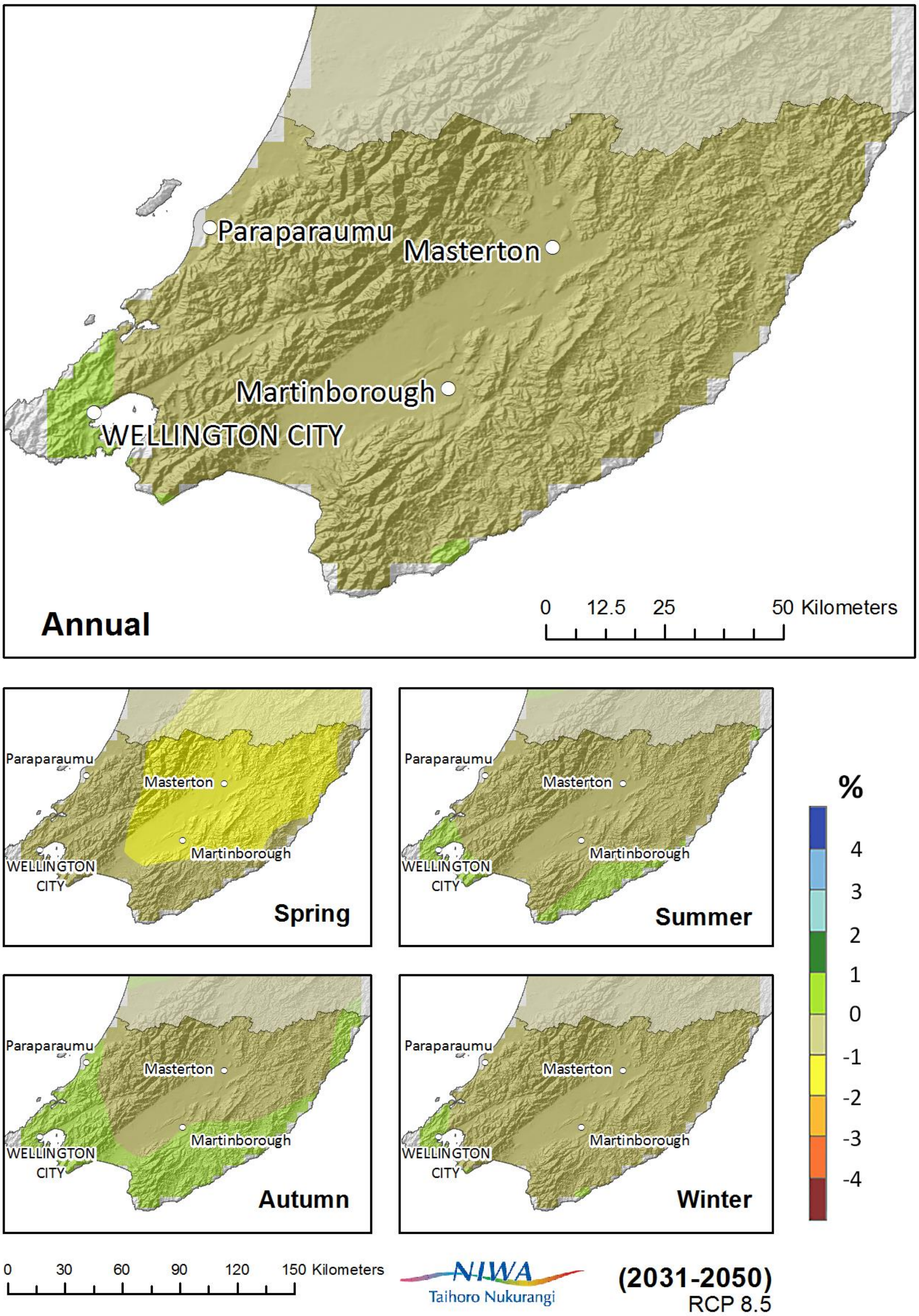

Figure 4-54: Projected change in annual and seasonal relative humidity (change in relative humidity, which is measured in %) at 2040 for RCP8.5, for the Wellington Region. Projected change in relative humidity is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

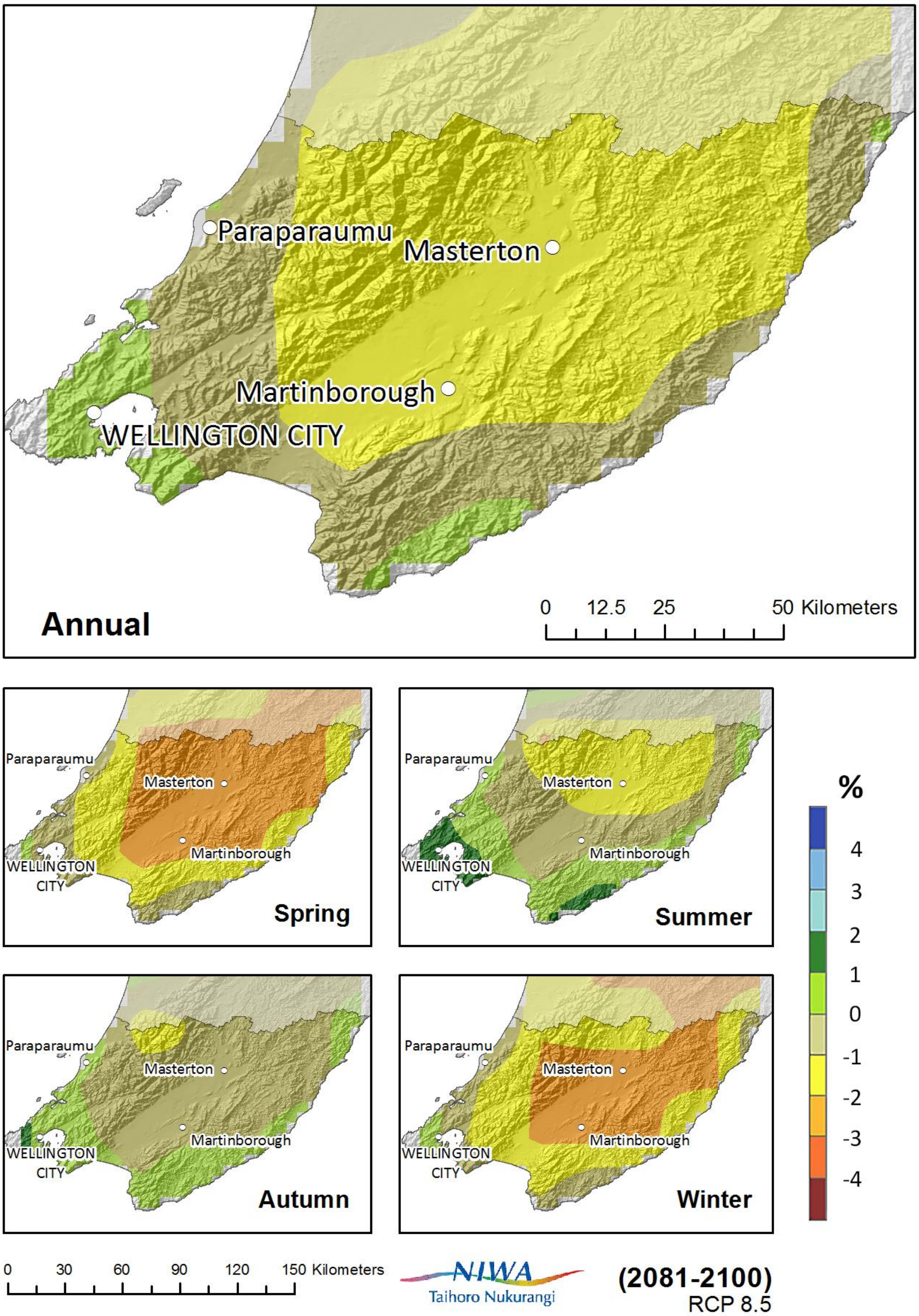

Figure 4-55: Projected change in annual and seasonal relative humidity (change in relative humidity, which is measured in %) at 2090 for RCP8.5, for the Wellington Region. Projected change in relative humidity is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

5 Climate change case studies for Greater Wellington

5.1 Growing degree day projections at different resolutions

Greater Wellington Regional Council asked NIWA to undertake an experiment which combined high spatial resolution maps of annual growing degree days (base 10°C) for the climatology period 1981-2010 with lower resolution maps which show projections of future growing degree days (GDD). Projections for GDD are presented in Section 4.1.3.

The purpose of this case study was to produce high resolution maps showing the projected future climatology of GDD. The downscaled output of NIWA's Regional Climate Model, which is used to calculate the future change in GDD, has a lower resolution (5 km) than the climatology maps (500 m). The future GDD values were calculated by adding the 1981-2010 climatology values to the projected change. As the spatial resolution differed between the two datasets, all 500 m pixels (from the climatology maps) were assigned the same change value from the overlapping 5 km pixel (from the Regional Climate Model).

Note that the climatology periods for the maps are different – the historical climatology maps are based on 1981-2010 *median annual* growing degree days, and the base period for the projections is 1986-2005, and these are given as an *annual average* (rather than median). However despite these methodological differences, we do not believe that there is a significant difference in the data presented.

Figure 5-1 shows the future climatology for GDD at two time periods (2040 and 2090), for two RCPs (RCP4.5 and RCP8.5), for GDD base 10°C. All maps show similar patterns of GDD into the future, with a maximum of 2100-2250 GDD projected under RCP8.5 at 2090.

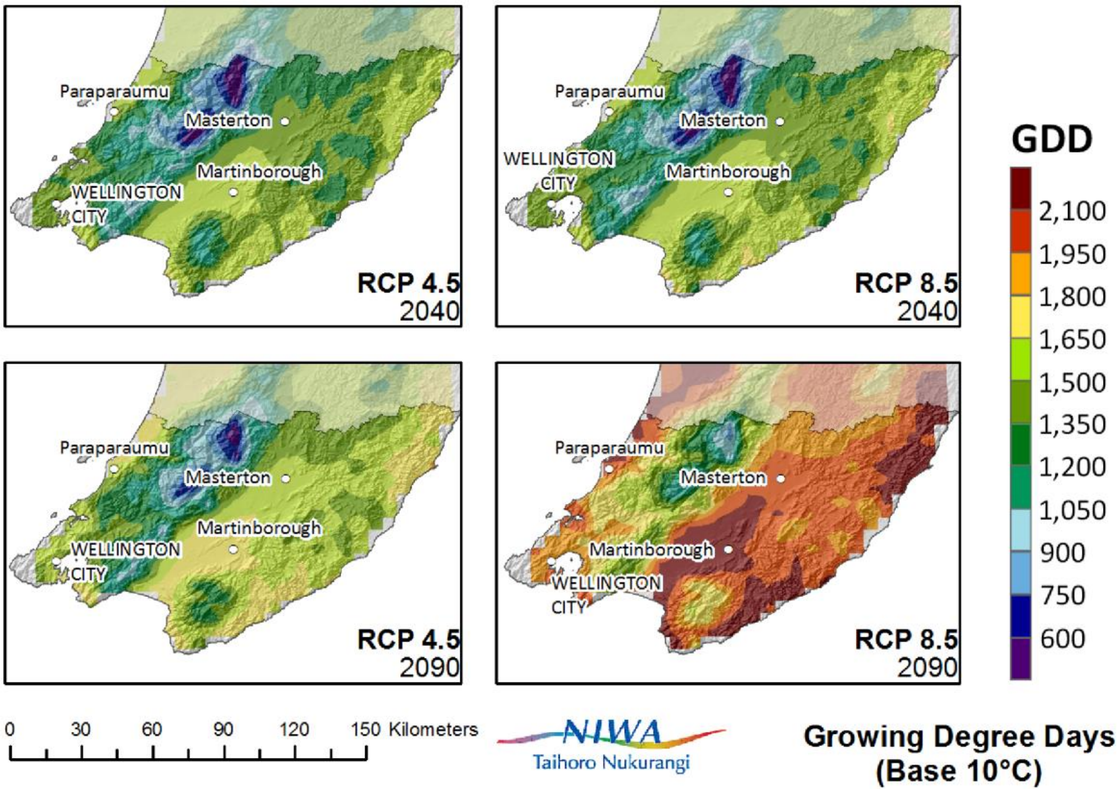

Figure 5-1: Projected number of growing degree days (base 10°C) for RCP4.5 and RCP8.5 at 2040 and 2090. Results are based on projections using NIWA's Regional Climate Model, based on the average of six global climate models. © NIWA.

5.2 Uncertainty in rainfall projections along a transect

Greater Wellington Regional Council asked NIWA to undertake a brief analysis of the variability in the seasonal rainfall projections across a transect from the west to the east of the region, focussing on the Ruamahanga catchment, to better understand the uncertainty in the rainfall projections and the effect of complex mountain terrain.

The transect chosen is the VCSN line centred on 40.875°S, comprising 25 grid-points from 175.025°E (the west coast near Waikanae) to 176.225°E (east coast just north of Castlepoint) (Figure 5-2). This transect captures the high altitude orography in the Tararuas near Mt Hector. The maximum VCSN altitude (for a 5km grid-box) is 1184m, whereas the highest point altitude near the transect occurs for Mount Hector (1529m, at 40.952°S and 175.282°E). The highest altitudes along this transect lie at the western edge of the Ruamahanga Whaitua catchment.

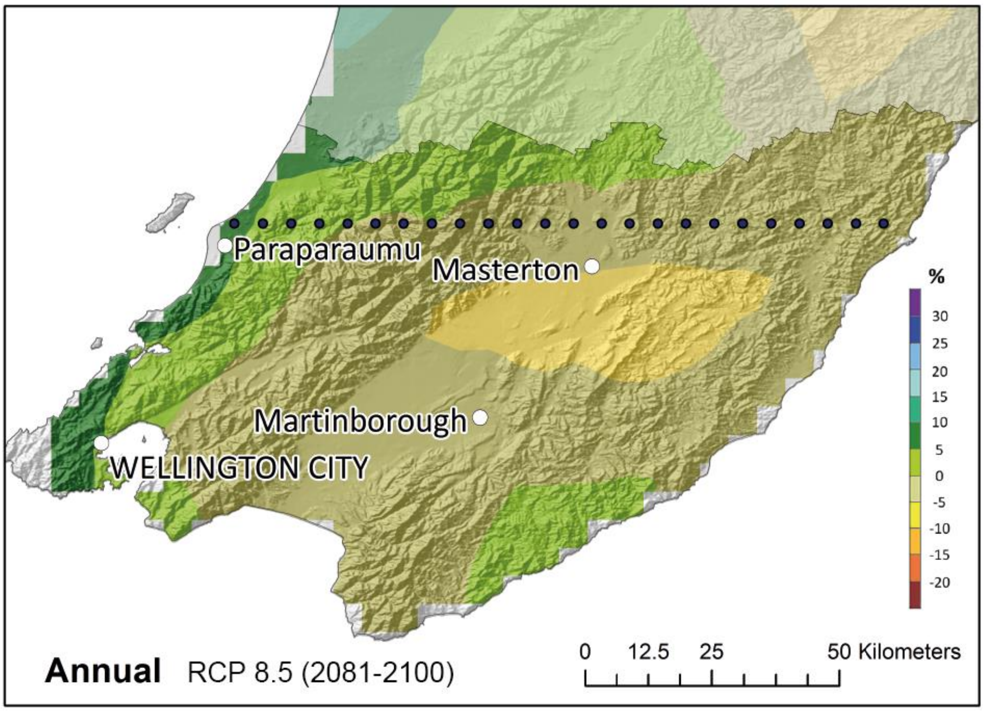

Figure 5-2: VCSN transect selected for analysis of variability of rainfall projections. Separate VCSN points are indicated. The base map shows annual mean precipitation change for RCP8.5 at 2090 - the same as Figure 4-23.

The precipitation projections are taken from the analysis of Mullan et al. (2016), who produced regional climate model simulations from six climate models. The precipitation signal under global warming is not large for the Wellington Region, particularly for the six-model (ensemble) average as presented earlier in this report in Figure 4-20 to Figure 4-23.

There are four causes of variability in the projections, and their associated undertainties:

- Variation with climate model. Models may have different approaches in their representation of physical interactions at the sub-grid scale. Different parameter settings can lead to a range in climate sensitivity at the global scale; regionally, different trends in temperature gradients will lead to differences in the intensities and tracks of weather systems, and thus possibly quite different rainfall changes.
- Variation with RCP. In general, one expects a stronger change from the current climate as the degree of greenhouse forcing increases; thus, greater warming and larger precipitation changes (either positive or negative) are expected for the high emission RCP8.5 relative to moderate emission RCP4.5.
- Variation with time. This is partly a climate signal (as the forcing from the RCP increases with time), but also contains a large random component due to unpredictability of day-to-day weather that influences the longer time-scale. For example, random chaotic fluctuation will influence which year a particular model develops El Niño conditions. This random variability is much more marked in precipitation than in temperature.

- Variation with location. Here, the interest is in the variation along the west-east transect. The net effect will depend on the overall change in the frequency of prevailing westerly versus easterly weather conditions.

Figure 5-3 and Figure 5-4 show projected precipitation changes along the transect, for each season and for RCP4.5 and RCP8.5. The results focus on seasonal changes to the end of this century; that is, from the 1986-2005 period used to define the 'current' climatology (Mullan et al., 2016) out to the 2081-2100 period (abbreviated in the figure heading as 2090). It is evident from these figures that the largest source of uncertainty is the difference between models. For example, in the summer season five of the models project a decrease, or at least a minimal increase, in precipitation in the Ruamahanga Whaitua. However, one model (GISS-EL-R) goes completely the opposite way, and projects rainfall to increase by about 20%. Further research into model skill is needed to assess whether the the outlier can be removed.

Variation with RCP is not strong in the Wellington region, due to high variabilty in time. For example, in the winter season under RCP4.5, the NorESM1-M model has substantial increases in precipitation along the transect, whereas the HadGEM2-ES model has the largest decrease. However, under RCP8.5, NorESM1-M is only marginally wetter than a couple of the other models, and HadGEM2-ES is no longer the driest.

Nevertheless, it is possible to identify orographic effects on the precipitation change in some cases. In the winter season when the prevailing westerlies strengthen, the precipitation change is about 5% larger immediately upstream of the peak in orography (a consequence of the NIWA method to downscale from the model 28km-resolution grid to the VCSN 5km-resolution grid). For some seasons and models, a rainfall enhancement is seen to the east of the peak orography, presumably a reflection of a higher frequency of rain-bearing easterly winds. However, due to the fact that the complex orography will modulate the rainfall patterns, such influences are not dominant at the downscaling resolution used in this analysis.

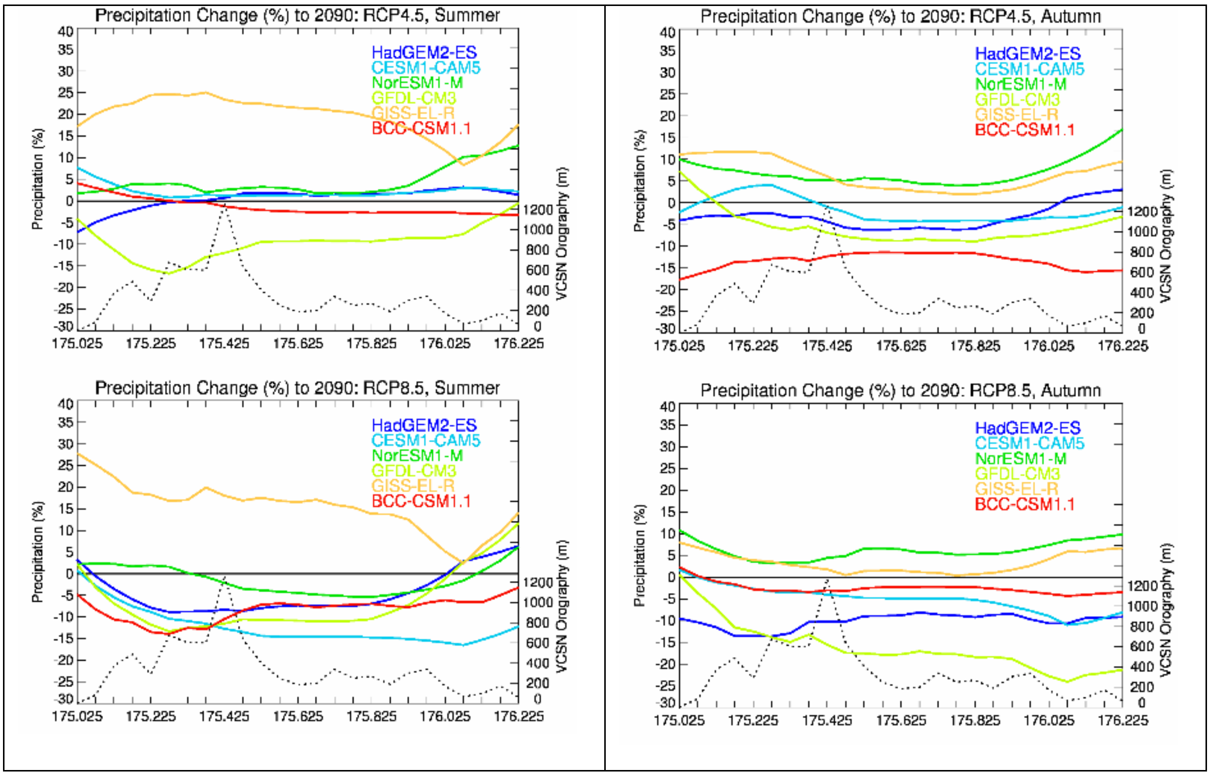

Figure 5-3: Projected changes in precipitation (in %) for 6 climate models (see colour-coded inset labels), between 1986-2005 and 2081-2100, under RCP4.5 (upper panels) and RCP8.5 (lower panels), for summer (left panels) and autumn (right panels). Changes are graphed along a longitude transect from Waikanae to Castlepoint in the Wellington Region, where the dotted line (using the right-hand scale) shows the VCSN orographic heights along the transect. The westernmost seven grid-points (to 175.325°E) cover the Kapiti Coast Whaitua catchment, the easternmost five grid-points (from 176.025°E) cover the East Wairarapa Whaitua catchment, with the remaining 13 central grid-points covering the Ruamanga Whaitua catchment.

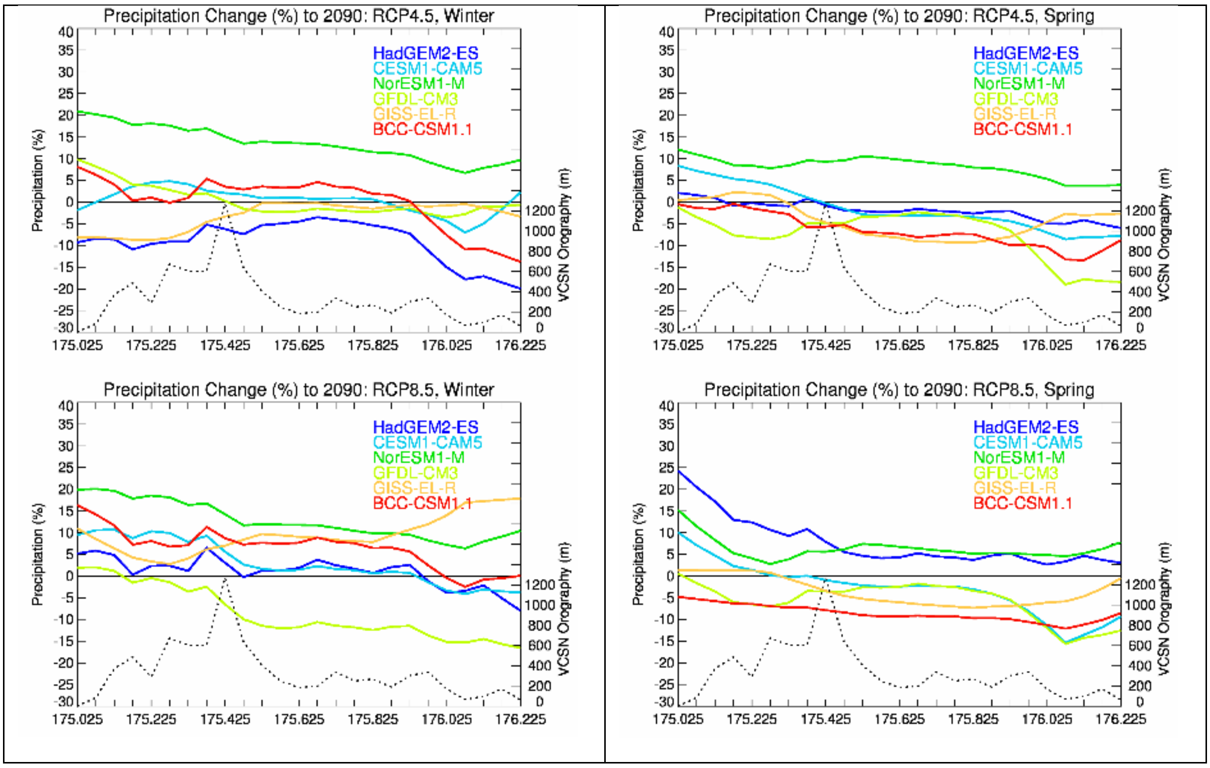

Figure 5-4: As Figure 5-3, but for the winter (left panels) and spring (right panels) seasons.

Figure 5-5 collects all the models and RCPs together in the same graph, but averages them across the transect – separately for the western and eastern parts of the Wellington region. It is therefore similar to Figure 4-40, except that the projections are shown only for the six regional model simulations, and the different models are identified individually.The model outliers are clearly evident; for example, the GISS-EL-R model is wetter in the summer season (as noted above), and the GFDL-CM3 model tends to be drier in the autumn, winter and spring seasons.

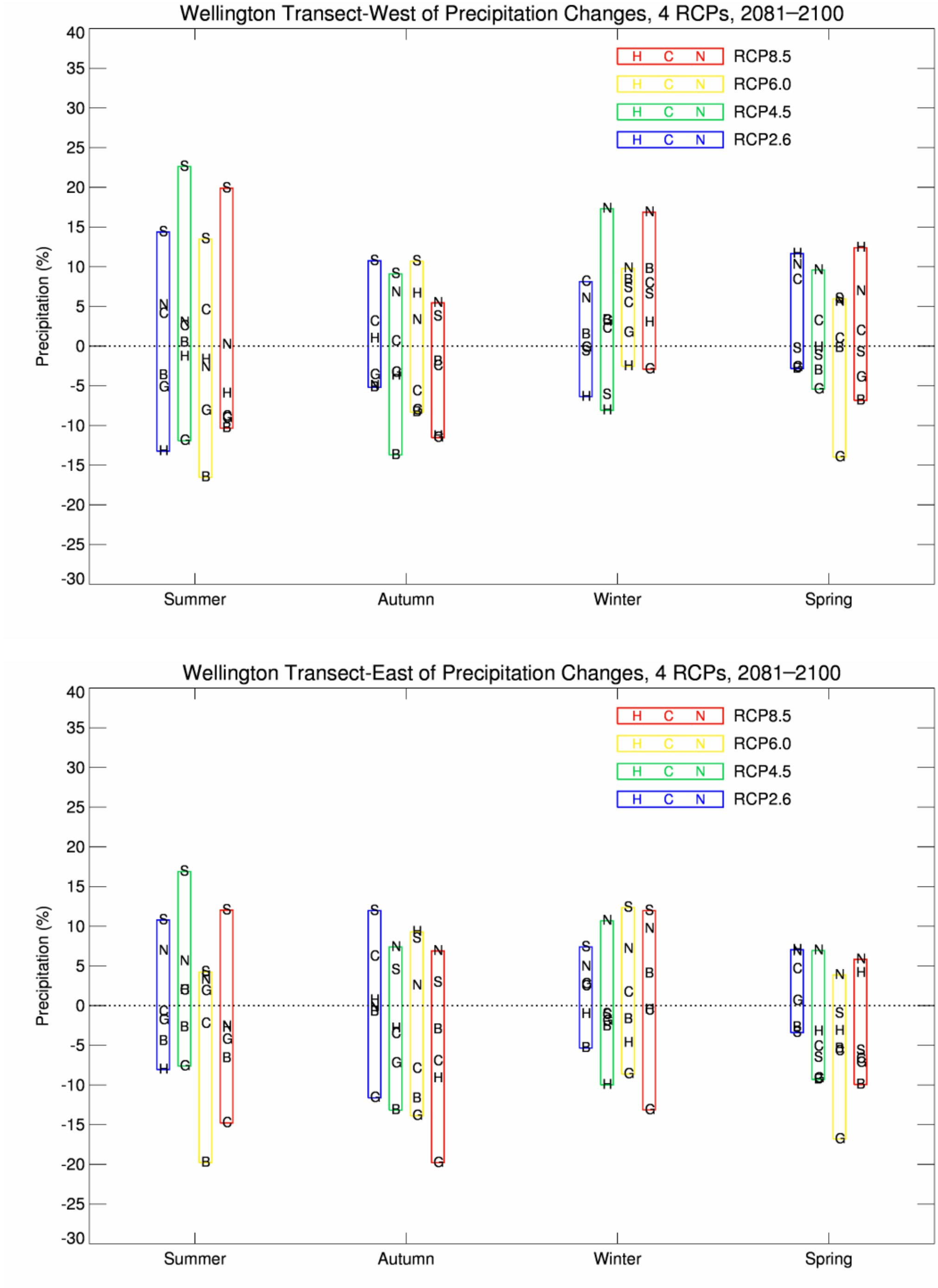

Figure 5-5: Projected changes in precipitation (in %) to 2090 for each season, averaged along the Waikanae to Castlepoint transect. Changes are compared between the four RCPs (see inset labels), and for the six climate models labelled as follows: H=HadGEM2-ES, C=CESM1-CAM5, N=NorESM1-M, G=GFDL-CM3, S=GISS-EL-R, and B=BCC-CSM1.1. The upper four panels are labelled 'West', and represent the average % changes along the transect up to the highest point (at 175.325°E) in the VCSN altitude data. The lower four panels are labelled 'East', and represent the average % changes along the transect to the east of the highest VCSN point (i.e., from 175.375°E to the Wairarapa Coast).

There are some differences between the West and East transects, but many similarities as well. For example, under RCP8.5 at 2090:

- In summer, there is a good consensus for no change or drier conditions in both the West and East parts of the transect (only one model, GISS-EL-R, indicates increased rainfall).
- In winter, there is a good consensus for no change or wetter conditions in both the West and East parts of the transect (only one model, GFDL-CM3, indicates reduced rainfall).

At least part of the uncertainties in the 2090 projections are due to multi-decadal variability in time in the rainfall climate. This can be seen in Figure 5-6 and Figure 5-7, where the trends are clearly not monotonic in time. For example, the GISS-EL-R model shows a strong wet bias in summer at mid-century and at end-of-century, but is more muted in its projections in the intermediate 20-year periods centred on 2060 and 2070 (Figure 5-6). The previous figures in this section all apply at 2090, and thus just sample the right-hand end point in Figure 5-6 and Figure 5-7.

As with Figure 5-4, the projected changes are similar in both the west and east transects.

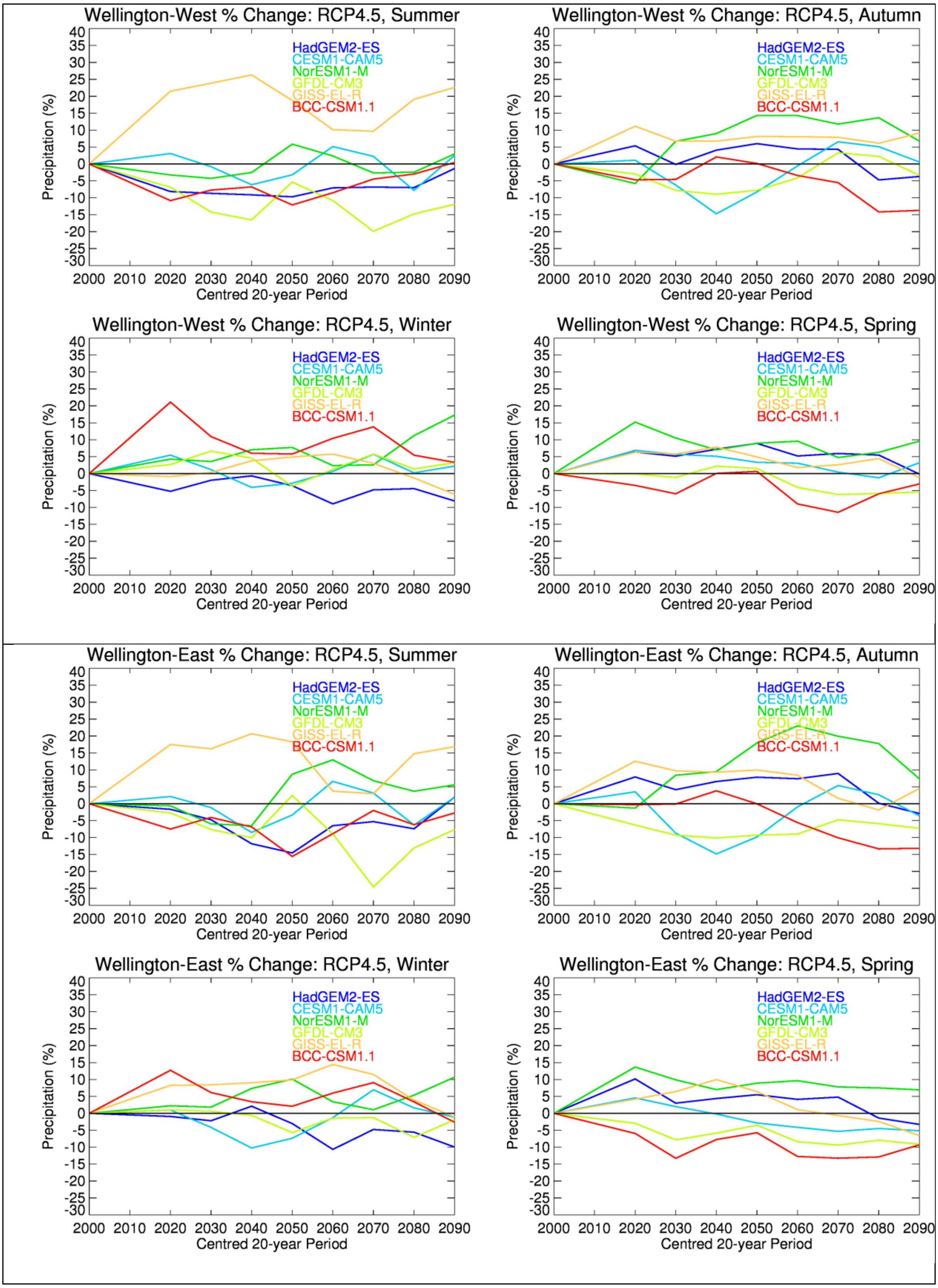

Figure 5-6: Projected changes in precipitation (in %) for 6 climate models (see colour-coded inset labels), averaged along the Waikanae to Castlepoint transect, between 1986-2005 (labelled as '2000') and overlapping 20-year periods from 2011-2030 ('2020') to 2081-2100 ('2090'). Projections are for RCP4.5 forcing, and separate panels are given for each season.

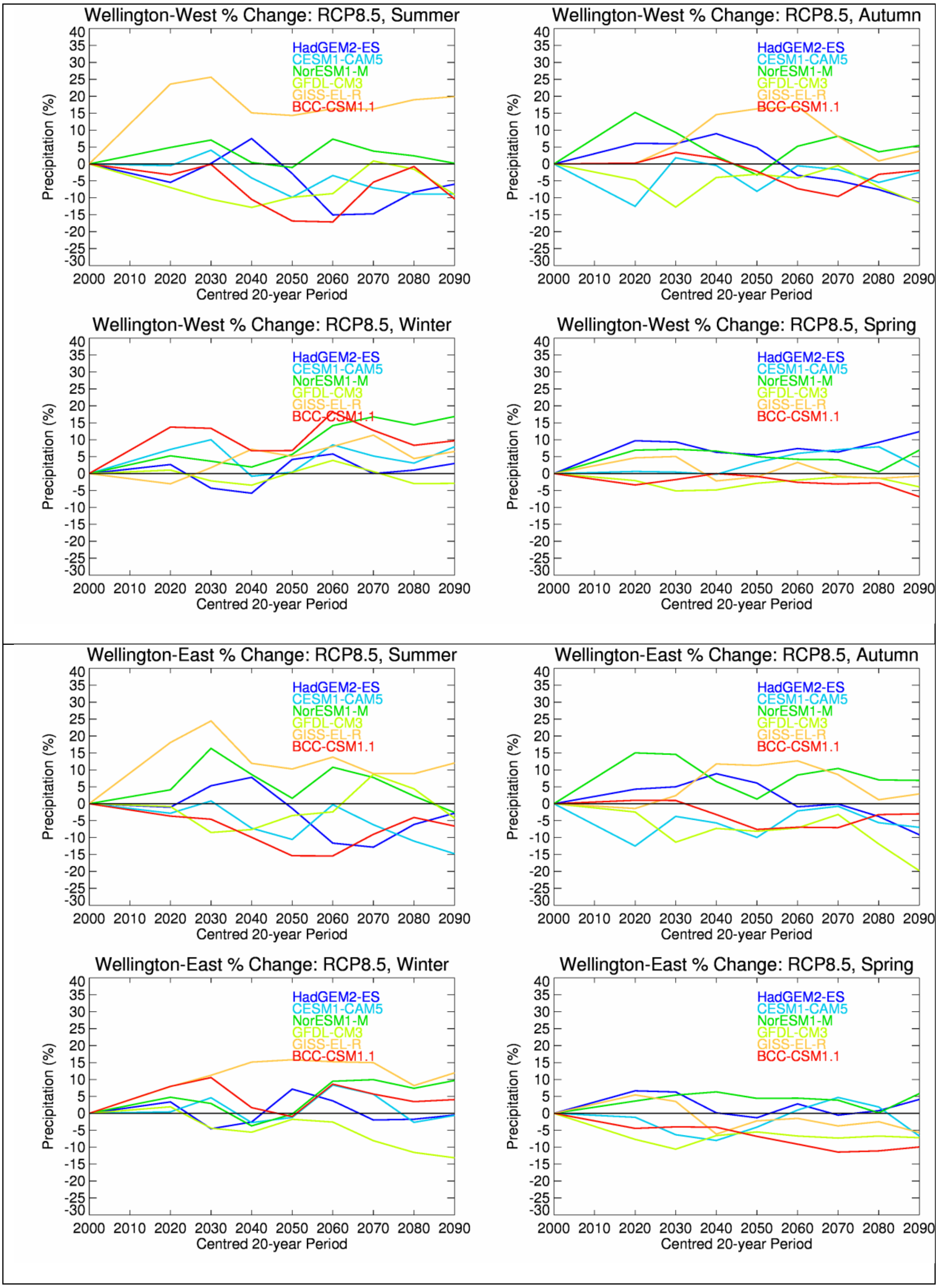

Figure 5-7: As for Figure 5-6, but for RCP8.5.

5.3 Projections of different aspects of climatic drought

Future projections of three different measures of climatic drought are presented in this section. Figure 5-8 shows the projected changes in Potential Evapotranspiration Deficit (PED) for the July-June 'hydrologic year' (the same period as Figure 4-42), Figure 5-9 shows projected changes in the number of days per year of soil moisture deficit, and Figure 5-10 shows projected changes in the number of days per year of PED accumulation over 300 mm.

The three measures of drought considered here can be considered as indicators of different aspects of drought. Annual PED (Figure 5-8) indicates annual drought intensity, days of soil moisture deficit (Figure 5-9) indicates decadal drought frequency, and days of PED accumulation above 300mm (Figure 5-10) indicates the length of drought.

PED is explained in Section 3.2.3. Soil moisture deficit is calculated based on incoming daily rainfall (mm), outgoing daily potential evapotranspiration (PET), and a fixed available water capacity (the amount of water in the soil 'reservoir' that plants can use) of 150 mm. Evapotranspiration is assumed to continue at its potential rate until about half of the water available to plants is used up, whereupon it decreases, in the absence of rain, as further water extraction takes place. Evapotranspiration is assumed to cease if all the available water is used up.

As discussed in Section 4.4, smaller increases in PED are projected for high elevations of the Tararua and Rimutaka Ranges, as well as the western parts of the region, and larger increases in PED are projected for the inland Wairarapa region (Figure 5-8). By 2090 under RCP8.5, increases in PED of over 160 mm/year are projected for the area between Masterton and Martinborough, and further southwest of Martinborough. At both time periods for both scenarios, the inland Wairarapa region is projected to experience the largest increase in PED compared with the baseline period.

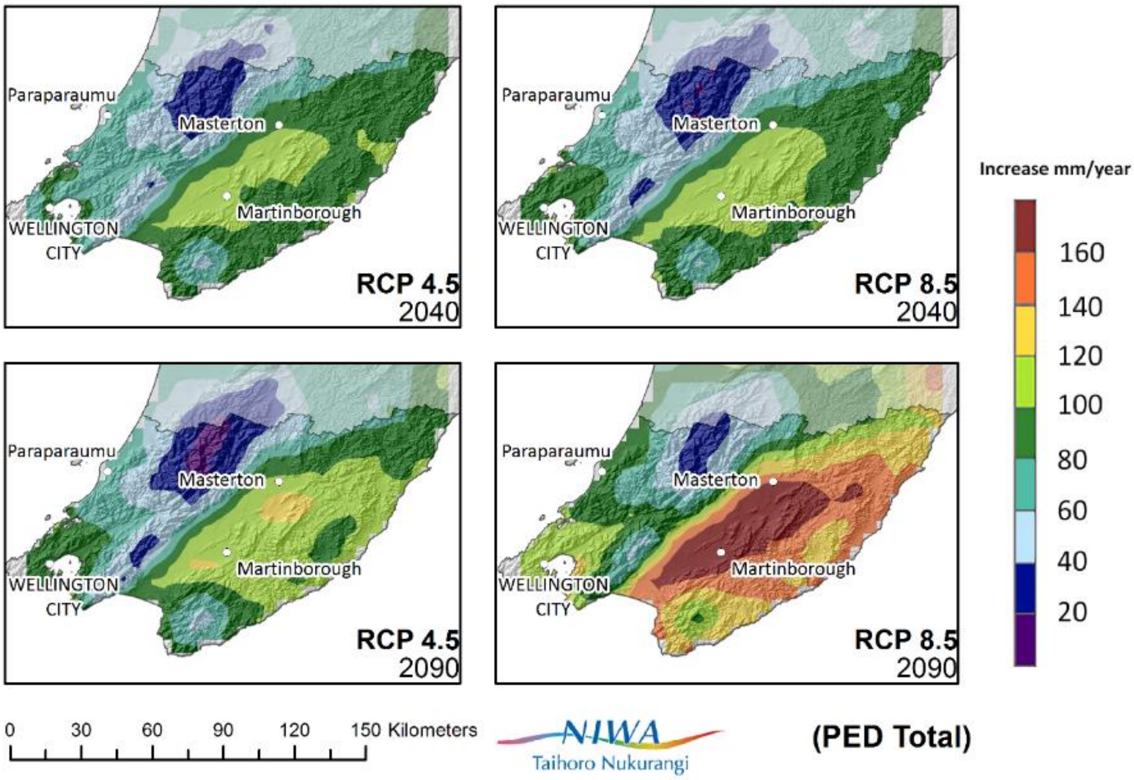

Figure 5-8: Projected changes in Potential Evapotranspiration Deficit (PED, in mm accumulation over the July-June 'hydrologic year') for the Wellington Region, for RCP 4.5 and 8.5, at 2040 and 2090. Projected change in PED is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

Considering the projections of the number of days in soil moisture deficit (SMD, Figure 5-9), there is a change in pattern of where the driest soils are projected to be compared with PED. Looking at 2040 under RCP4.5 and RCP8.5, the largest increase in days of SMD is for the eastern slopes of the Tararua and Rimutaka Ranges (up to 16 more days of SMD for the southeastern Rimutaka Ranges and up to 12 more days of SMD for the remainder of the eastern margin of the ranges). The Wairarapa is projected to experience only small changes in days of SMD at 2040 under both scenarios, and some areas are projected to experience small decreases in days of SMD compared with the historical period. By contrast, looking at 2090 under RCP8.5, the largest increase in days of soil moisture deficit is observed in the northeast of the Wellington Region (>36 days). Much of the Wairarapa region is projected to experience an increase of more than 28 days of SMD. The smallest increases in days of SMD are for the highest elevations of the Tararua Ranges. RCP4.5 at 2090 shows a similar pattern, albeit with a smaller increase in the number of days of SMD.

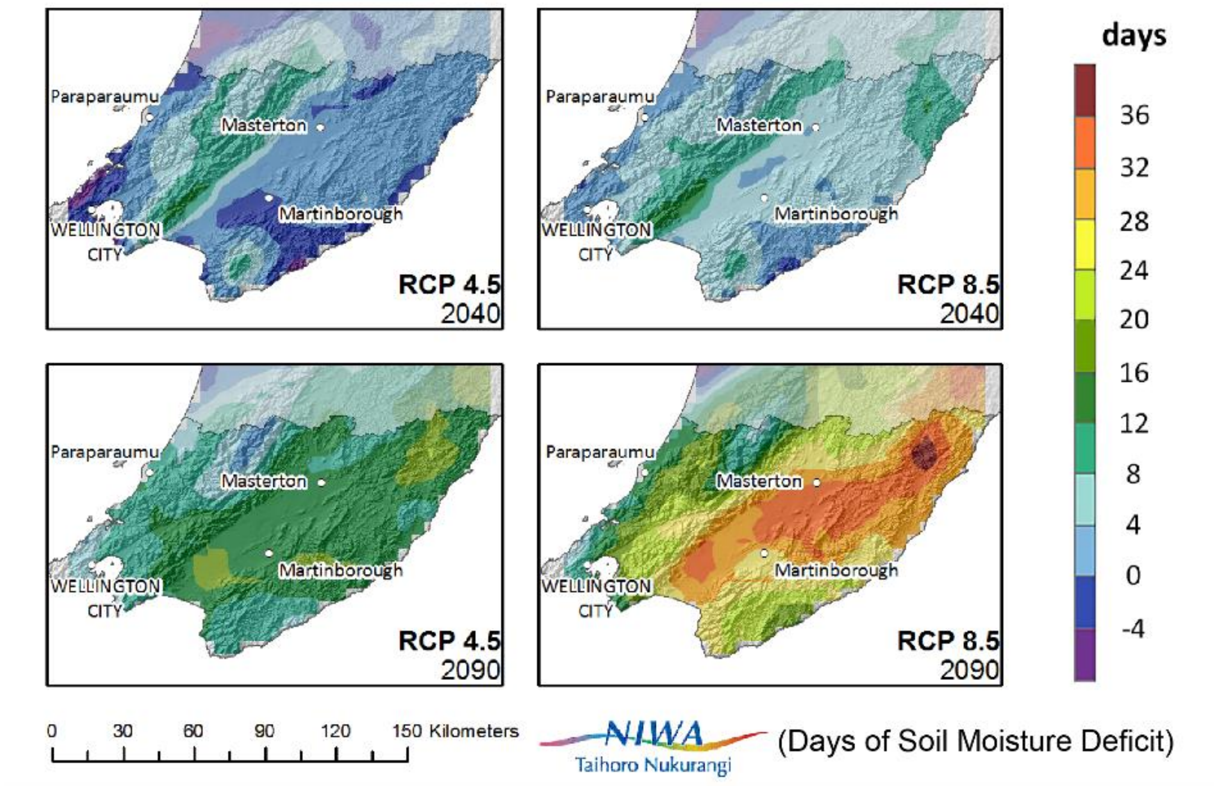

Figure 5-9: Projected changes in the number of days per year of soil moisture deficit (accumulation over the July-June 'hydrologic year') for the Wellington Region, for RCP4.5 and RCP8.5, at 2040 and 2090. Projected change in days of SMD is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

The projections for the number of days where PED is greater than 300 mm (Figure 5-10) show that the area around Martinborough is projected to experience the highest increase, with increases of more than four days per year projected at both time slices for both scenarios, and over 16 more days per year projected at 2090 under RCP8.5. There is zero or a minimal change in the number of days with PED >300mm for most of the region, indicated by the blue shades (<4 days per year).

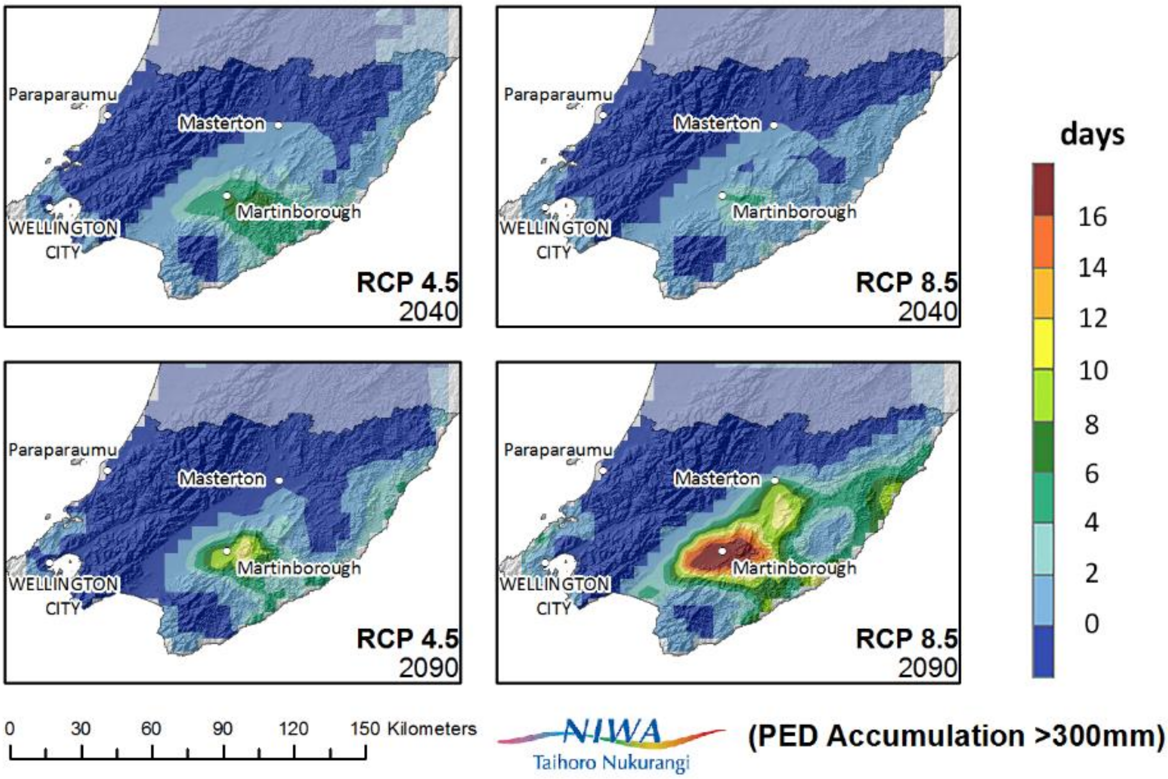

Figure 5-10: Projected changes in the number of days per year of Potential Evapotranspiration Deficit (PED) accumulation over 300 mm (accumulation over the July-June 'hydrologic year') for the Wellington Region, for RCP 4.5 and 8.5, at 2040 and 2090. Projected change in PED is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

The three measures of drought considered here all show similar patterns for 2090 – that the Wairarapa is projected to be the most drought-prone part of the Wellington Region and quite significant changes are expected. At 2040, two of the measures show this same pattern (annual PED and PED accumulation >300mm), albeit to a lesser spatial extent and intensity. However, the pattern of days in soil moisture deficit is different, where the largest increase at 2040 is for the eastern slopes of the Tararua and Rimutaka Ranges.

6 Commentary on other climate change impacts and risks in Wellington Region

The main purpose of this report has been to draw together existing information on how Wellington Region's climate may change in the future. At Greater Wellington Regional Council's request, we have compiled information on climate change impacts for different sectors in the Region: biodiversity, drought impacts on agriculture and horticulture, sea level rise, biosecurity, river flows, wildfire, and soil temperature. The resourcing did not extend to undertaking new research on the likely impacts of climate change on these industries, what is presented here is a compilation of existing research in Wellington, New Zealand, and internationally.

Ways in which councils can investigate some of the physical climate issues are outlined in the guidance manual published by the Ministry for the Environment (Ministry for the Environment, 2008a). These have not been updated in the recent report for the Ministry (Mullan et al., 2016) as the material is considered to be excellent guidance and still relevant to the new projections. The report on coastal hazards and climate change is also useful (Ministry for the Environment, 2008b) and this will be updated in mid-2017 (Ministry for the Environment, 2017).

The Ministry for the Environment climate change guidance manuals recommend that councils should build consideration of climate change into their planning activities rather than considering them in isolation, and should take a risk management approach. Issues surrounding climate change impacts, especially related to local government as well as Maori communities, are covered by Manning et al. (2014). As illustrated by Figure 6-1, consideration of climate change becomes particularly important for designing climate-sensitive infrastructure or assets which are likely to be around for many decades, and for resource use and land development planning over similar timescales.

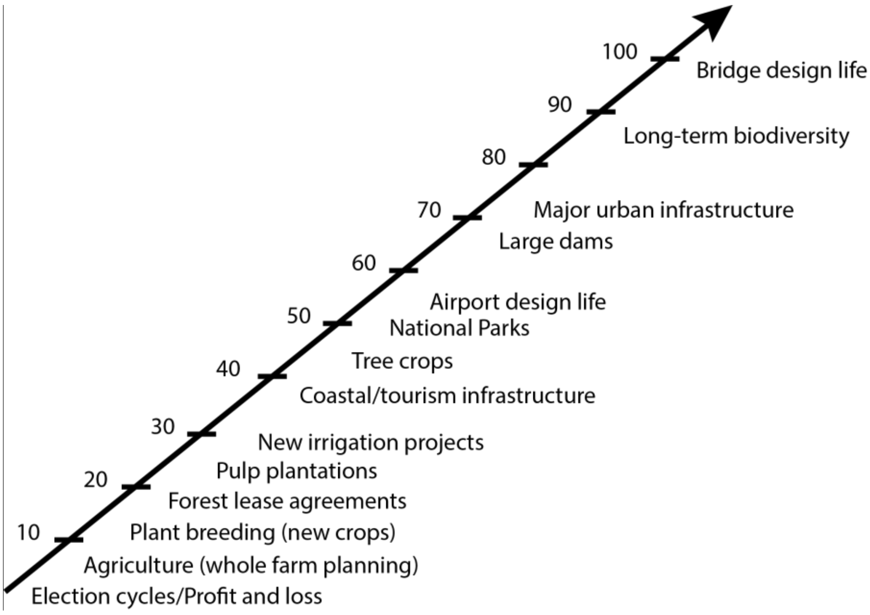

Figure 6-1: Time scales and adaptation. Numbers are years from present. Planning for human-induced climate change becomes increasingly important as one moves right along this line. After R. Jones, CSIRO.

6.1 Biodiversity

In general, biodiversity is at greater risk from predation, human impacts and human responses to climate change rather than the effects of climate change itself. Many 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), hydroelectric power schemes (a 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).

However, changes to the climate will have some effects on New Zealand's (and Greater Wellington's) biodiversity. These impacts are discussed in the following subsections.

6.1.1 Terrestrial

This section is summarised from McGlone and Walker (2011).

The majority of New Zealand plants and animals are adapted to cooler average conditions than those prevailing at present, due to the past 2.5 million years being mostly colder than now. Climate change will result in a range of different effects on terrestrial biodiversity (some of these also relate to marine and freshwater biodiversity changes):

- Range and altitude change. Due to warming, more suitable habitats may open up further south or higher up beyond their current range. However, some species that are unable to migrate will find their current range increasingly unsuitable. A permanently warm climate regime will strand the cold-adapted alpine component section of the biota in a small, and probably shrinking, climatic space.
- Phenological alterations. The timing of seasonal activities such as flowering, breeding, growth and migration may alter and disrupt relationships between species.
- Species interactions alterations. Fluctuations in abundance and changing range limits will bring new combinations of organisms and new interactions with implications for both species and ecosystems, including disease.
- Trophic interaction alterations. Plant productivity, below-ground processes (decomposers and mycorrhyzial associations), and predator-prey interactions will be affected by climatic changes and increasing CO_2 concentrations.
- Exotic organisms are advantaged. As climate changes, existing indigenous species may be disadvantaged relative to exotic organisms better suited to new prevailing climates. Warmer and drier winters are thought to extend the breeding seasons of some mammalian predators (e.g. rodents, goats, pigs and possums).

Climate does not seem to be a major controlling factor for indigenous New Zealand birds; habitat modification and predation are much more important. There are no obvious gradients of indigenous bird species related to climate, so there is no basis for assuming that warming climates will necessarily induce range changes in indigenous bird species. This may not be true for some exotic species however, with myna populations contracting to the northern North Island following introductions across New Zealand.

Given the sensitivity to ambient temperatures of reptiles, warming temperatures may lead to positive or negative effects, depending on the species. Temperature during pregnancy of viviparous lizards can have a wide range of effects, including changes in offspring body size, shape, locomotor speed, scale pattern, and sex (Hare et al., 2009). Modelling results show that for tuatara on southern refuge islands, sex ratios will increasingly tilt towards males due to rising temperatures until, with a mean annual temperature rise of 4°C, all will be born male (Mitchell et al., 2008). However, there is reason to be sceptical about these results as the tuatara lineage has survived warmer temperatures in the past and until recently, tuatara thrived in Northland where mean summer temperatures are about 6°C warmer than the southern tuatara islands.

The direct responses of terrestrial biodiversity to future climate changes will be challenging, due to uncertainty about climate projections, species' responses to climate change and the ability of species to adapt (compared with other parts of the world, e.g. Northern Hemisphere) (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 (See section 6.4) and human-related threats, such as habitat loss (Christie, 2014). Land use and land management practice change in anticipation of climate change will result in further restrictions of native species abundance and distribution.

Some mitigation aspects of climate change might have negative impacts on biodiversity. Afforestation with exotic tree species may lead to reductions in catchment water yield, with negative impacts on stream flow and freshwater biodiversity, stabilisation of previously dynamic systems (e.g. pines on coastal dunes) with consequent loss of indigenous flora, invading areas (e.g. alpine and drylands) where native forest was either absent or limited, and creating flammable forest communities (see Section 6.6 for more information) (McGlone and Walker, 2011).

6.1.2 Freshwater

This section is summarised from Death et al. (2016). For more information on the impacts of climate change on freshwater conservation, see Robertson et al. (2016).

Climate change may have a significant impact on freshwater biodiversity. Currently, there are multiple interacting pressures on freshwater resources (e.g. water abstraction, invasive species, sedimentation, channelization, etc.) that the effects of climate change may intensify (Death et al., 2016).

The distribution of riparian vegetation is likely to alter as temperature and rainfall change, which may have impacts on flood mitigation and detrimental effects on river biota. Due to climatic changes (as well as human responses to these changes), there are likely to be increased distributions of already established invasive species (both plant and animal) and new species that are likely to establish

Many native species (e.g. non-migratory galaxiids, wetland birds) are already under extreme pressure from predation and competition by introduced species (McIntosh et al., 2010, McIntosh et al., 1994, Cruz et al., 2013). Shifts in the amount and distribution of suitable habitat resulting from climate changes as well as invasive species and other effects are complex and need to be considered in future management.

Reductions in rainfall, potential increases in severe floods, as well as the human impact of greater abstraction of freshwater for irrigation, will lead to impacts on freshwater ecosystems. The role of floods in New Zealand rivers is extremely important for maintaining ecological integrity, so with changes to the hydrological regime the changes to biological communities may be dramatic (Death et al., 2016). 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). For example, the damselfly *Xanthocnemis* can survive up to eight days out of water and has a flexible life cycle allowing it to cope to some degree with changing flow regimes, whereas other species (e.g. water boatman *Sigara*) are unable to cope with any drying and are not flexible. Habitat size, availability and quality may be reduced for some species, and drought may threaten already isolated fish and invertebrate populations.

Increases in rainfall may lead to more sedimentation and turbidity in waterways. Banded kokopu (*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).

Water temperatures are predicted to increase. In New Zealand, the temperature effects on the distribution of riverine organisms are likely to be secondary to the changes from altered flow regimes (Death, 2008, Death et al., 2015). However, increased temperatures will affect many species through decreased dissolved oxygen in water (Woodward et al., 2010) and heat stress (McGlone and Walker, 2011). Changes in temperatures will favour some invasive species such that their distributions will increase. However, some heat-tolerant native species may fare better than introduced fish species (e.g. salmonids). Life cycle patterns are expected to change in response to water temperature increases, including spawning times, locations, and triggers for migration.

A side-effect of future changes to rainfall and a trend towards renewable energy means that more hydroelectricity systems are likely to be constructed. These have a major impact on freshwater and riparian biodiversity. When dams are constructed, original riparian habitat is lost in the flooded zone behind the dam. Some indigenous diadromous fish populations (e.g. whitebait and long-finned eel, *Anguilla dieffenbachii*) are depleted through loss of connectivity between feeding and breeding habitats. Downstream of a dam, impeded water flows decrease the river bed width and available habitat space for biota. Less sediment deposition causes river bed 'armouring', which reduces three-dimensional habitat structure and hence productivity within the river bed (McGlone and Walker, 2011).

6.1.3 Coastal

Marine and coastal ecosystems are likely to be influenced by increases in sea water temperature, increases in storm events, and more variable precipitation with more intense rainfall events (Hewitt et al., 2016).

Soft shorelines (beaches and estuaries) are likely to be more severely affected by sea-level rise than hard (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 (i.e. coastal retreat and reconfiguration as sea level rises). The most probable human response to sea-level rise will be by building hard barriers, planting sand dunes, replenishing beaches, and infilling estuaries to prevent erosion and to protect property and infrastructure. This scenario (often termed 'coastal squeeze') means that rising sea levels will remove large areas of habitat at the current coastal margin (McGlone and Walker, 2011).

Loss of productive estuarine habitats and biota is likely to accelerate, with the more visible ecological effects being reduced populations and altered migratory patterns of coastal birds, and declines in certain marine fishes (e.g. snapper, *Pagrus auratus*). Removal of species' habitats by coastal squeeze is already apparent in coastal dunes in some places. The effects of changes in waves and freshwater inputs will also have significant impacts for coastal ecosystems (Hewitt et al., 2016).

Climate change is likely to affect sea and shorebirds through altered sea conditions reducing the abundance of marine food or the birds' ability to access it (McGlone and Walker, 2011). The El Niño-Southern Oscillation is often claimed to explain fluctuations in seabird numbers (e.g. due to sea temperatures and therefore food availability), so changes to ENSO may affect populations of seabirds into the future. A more El Niño-like future may lead to declines in red-billed gull populations as their breeding success is positively related to krill abundance, which is positively related to La Niña (Mills et al., 2008).

There has been interest in generating electricity from Cook Strait's tidal flow with turbines (New Zealand Herald, 2013). Although this method of renewable electricity generation currently has limited support, it could potentially return to favour in the future. Tidal power generation may have negative impacts on marine and coastal biodiversity by restricting natural water flow (especially in estuaries if turbines are placed at their mouths), and by generating high levels of noise which might displace cetaceans and fish as well as potentially causing physical hazards (McGlone and Walker, 2011).

6.1.4 Oceanic changes

This section includes information extracted from a very recent report on climate changes, impacts and implications for New Zealand's Exclusive Economic Zone (Law et al., 2016). This report has much more detail regarding likely changes to New Zealand's marine environment to 2100, and can be downloaded from http://ccii.org.nz/outputs (see Marine Case Study).

There is growing awareness that climate change is altering the physical and biogeochemical nature of the open ocean with impacts on, and implications for, marine ecosystems and the socio-economic benefits and ecosystems services we gain from the ocean (Bopp et al., 2013, Weatherdon et al., 2016). The recent IPCC assessment identified that current and projected changes in ocean properties are unprecedented in relation to past records (Portner et al., 2014), raising concerns regarding the capacity of marine ecosystems to cope with the rapid rate of change. The oceans contain 93% of the additional heat retained by the globe (Levitus et al., 2012) arising from increasing greenhouse gas concentrations, and so increasing ocean temperature is a primary feature of climate change in marine ecosystems.

Warming and major changes in current flow have already resulted in regional shifts in the abundance and distribution of a number of different marine biotic groups (Poloczanska et al., 2013). The observed poleward migration of species may result in major changes in ecosystems and species interactions in some locations, with negative impacts on food and economic security in tropical and subtropical regions (Hoegh-Guldberg et al., 2014). The uptake of anthropogenic CO_2 also leads to ocean acidification, which is causing changes in water chemistry and pH that impact a variety of biological groups, particularly carbonate-forming organisms and algae, and marine ecosystem productivity and biodiversity.

Ocean acidification

The transfer of anthropogenic CO_2 into the ocean is altering the oceans carbonate buffering system, lowering pH and carbonate ion availability whilst increasing dissolved CO_2. As pH and dissolved inorganic carbon species play critical roles in a number of physiological processes and also influence nutrient availability, changes in these properties will have a fundamental impact upon marine biogeochemistry and ecosystems.

pH is a measure of hydrogen ion concentration and describes the relative acidity/alkalinity of a solution. Over recent geological time the pH of the ocean has been relatively stable at ~8.2, but since the late 1870s it has declined to 8.1 in response to anthropogenic CO_2 emissions (Raven et al., 2005). As pH is on a negative logarithmic scale, this decline of 0.1 is equivalent to an increase in hydrogen ion concentration of ~30%.

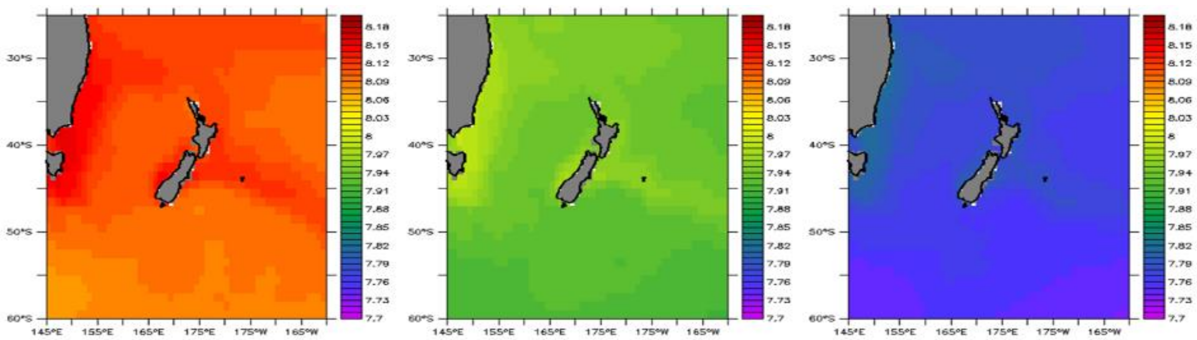

Figure 6-2: The spatial variation in mean surface pH in the Southwest Pacific. For the present-day (1976-2005, left panel), and projected for Mid-Century (2036-2055, central panel) and End-Century (2081-2100, right panel) using the GFDL-ESM2G model under RCP8.5.

As pH is primarily determined by atmospheric CO_2 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 6-2, which shows that the effect of future changes in atmospheric CO_2 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 trend of ~0.03 partially reflects the higher solubility of CO_2, and so lower pH, in colder water. Surface waters in the Subtropical Front on the Chatham Rise have marginally higher pH, due to CO_2 uptake by phytoplankton in this region.

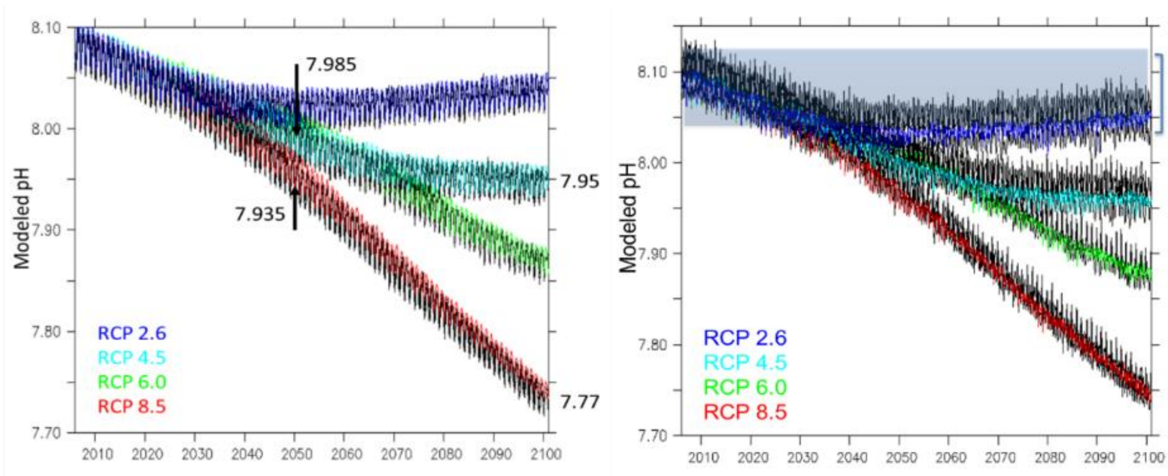

Figure 6-3: Projected surface pH for the New Zealand Exclusive Economic Zone under each RCP, with the Mid and End-Century mean pH identified for RCP4.5 and 8.5 (left panel). For each RCP the black line indicates the mean of the six climate models, and the coloured line the best model. The right panel shows the same information but for the Chatham Rise region only, with the current pH range (8.04-8.13) indicated by the horizontal blue band. The current pH range was derived from measurements in Subantarctic surface water off the Otago shelf over a 16-year period (1998-2014) on the Munida time series (Bates et al., 2014).

Figure 6-3 illustrates how the projected pH differs under different future emission scenarios. The annual sawtooth pattern reflects seasonal variation in pH, with a maximum in summer resulting from phytoplankton uptake of dissolved CO_2, and a minimum in winter when phytoplankton abundance is low. This seasonality results in a relatively large annual pH range of ~0.05, which obscures any difference in the four RCP projections until around 2035. However the pH under the different RCPs subsequently deviates, declining to 7.99 by 2050, and 7.95 by 2100, under RCP4.5. The RCP8.5 scenario shows a steeper decline to 7.94 and 7.77 by 2050 and 2100, respectively. This decline of 0.33 pH units by 2100 is equivalent to an increase in hydrogen ion concentration of 116% since the pre-industrial period. This is consistent with trends in the global ocean, and represents both the lowest pH, and the fastest rate of change in pH, in the last 25 million years (Turley et al., 2006).

Research to date suggests that declining surface pH (and associated increases in dissolved CO_2) may cause changes in phytoplankton biodiversity and bacterial processes that will impact marine foodwebs and ocean carbon uptake. In particular, the abundance and distribution of planktonic organisms with carbonate shells, and the foodwebs they contribute to, may be negatively affected by acidification. As pH sensitivity differs between species this makes it difficult to predict when deleterious effects may occur.

Changes in sea surface temperature (SST)

Changes in the temperature of the surface ocean are already evident globally, although there is significant regional variation in the degree of warming. Projections for the Southwest Pacific show an increase in SST by Mid- and End-Century, regardless of RCP and climate model. The mean increase is ~1°C by Mid-Century, and ~2.5°C by End-Century for RCP 8.5.

Figure 6-4 shows the spatial variation of change in SST for End-Century under RCP 8.5, 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 6-4) associated with the southerly penetration of the East Australian Current off south-east Australia in region 2 (Ridgway, 2007). This 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 transfers 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. Although no temperature change was observed during the 1990's, surface warming in the Tasman Sea has been observed more recently (P. Sutton, pers. comm.). Warming of >2.5°C is also evident in the eastern Chatham Rise by End-Century (region 6), whereas warming is lowest in Subantarctic waters (region 7).

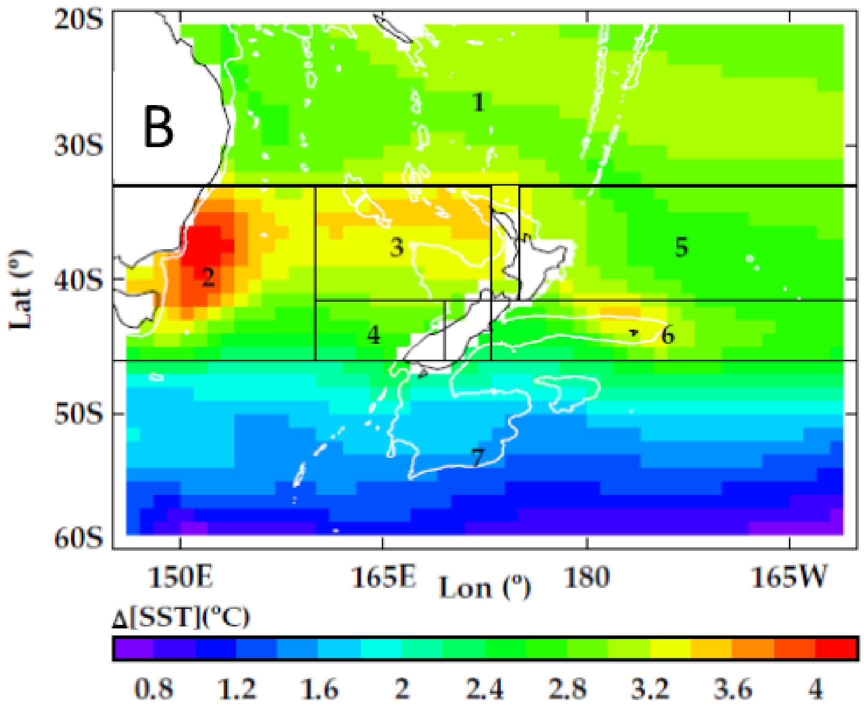

Figure 6-4: Regional variation of the projected change in SST for the End-Century (2081-2100) compared with present-day (1976-2005) under RCP8.5 (Rickard et al., 2016).

Changes to nutrients and potential impacts on fish

The availability of nutrients is critical for phytoplankton growth. For example, waters characterised by low concentrations of macronutrients (nitrate, phosphate and silicate), support low phytoplankton biomass and productivity and lower carbon export to the deep ocean per unit area. Conversely, regions of high surface macronutrient concentrations are characterised by high plankton productivity and more productive fisheries, such as the Subtropical Front water in the Chatham Rise region. One notable exception in NZ waters are the high nutrient-low chlorophyll Subantarctic waters to the southeast, where phytoplankton growth is limited by low dissolved iron (Boyd et al., 1999).

No significant change is projected for macronutrient concentrations by Mid-Century, but there is a significant decline by End-Century under both RCP4.5 (the assessment was not performed for RCP2.6 and RCP6.0) and RCP8.5. Although there is scatter in the projections by different models, with some indicating an increase in future concentrations, the mean over the models shows a decline from present-day, of ~0.5 (9.2%) and 0.04 (7.8%) mmol/m^3 in nitrate and phosphate concentrations, respectively by End-Century under RCP8.5. The projected change by the *End-Century* under RCP4.5 is similar to that projected for *Mid-Century* under RCP8.5. Projections also indicate an overall decline in mean silicate concentration, of 0.18 mmol/m^3, which is 5.6% of present-day concentrations. Conversely, dissolved iron, which is an important micronutrient, increases under both RCP4.5 and RCP8.5 by 0.03 mmol m^{-3} by End-Century under RCP8.5, equivalent to 24% of present-day mean concentrations.

The projected changes in pH, SST and nutrient availability may alter regional productivity and foodwebs. Increases in observed SST are already driving regional changes in marine ecosystems with a reduction in temperate species, increase in sub-tropical species and shift towards nutrient-poor conditions (Frusher et al., 2014). Globally there is evidence that oligotrophic (low-nutrient) waters are expanding, in response to warming (Polovinia et al., 2011) and, as 50% of NZ waters are, at least seasonally, oligotrophic then future decreases in macronutrient availability may reduce productivity in the EEZ. The Chatham Rise is the most productive region in NZ waters, and the projected decline in macronutrients may have ramifications for fisheries in this region. Conversely an increase in iron availability in warmer Subtropical waters, particularly the Tasman Sea region, may increase regional primary productivity, but this is unlikely to offset the overall decline in primary productivity in NZ waters by End-Century.

The regional variation of the impact of climatic change in New Zealand waters needs to be considered in management and policy decisions. For example, regions that are most sensitive to climate change include Subantarctic waters south of 50°S and the eastern Chatham Rise, which support important fisheries, and Subtropical waters north-east of NZ, which contain the Kermadec Marine reserve.

6.2 Drought impacts on pasture and crops

It is likely that much of the Wellington Region, particularly the eastern part of the region, will experience more drought conditions in the future than at present (discussed in Section 4.4). Drought has significant impacts on primary industries in the Wellington Region.

This section is based on information from Clark et al. (2012). For more detailed information about impacts of drought and other climate variables on land-based sectors in New Zealand, see Clark et al. (2012).

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 broad-acre crops. 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 growth in different ways. When water supply is less than crop demand, yield is mainly reduced by limited canopy expansion and increased leaf senescence (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 grapes, rainfall can have positive or negative effects. Girona et al. (2006) found that 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.

The effect of increased CO_2 levels on plants under limited water supply may help with the effects of drought. Under limited water supply conditions, the effect of CO_2 fertilisation is more evident. Higher CO_2 concentrations reduce the loss of water vapour through leaf transpiration and, therefore, improve the water use of crops (Leakey et al., 2009). The faster growth of plants due to CO_2 fertilisation may enable plants to avoid exposure to late-season droughts.

Orwin et al. (2015) considered the impacts of drought on soil processes in four primary sector systems (Figure 6-5). For the cropping industry (Figure 6-5a), drought has a significant negative effect on aboveground crop biomass, leaching, and denitrification (loss of soil fertility). For intensive grazing, drought also has a negative effect on nitrogen fixation in addition to those effects stated for cropping. In extensive grazing systems, drought causes increased erosion.

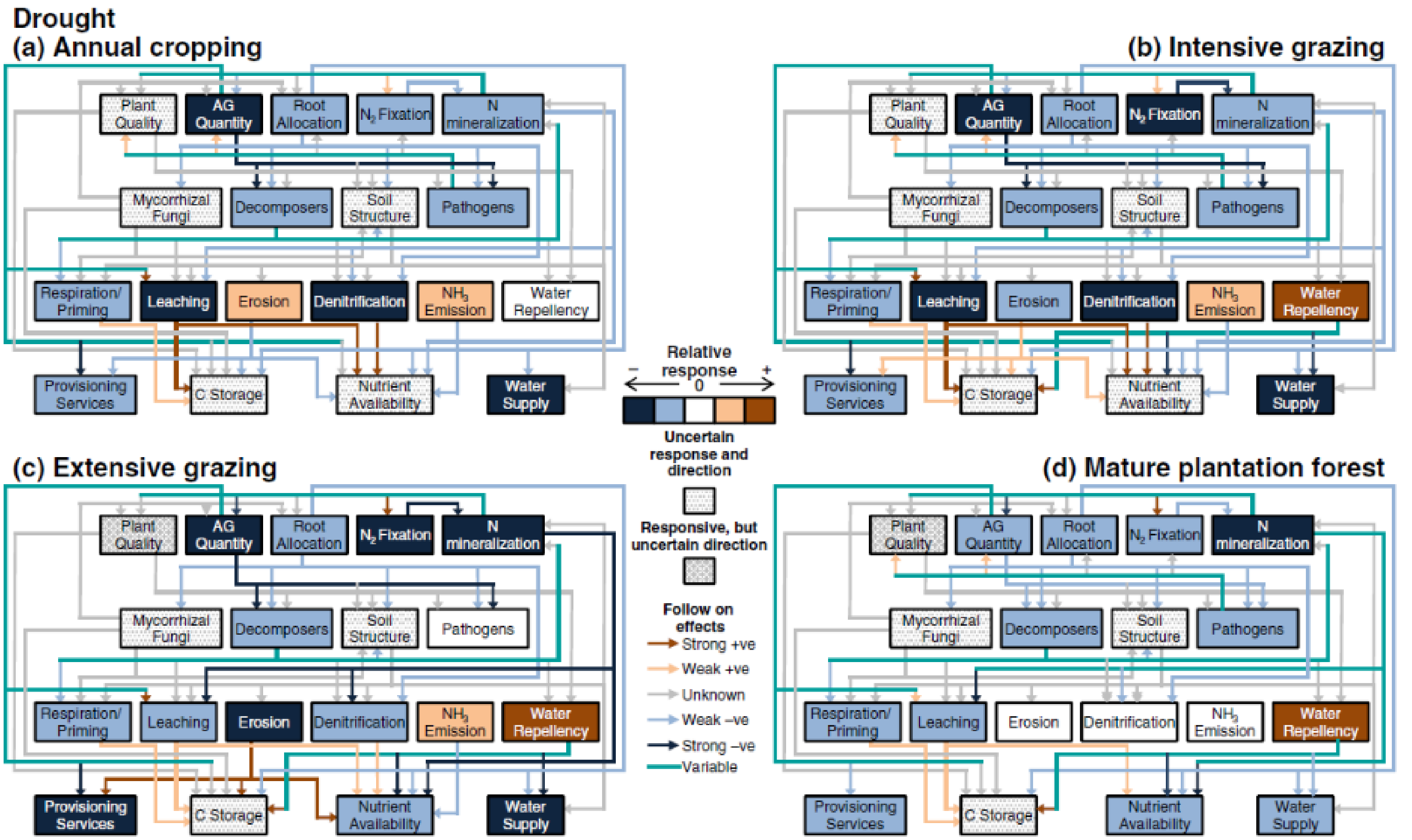

Figure 6-5: Impact of drought on soil processes, natural capital and service delivery in four primary sector systems. Colours of boxes indicate the direction of responses of a given variable to drought and its relative importance for that system compared to the others. Arrows indicate the impact of a change in one variable on other variables. AG = aboveground, +ve = positive, -ve = negative. After Orwin et al. (2015).

Farmers 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 (Section 4.2 and 4.4).

6.3 Climate change and sea level

One of the major and most certain (and so foreseeable) consequences of increasing concentrations of carbon dioxide[6] and associated warming, is the rising sea level (Parliamentary Commissioner for the Environment, 2015).

The Intergovernmental Panel for Climate Change (IPCC) released its Fifth Assessment Report (AR5) in 2013/14. IPCC AR5 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, the amounts of snow and ice have diminished, and sea level has risen (IPCC, 2014a).

On behalf of the Ministry for the Environment, NIWA has led the team working on the revision of the *Coastal Hazards and Climate Change* guidance for local government that was last revised in 2008. It provides specific guidance on sea-level rise scenarios to use for adapting to coastal climate change in New Zealand, following on from the IPCC Fifth Assessment Report in 2013-2014. It is based on a 10-step decision cycle and includes risk assessment approaches tailored to uncertainty in the rate of rise in sea level, a dynamic adaptive pathways planning approach to work with uncertainties and principles for engaging with coastal communities and stakeholders to achieve robust adaptation strategies. The coastal guidance will be released by the Ministry around mid-2017.

6.3.1 Impacts of sea-level rise

The rise in sea level is of great relevance for long-term decisions made in coastal areas, for two main reasons:

1. The long-term impacts on coastal populations, developments, and environments, are potentially large (e.g. Hinkel et al., 2014, Nicholls et al., 2011), because past coastal developments were built on the premise of a relatively “stable” sea level.

2. The sea-level response to warming of the Earth’s climate system makes it an integrated global indicator – more than 90% of the energy that is stored in the climate system ends up in the oceans (Rhein et al., 2013). Observed sea-level rise, however, needs to be interpreted in light of substantial lags (decades to millennia) in the ongoing response to warming of the oceans and melting of glaciers and ice sheets (IPCC, 2013, Dangendorf et al., 2014).

Rising sea level in past decades is already affecting human activities and infrastructure in coastal areas, with a higher base mean sea level contributing to increased vulnerability to storms and tsunami. Key impacts of rising 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
- exacerbated erosion of sand/gravel shorelines and unconsolidated cliffs (unless sediment supply increases)

[6] Global average now above 400 ppm.

- 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 most development in coastal areas, along with environmental, societal and cultural effects. Infrastructure will also be increasingly affected, such as wastewater treatment plants and potable water supplies, besides capacity issues with stormwater and overland drainage systems. Public transportation and roading infrastructure will also be affected.

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 sea-level rise for a regional sea, e.g. the sea around New Zealand. There can be significant variation in the response to warming and wind patterns between different regional seas around the Earth
- local (or relative) sea-level rise, which is the net rise from absolute, regional-sea offsets and local vertical land movement (measured relative to the local landmass). Local or regional adaptation to sea-level rise needs to focus on this combined local rise.

The first two types of sea-level change 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 changes in the Earth's crust following the last Ice Age[7]).

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

A report on New Zealand's coastal sensitivity by Goodhue et al. (2012) found that the east coasts of both the North and South Islands are more sensitive to erosion and inundation caused by climate change, because of a combination of factors such as wave exposure, relatively low tidal ranges, sediment budget deficits, and proximity to tidal inlets. Conversely, west coast shores are less sensitive to climate-driven change, mainly because they are already regularly exposed to high wave energy.

The present Mean High Water Spring level around New Zealand coastlines will be exceeded much more frequently by high tides in the future, particularly on sections of the coast where the tide range is relatively small, such as in Wellington (compared with those sections of the coast where the tide range is relatively large, e.g. Tasman/Golden Bay). Problems will be exacerbated for coastlines with smaller tidal ranges in proportion to sea-level rise, where high tides will more often exceed current upper-tide levels, thus allowing more opportunity to coincide with storms or large swell.

Sea-level rise will have a greater influence on storm inundation and rates of coastal erosion on the central parts of the east coast (Napier/Gisborne) and Cook Strait/Wellington areas (due to their smaller tidal range) than on coastal regions with larger tidal ranges (e.g. west coast – Taranaki, Nelson, Westport) (Ministry for the Environment, 2008b).

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

Coastal dune systems are particularly vulnerable to sea-level rise due to the lower erosion threshold of sand compared with unconsolidated cliffs. With sea-level rise, natural dune systems will in most cases gradually erode and move inland due to the increased frequency of waves attacking the backshore and foredune, unless the supply of sand can keep pace with erosion (Ministry for the Environment, 2008b). However, where there is development close to the coast, there will be a need for communities and councils to weigh up staged response options or planning pathways which may require a move away from hard-engineered structures transitioning to some form of managed retreat at a defined trigger or decision point (Ministry for the Environment, 2017). Dune stabilisation by planting or beach sand nourishment will likely be a short-term solution (pathway) until sea-levels reach a point where planted dunes alone cannot stop major coastal erosion, or the economics of more regular beach replenishment becomes unsustainable.

6.3.2 Trends for sea-level rise (global and New Zealand)

After a period of relative stability over the past 2000–3000 years, sea level began to rise on a global scale from the late 1800s (Figure 6-6). The trend over this entire period is around 1.7-1.8 mm/yr (see IPCC Working Group I AR5 report, (Church et al., 2013b)).

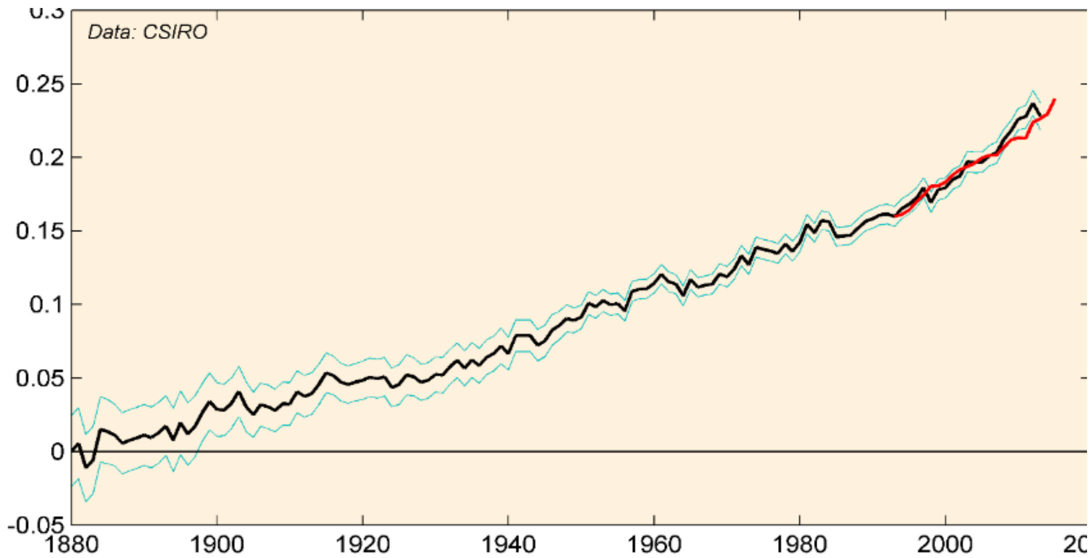

Figure 6-6: Cumulative changes in global mean sea level (MSL) since 1880, based on a reconstruction of long-term tide gauge measurements to end of 2013 (black) and recent satellite measurements to end 2015 (red). Lighter lines are the upper and lower bounds of the likely range (± 1 standard deviation) of the MSL from available tide gauges, which is a function of the number of measurements collected and the precision of the methods. Source: tide gauge data from Church and White (2011), updated to 2013; satellite data from CSIRO (2016).

Recent studies have demonstrated that the anthropogenic contribution to the observed global sea-level rise in the 20th century has been around 45–50% (Kopp et al., 2016, Dangendorf et al., 2015). The contribution since 1970 has risen to 69% [±31%] of the observed increase in global mean sea level (Slangen et al., 2016).

For the satellite era (from 1993 onwards, Figure 6-7), the recent trend in global-average MSL to August 2016, based on the CSIRO analysis of satellite altimeter data[8], is 3.4 ± 0.1 mm/yr. This rate of

[8] www.cmar.csiro.au/sealevel/sl_hist_last_decades.html Rate includes adjustments for both inverse barometer and glacial isostatic adjustment.

increase, averaged over the past 23 years, is nearly double the global-average rate over the historic rate over the entire 20th century of 1.7-1.8 mm/yr based on hundreds of sea-level gauges (Church et al., 2013b, Church and White, 2011). Natural climate variability from interannual to decadal climate cycles, especially the 20–30 year Inter-decadal Pacific Oscillation (IPO) (which changed phase around 1999, partway into the satellite era) in combination with the shorter 2-4 year El Niño-Southern Oscillation (ENSO), have contributed to part of the recent increase in the global trend (more so in the western Pacific including New Zealand for that period), but it is clear that anthropogenic climate change is also contributing an increasing proportion of this more recent increase in global sea-level rise. The year-to-year variability in the global mean sea level shown in Figure 6-7 is due to ENSO e.g., peak as end of 2015 coincided with an El Niño and the trough in 2011, with a La Niña, while the more gradual rise from 1998–1999 is due in part to the IPO (with a more obvious rise in Pacific areas including New Zealand).

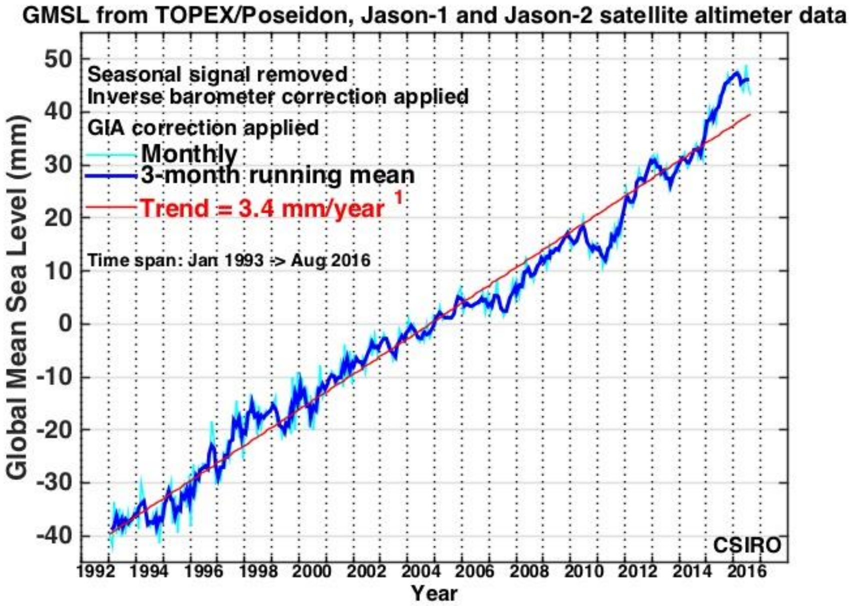

Figure 6-7: Time series and trend in global average sea level over the satellite era from January 1993 to August 2016. Adjustments for glacial isostatic adjustment (GIA), following crustal response to the last Ice Age, and inverted barometer (annual air pressure differences) have been made. Retrieved from CSIRO web site: http://www.cmar.csiro.au/sealevel/sl_hist_last_decades.html

Changes in annual local MSL at the four main ports in New Zealand since 1900 are shown in Figure 6-8. Annual MSL is plotted relative to the average for each time series over the same 1986–2005 baseline period used for IPCC AR5 projections. The initial period of IPCC global-mean projections of SLR for RCP 8.5 and RCP 2.6 scenarios are also shown for a general comparison with observations to end of 2015 on how sea level is tracking. Yearly and decadal variability in the observations from the 3-7 year El Niño-Southern Oscillation and longer IPO cycle, partially mask the underlying trend, so makes it difficult to isolate how that underlying rising trend is tracking relative to the projections (Figure 6-8). For example, the annual MSL for ports is currently above the RCP projection lines, but in part this is due to the IPO shift to the negative phase in 1999 (Figure 6-8), which raised mean sea level throughout the western Pacific.

This masking effect of natural climate variability on sea-level rise trends requires long records to extract robust historic trends, and also may require one or two decades more monitoring to confirm which sea-level rise RCP scenario is being followed (because there is little difference at present between the sea-level rise projections – see dotted lines in Figure 6-8). Also when the IPO shifts back to the positive phase, annual MSL around New Zealand may dip at times below the RCP projection lines, but still with a rising trend.

Local sea-level trends over the past 60-100 years with standard deviations were analysed at 10 gauge sites by Hannah and Bell (2012), with an average rise of 1.7 mm/year from early last century up to 2008. The trends have been updated to 2015 (except for Whangarei), as shown in Figure 6-9, with the national average rate now closer to 1.8 mm/year. Wellington Harbour sea level has risen by 2.23 mm/year since the early 20th century (Figure 6-9). Over the satellite era since 1993, the SW Pacific have also experienced increased rates of rise, with the ocean around New Zealand rising since 1993 to mid-2016 at an average of 4.4 ±0.9 mm/yr, which is considerably higher than the global average from the satellite record of 3.4 mm/yr (Figure 6-7). This difference is largely due to the IPO shift in 1999, when annual sea level around New Zealand rose by 5–6 centimetres (Figure 6-8).

The reader is directed to Bell and Hannah (2012) for detailed information about historical variability and trends in Wellington sea level.

Adaptation to sea-level rise requires knowledge on why and how **local** sea-level rise around New Zealand is affected by ongoing vertical land movement (but as earthquakes occur, any sudden uplift or subsidence needs to be factored in from thereon). Of most concern is the presence of any significant ongoing **subsidence** of the landmass, which will exacerbate the absolute ocean sea-level rise (Figure 6-10).

Future projections of sea-level rise at some locations or regions in New Zealand will also need to factor in estimates of ongoing vertical land movement. Based on analyses by GNS Science (on behalf of NIWA) of continuous GPS (or cGPS) gauges around the coast, Figure 6-11 shows the average rate of vertical land movement over the past decade around our shorelines (Beavan and Litchfield, 2012). The southern North Island, including the Wellington Region, is tectonically active with high rates of vertical movement relative to the rest of New Zealand. Land subsidence rates around the coast of the Wellington Region are around 1-4 mm/yr (Beavan and Litchfield, 2012). This vertical movement (over the last decade) is associated with interseismic slow slip events associated with faults. It is unclear how frequent and over what periods these slow-slip events will occur in the future, but it is important to continue ongoing cGPS monitoring to measure the future progression of subsidence events. Any land subsidence will exacerbate the effects of sea-level rise for the Region, particularly in the period until sea-level rise becomes substantial. For example, if subsidence due to slow-slip was to continue for Wellington City at say 2 mm/yr, then by the time absolute sea-level rise reaches 0.4 m (between 2055-2075), subsidence would add a further 0.08-0.12 m to the resulting relative sea-level rise, thereby compounding the coastal hazard risk exposure over the next few decades. For much higher absolute sea-level rise or rates of change towards the latter part of this century and beyond, the subsidence (assuming similar rates in the future) would become a smaller proportion of relative sea-level rise for the Wellington Region.

Large changes in vertical deformation due to earthquakes are always possible, and if one occurs it can have a dramatic effect (vertical changes of centimetres to metres) on the coastal elevation (as seen in 2016 following the Kaikoura earthquakes). Future major earthquake displacements for a particular locality are deeply uncertain (both when and by how much). Unlike the ongoing sea-level rise, they could be either subsidence or uplift, other than those areas with a clear history at geological timescales of only uplift or subsidence (Beavan and Litchfield, 2012), such as uplift on the open coast of the Wellington Region.

For foreseeable land-use planning timeframes, the coastal guidance (Ministry for the Environment, 2017) does not recommend factoring in future occurrences of earthquake-generated uplift or subsidence events, due to the deep uncertainty of when and how much land elevations may change following a major tectonic event.

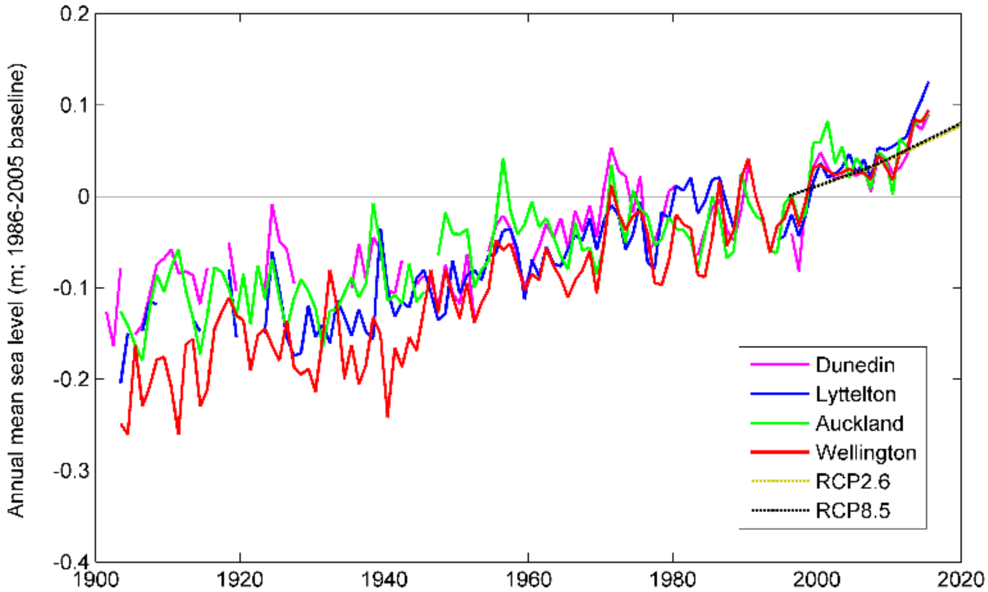

Figure 6-8: Change in annual local MSL for the four main ports from 1900–2015, and initial global-mean SLR projections for RCP2.6 and RCP8.5 to 2020. Relative to the average MSL over the baseline period 1986–2005 (used for IPCC AR5 projections of sea-level rise, with mid-point at 1996). (Source data: Hannah and Bell (2012), updated to 2015 in Ministry for the Environment (2017); Church et al. (2013a)). [Reproduced from Ministry for the Environment (2017)]

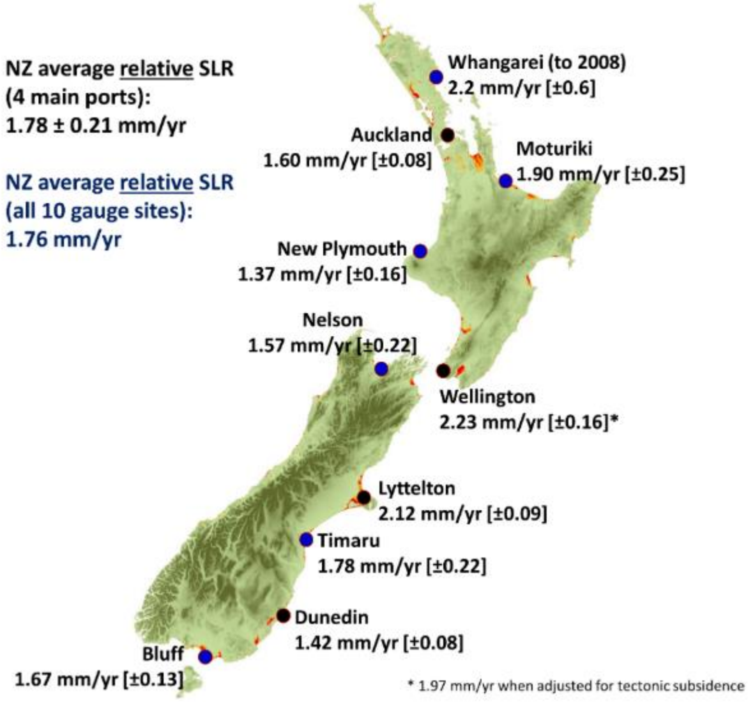

Figure 6-9: Historic long-term relative SLR rates for the 20th century up to and including 2015 (excluding Whangarei), determined from longer sea-level gauge records at the four main ports. Note: Standard deviations of the trend are listed in the brackets. Sources: analysis up to end of 2008 from Hannah and Bell (2012) updated with seven years of MSL data to end of 2015 (J Hannah, pers. com, 2016); sea-level data from various port companies is acknowledged. [Reproduced from Ministry for the Environment (2017)]

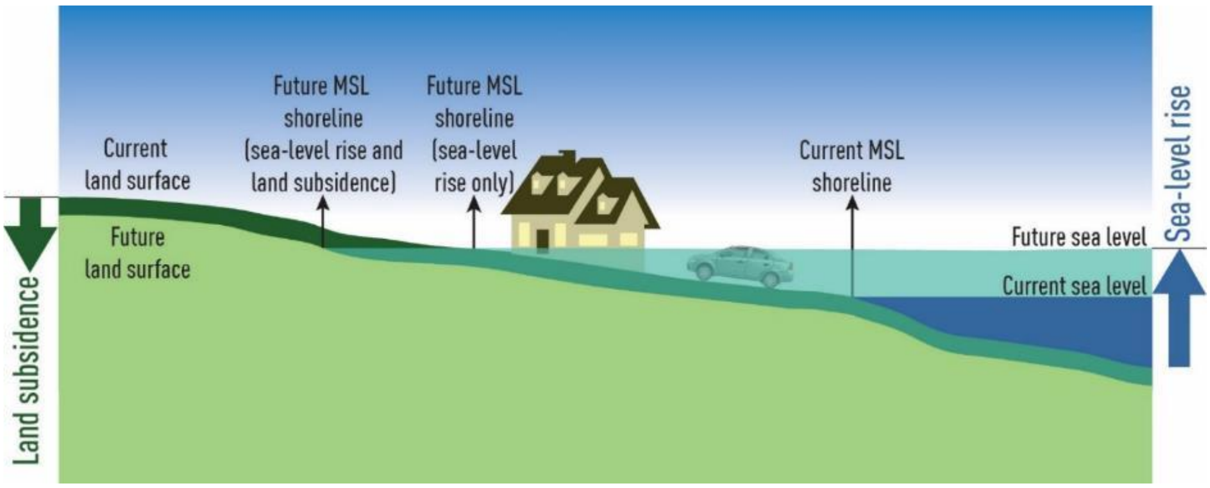

Figure 6-10: The difference in mean sea level (MSL) shoreline between absolute SLR (SLR only) and local (relative) SLR where land subsidence occurs (SLR + land level changes). [Graphics: Aarti Wadhwa].

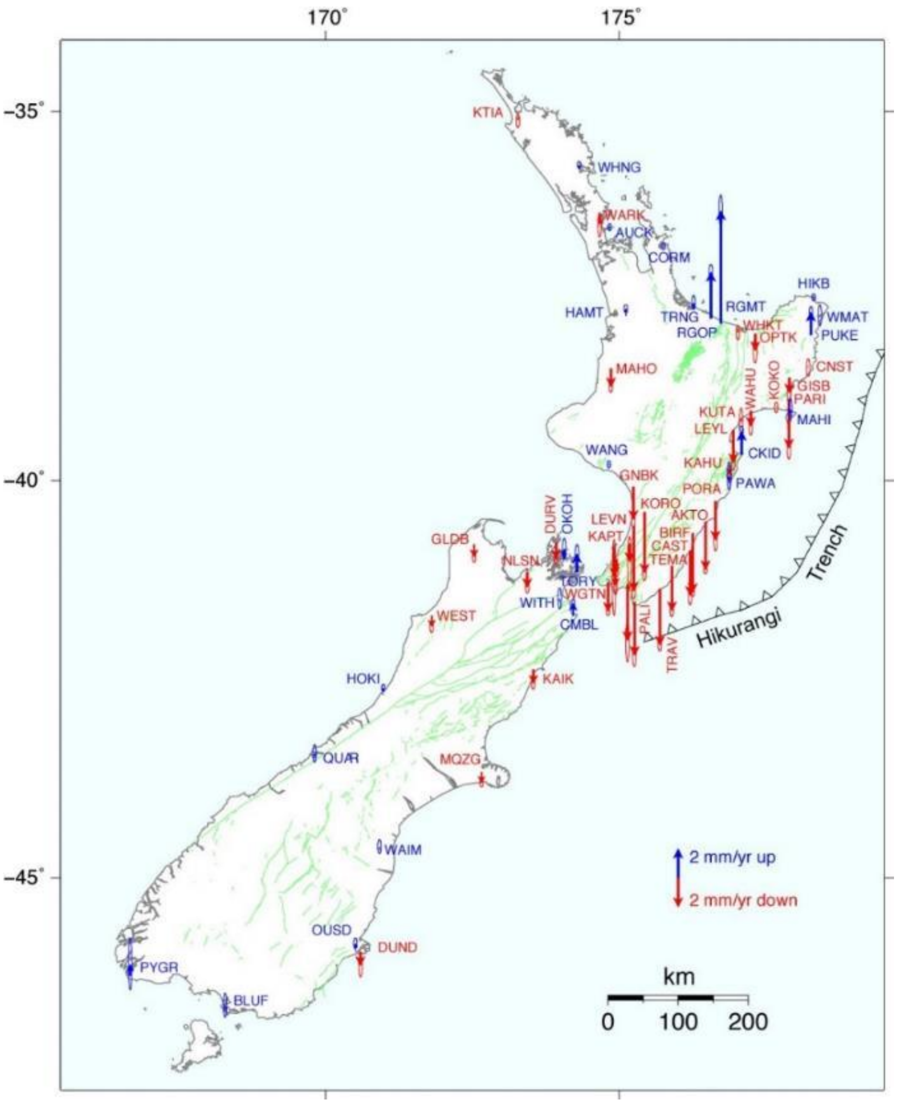

Figure 6-11: Average vertical land movements (mm/yr) for near-coastal cGPS sites across New Zealand. Blue arrows show average uplift and red arrows average subsidence over ~10-year period. (Source: Beavan and Litchfield, 2012).

6.3.3 Projections for sea-level rise

The primary climate driver for sea-level rise is global and regional surface temperature, which is strongly influenced by greenhouse gas emissions. With the greenhouse gases currently in the atmosphere and the heat stored in the ocean, the world is already committed to further temperature increases, and an ongoing lagged response to sea-level rise, because of the inertia in the melting of the vast polar ice sheets. Cumulative global emissions to date have already committed the Earth to an eventual 1.6–1.7 m of global SLR relative to the present level (Strauss et al., 2015, Clark et al., 2016), even if no further net global emissions occur. However, depending on how continuing emissions track during the rest of this century (particularly the next few decades), realising this present commitment to SLR could take 1-2 centuries.

The IPCC AR5 (Church et al., 2013a) projections out to 2100 are provided below. These are solely derived on process-based model results for the four different RCPs, and cover only the "likely range" of variability for each RCP, which covers the middle 66% spread (17th and 83rd percentile range) of model results for the particular RCP (Church et al., 2013b).[9]

Headline projections by IPCC in the AR5 are summarised in the IPCC 'Summary for Policymakers' from Working Group I (IPCC, 2013) and Synthesis Report (IPCC, 2014a).

The range of global-average sea-level rise projections derived by IPCC, based on process-based models, is shown in Figure 6-12, covering the likely ranges for the lowest and highest RCP2.6 and RCP8.5 scenarios up to 2100, and all four RCPs for the averaging period 2081–2100 towards the end of this century.

The zero baseline for these projections is the averaging period for MSL from 1986–2005 (same as for Figure 6-8).

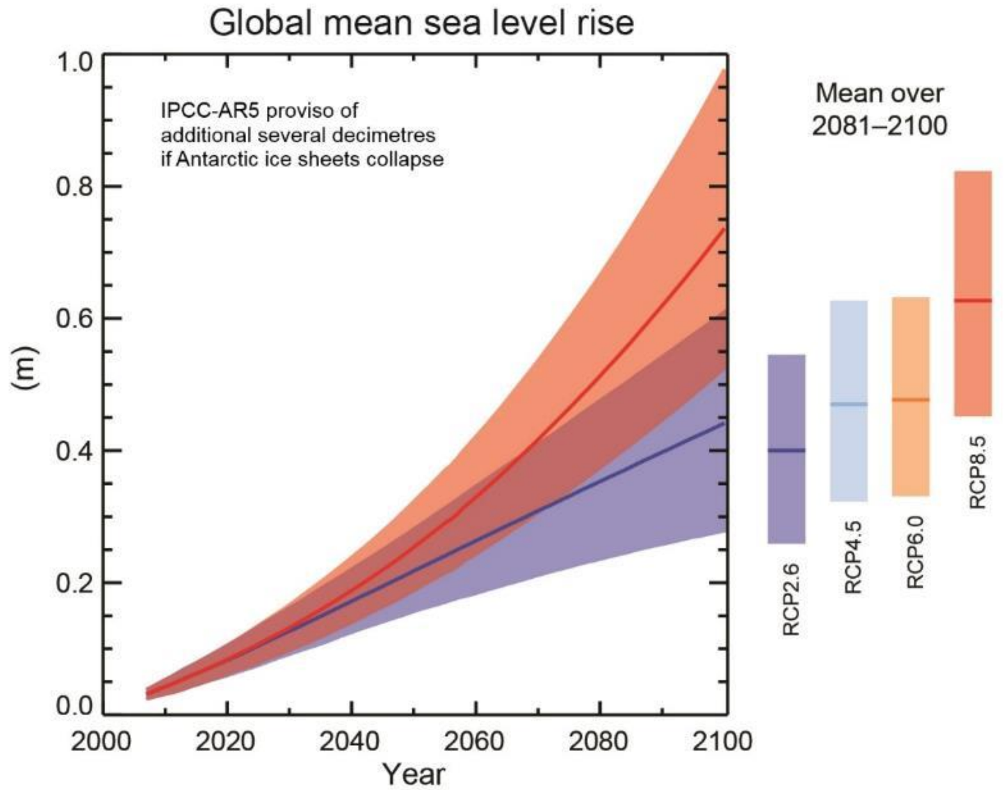

Figure 6-12: IPCC AR5 projections of global-average MSL rise (metres, relative to a base MSL of 1986-2005) covering the range of scenarios from RCP2.6 to RCP8.5. The heavy line shows the median estimate for that RCP, while the shaded area covers the "likely range" projections for the RCP, with a 33% chance SLR could be outside that range. The bars on the right show the median and "likely range" for all four RCPs averaged over the last two decades of this century (2081–2100), hence are lower than projections ending at 2100 in the main plot. (Source: IPCC (2013)).

Key statements on sea-level rise in the IPCC AR5 (using the calibrated language for uncertainty and confidence in italics), include (Church et al., 2013a):

- Global mean sea-level rise will continue during the 21st century, *very likely* at a faster rate than observed from 1971 to 2010.

[9] That means there is a 33% chance that SLR could lie outside the "likely range" (up or down) for that RCP.

- By 2100, sea-level rise will *likely* (i.e. 66% chance) be in the range 0.28–0.61 m [RCP2.6], 0.36–0.71 m [RCP4.5], 0.38–0.73 m [RCP6.0] and 0.52–0.98 m [RCP8.5].
- Onset of the collapse of the Antarctic ice sheets could cause global MSL to rise substantially above the *likely* range (Figure 6-12) during this century. While the contribution cannot be precisely quantified, there is *medium confidence* that it would not exceed several tenths of a metre[10] of sea-level rise by 2100.
- It is *virtually certain* that global mean sea-level rise will continue for many centuries beyond 2100, with the amount of rise dependent on future emissions.
- The threshold for the loss of the Greenland ice sheet over a millennium or more, and an associated sea-level rise of up to 7 metres, is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) of global warming with respect to pre-industrial temperatures.

Abrupt and irreversible ice loss from the Antarctic ice sheet is possible, with some models suggesting that some ice shelves in parts of West Antarctica could be lost before 2100 under RCP8.5 (DeConto and Pollard, 2016).

6.3.4 Climate change impacts on other coastal hazard drivers

While it is expected that the intensity of tropical cyclones and extratropical cyclones will increase (i.e. wind speed and rain rates), it is likely that their frequency will either decrease or remain essentially unchanged (IPCC, 2013). These storms affect the coastal zone through impacts on waves, storm surge, and swell.

Some high-resolution atmospheric models in the IPCC Fifth Assessment Report have realistically simulated tracks and counts of tropical cyclones and models are able to capture the general characteristics of storm tracks and extratropical cyclones with evidence of improvement since the IPCC Fourth Assessment Report. However, uncertainties in projections of cyclone frequency and tracks make it difficult to project how future changes will impact particular regions.

In addition, the projections of storm surges (increase in sea level caused by the inverse barometer effect from large storms such as tropical cyclones) have low confidence, in part due to the high uncertainty surrounding future storminess. Changes in storm surge will depend on changes in the frequency, intensity, and/or tracking of low-pressure systems, and the occurrence of stronger winds associated with these systems (IPCC, 2013). Expected changes in wind and atmospheric patterns, storms and cyclones around New Zealand and the wider southwest Pacific and Southern Ocean regions also have the potential to change the wave climate experienced around New Zealand in the future. In turn, this will influence patterns or coastal erosion and the movements of beach and nearshore sediments within coastal zones.

At a large scale, it is likely that the mean significant wave heights will increase in the Southern Ocean as a result of enhanced westerly wind speeds, especially in the austral winter months (5-10% higher at the end of the 21st century than the present-day mean). In addition, Southern Ocean-generated swells are likely to affect heights, periods, and directions of waves in adjacent basins (IPCC, 2013).

[10] Or decimetre (one-tenth of a metre).

A report published in 2012 for Greater Wellington Regional Council (Lane et al., 2012) assesses total storm inundation along the Wellington Region's shoreline from storm-tide (a combination of high tide plus storm surge) and wave setup inside the wave breaking zone. The assessment was based on modelling the combined effects of storm-tides and waves for selected storm events with a joint annual exceedance probability (AEP) of 1%. Inundation by storm-tides was modelled for present day sea levels, and for sea-level rise increments of 0.5 m, 1.0 m and 1.5 m. The model simulations showed that the coastline south and east of the Wellington Harbour (particularly the Wairarapa Coast) is exposed to the largest waves, with significant wave heights of over 6 m in places during some of the storm events simulated. In contrast, the Kapiti Coast receives smaller waves with significant wave heights less than 3 m in the storm events analysed. The storm surge contribution is similar to the tidal contribution in parts of the region, with simulated storm surge for the historic events contributing up to 0.33 m in Wellington Harbour and 0.65-0.71 m along the Kapiti Coast. As sea levels rise, total storm inundation levels will threaten low-lying areas of Wellington Central City, potentially large areas of Petone and Seaview, and to a limited extent Evans Bay and smaller areas of the Miramar Peninsula (Figure 6-13). Along the Kapiti Coast, total storm inundation levels will begin to threaten Otaki beach, low-lying areas of Waikanae, and narrow margins of the Porirua Harbour.

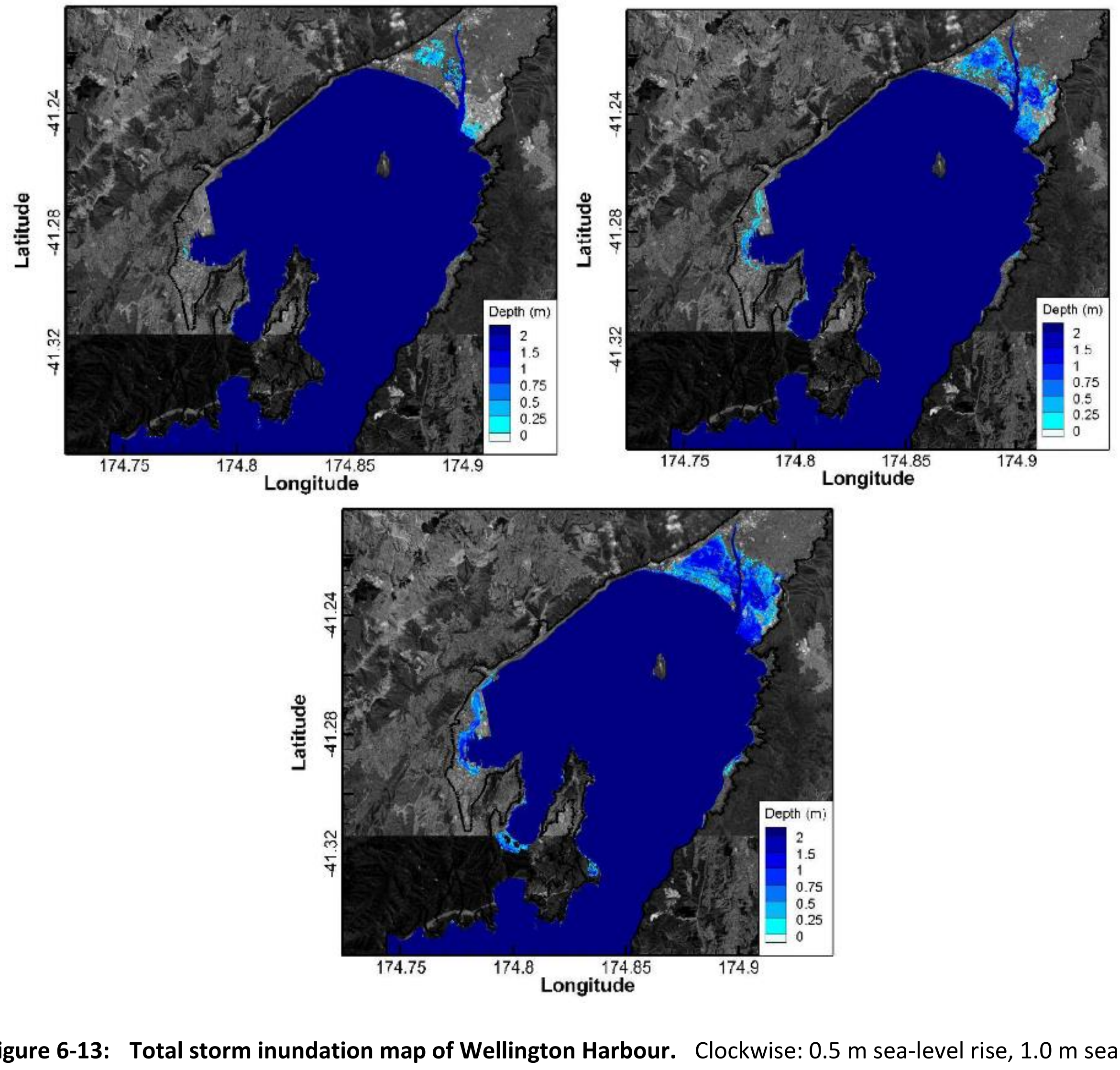

Figure 6-13: Total storm inundation map of Wellington Harbour. Clockwise: 0.5 m sea-level rise, 1.0 m sea-level rise, 1.5 m sea-level rise. Simulations are based on the 17 August 1990 event and represent a 1% AEP joint

probability wave and storm-tide producing the largest coastal water depths. After Lane et al. (2012). Figures showing other parts of the Wellington Region are presented in Lane et al. (2012).

6.3.5 Implications for adaptation

It is important to note that no probability can be assigned to the chance of a particular SLR being reached within a specific planning timeframe e.g. by 2100, or in next 100 years or longer.

Therefore given the uncertainty in SLR, especially into next century and beyond (Kopp et al., 2014), adaptation at the coast to climate change is best undertaken using an adaptive approach.

One such methodology is the dynamic adaptive pathways planning approach which is adopted in the forthcoming guidance manual for local government on coastal hazards and climate change to be published by the Ministry for the Environment in mid-2017. This approach hinges around setting out various inter-connected pathways for responding to climate change, where a decision point or trigger is agreed on collaboratively, when values or objectives would no longer be met for a community e.g. the trigger might be a SLR threshold beyond which increasing inundation damage or frequency of events becomes intolerable for the community, therefore requiring a pre-agreed switch to another pathway or response option when that threshold is reached. The timing window is related to various SLR scenarios used in the analysis (not just a single number for SLR) and including a higher SLR scenario for “stress testing” various response options to check their operating range and possible shelf-life.

The adaptive approach does rely on regular monitoring of climate-change drivers, updated scientific knowledge, number of damaging events and the effectiveness of the current hazard management strategy to determine if changes are needed to the pathways and decision points – including whether planning needs to be brought forward if SLR is faster than expected, or vice versa, planning is more measured if SLR is slower than anticipated.

Adaptive approaches therefore are able to more efficiently and effectively deal with the deep uncertainty around the rate of rise in sea level (especially the impacts from possible irreversible melting of polar ice sheets) – rather than trying to second-guess the future by using a “most likely” SLR and find that the particular adopted response locks in adaptation that may only be suitable for a narrow range of future sea level rise.

6.4 Biosecurity

6.4.1 Terrestrial biosecurity

Climate change is widely regarded as one of the greatest challenges facing ecological systems in the coming century. As New Zealand (and much of the Wellington Region) has an economy based on very efficient primary production systems, the risk of exotic pests and diseases affecting the primary industries needs to be minimised. Climate change will create new biosecurity challenges by allowing establishment of new exotic pests, 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 taxa 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, frost) and regional winds and currents which in turn may affect the ability of potential invaders to reach New Zealand and establish.

Big headed (*Pheidole megacephla*) and Argentine (*Linepithema humile*) ants are some of the worst invasive pest species in the world, as they have the capacity to wreak havoc on the native arthropod fauna, and they are already present in New Zealand's exotic fauna. Continued warming and drying eastern climates 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). A modelling exercise done for 17 different fruit fly species showed that one of the regions with the greatest potential for increase in fruit fly establishment (in terms of climate suitability) in the late 21st century is the Wairarapa (along with Auckland, Coromandel and East Cape) (Kean et al., 2015).

The arrival of new weeds 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 (Section 4.1.4), a much larger range of weed species will be able to compete with local species (McGlone and Walker, 2011). Some plants that are currently difficult to control in other (warmer) parts of the country may become established in the Wellington Region as the climate warms.

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 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) has 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 'sleeping' 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.

Some examples of sleeper invertebrate pests that are affected by temperature include (after Kean et al. (2015)):

- Migratory locust *Locusta migratoria,* found in grassland in the Wellington Region. 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 precipitate outbreaks will be more common under projected climate change scenarios and include above average summer and autumn temperatures, allowing for additional generations to develop.

The link between climate and infectious disease is complex, as the spread of disease depends on factors including virulence, levels of resistance and adaptation in the affected populations, the transmission rate of the disease, population density, and so on. In fact, habitat degradation and species loss (a potential effect of climate change) may prevent transmission of infectious diseases that depend on other species as intermediate hosts or for vectoring (McGlone and Walker, 2011).

New Zealand and the Wellington Region may come under pressure from novel diseases and vectors as the climate warms. For example, 12 mosquito species were present in New Zealand before human settlement, and four exotic (and potentially disease-spreading) mosquitoes have since established. However, over 30 other mosquito species have been intercepted at national entry ports (Derraik and Slaney, 2007). Some pathogens vectored by ticks (e.g. *Theileria orientalis*) and mosquitoes (e.g. West Nile virus and bovine ephemeral fever virus) are currently restricted in New Zealand due to temperature, but these diseases show explosive outbreak behaviour under favourable conditions (Kean et al., 2015)

The reader is directed to Kean et al. (2015) for more detailed information about the potential effects of climate change on current and potential terrestrial biosecurity pests and diseases in New Zealand.

6.4.2 Aquatic biosecurity

The primary source of entry for aquatic biosecurity risk organisms into New Zealand is and will remain to be through international shipping, whether 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, as a result of climate change, may result in species, including pests and pathogens, not usually seen in New Zealand waters to arrive and establish.

Long-term changes in environmental parameters, such as seawater temperature, may lead to new ecological compatibilities and may alter existing host-pathogen interactions. Such changes could contribute to the emergence of aquatic diseases in new regions (Castinel et al., 2014). A strengthening series of southward-flowing currents down the eastern North Island is likely to distribute warm-temperature species toward Cook Strait and the northern South Island (Willis et al., 2007). The establishment of these species may have negative impacts on wild fisheries and also on aquaculture operations.

As is discussed in Section 6.4.1 for terrestrial biosecurity, 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’.

6.4.3 Masting events

Many New Zealand plants sporadically have years with high seed production, called masts. Beech forests (located in the Tararua and Rimutaka Ranges) have particularly significant masting events. During these mast years, populations of invasive rodents (rats and mice) increase significantly which causes increases in the populations of top predators, particularly stoats. These increases in predator populations results in increased predation of indigenous species, particularly birds and lizards (Barron et al., 2016, McGlone and Walker, 2011).

Masting events are likely to occur if the last summer was warmer than the preceding summer. A 'mega-mast' year occurred in 2014, when 90% of beech forest in New Zealand was affected. Modelling studies show that most masting events are localised and widespread 'mega-masts' occur less frequently (11 'mega-masts' occurred during the past 40 years, but not always in the same areas). Using climate change scenarios to predict future masting events to 2100, it was concluded that mega-masts will continue to occur sporadically and at close to historic levels (Barron et al., 2016).

6.5 Hydrological impacts of climate change (changes to river flows)

This section includes information extracted from work being undertaken by NIWA for the Ministry for Primary Industry (MPI) on hydrological modelling of multi-model climate forecasts for agricultural applications, and climate change impacts on agricultural water resources and flooding.

Freshwater is important to a wide range of ecosystem goods and services of value to the Wellington Region and New Zealand. As a whole, irrigation is consented to abstract about 2% of New Zealand's total freshwater resource and contributes $4.8 billion to New Zealand's real GDP (Collins et al., 2012, NZIER and AgFirst Consultants NZ, 2014). These benefits of freshwater availability (especially to agricultural productivity) are particularly tangible when regions experience severe drought. At the other extreme, floods cause millions of dollars of damage to infrastructure and soils as well as loss of life (Pearson and Henderson, 2004, Insurance Council of New Zealand)[11]. While these freshwater issues pose challenges today, climate change and shifts in the hydrological cycle are likely to exacerbate such impacts in the future (Collins et al., 2012, IPCC, 2014a).

Previous climate change hydrological assessments based on the IPCC Fourth Assessment Report (IPCC, 2007) estimated that projected hydrological changes include reductions in snow cover (Hendrikx et al., 2012), shrinking glaciers (Anderson et al., 2010), shifts in mean river flow as well as their seasonal timing (Collins, 2016, Zammit and Woods, 2011), accentuated droughts (Clark et al., 2011) and floods (McMillan et al., 2010), and reductions in groundwater recharge (Aqualinc, 2008).

We present updated projections (using the median of the six RCM runs for RCP4.5 and RCP8.5) for the Wellington Region of changes to the mean discharge, the mean annual low flow (MALF), and the mean annual flood (MAF). All projected changes are between the present day (represented by the time slice 1986-2005) and two future periods 2036-2056 ('mid-century') and 2086-2099 ('end-century'). Note that the modelled river flows do not take into account other climate-induced hazards such as sea level rise and storm surge.

A study has recently been completed for Greater Wellington Regional Council by NIWA concerning climate change-related inflow projections for the groundwater management zone of the Ruamahanga Catchment. The reader is directed to Zammit and Yang (2016) for more information.

6.5.1 Mean discharge

Median changes (of the six RCM model runs) in the mean discharge are presented in Figure 6-14. Mean discharge exhibits a sub-regional patchwork of increases and decreases, depending on the RCP and projection period. For most of the Wellington Region there are decreases in mean discharge projected by mid-century under RCP4.5 for the centre and east of the region (0-20% decrease), and

[11] http://www.icnz.org.nz/statistics-data/cost-of-disaster-events-in-new-zealand/

increases in mean discharge for the inland northwest, as well as the west, south, and southeast coasts (0-20% increase).

This pattern is similar under RCP8.5 at mid-century (except there are decreases in discharge for the south coast for RCP8.5, 0-20%). By the end of the century, most of the region is projecting increases in mean discharge under RCP4.5 (0-20%), except for the northeast quarter of the region, as well as eastern Palliser Bay, which projects decreases in mean discharge (0-20%). Under RCP8.5 at end-century, most of the region experiences decreases in mean discharge up to 20% except for the west coast rivers which experience increases in mean discharge of up to 20%.

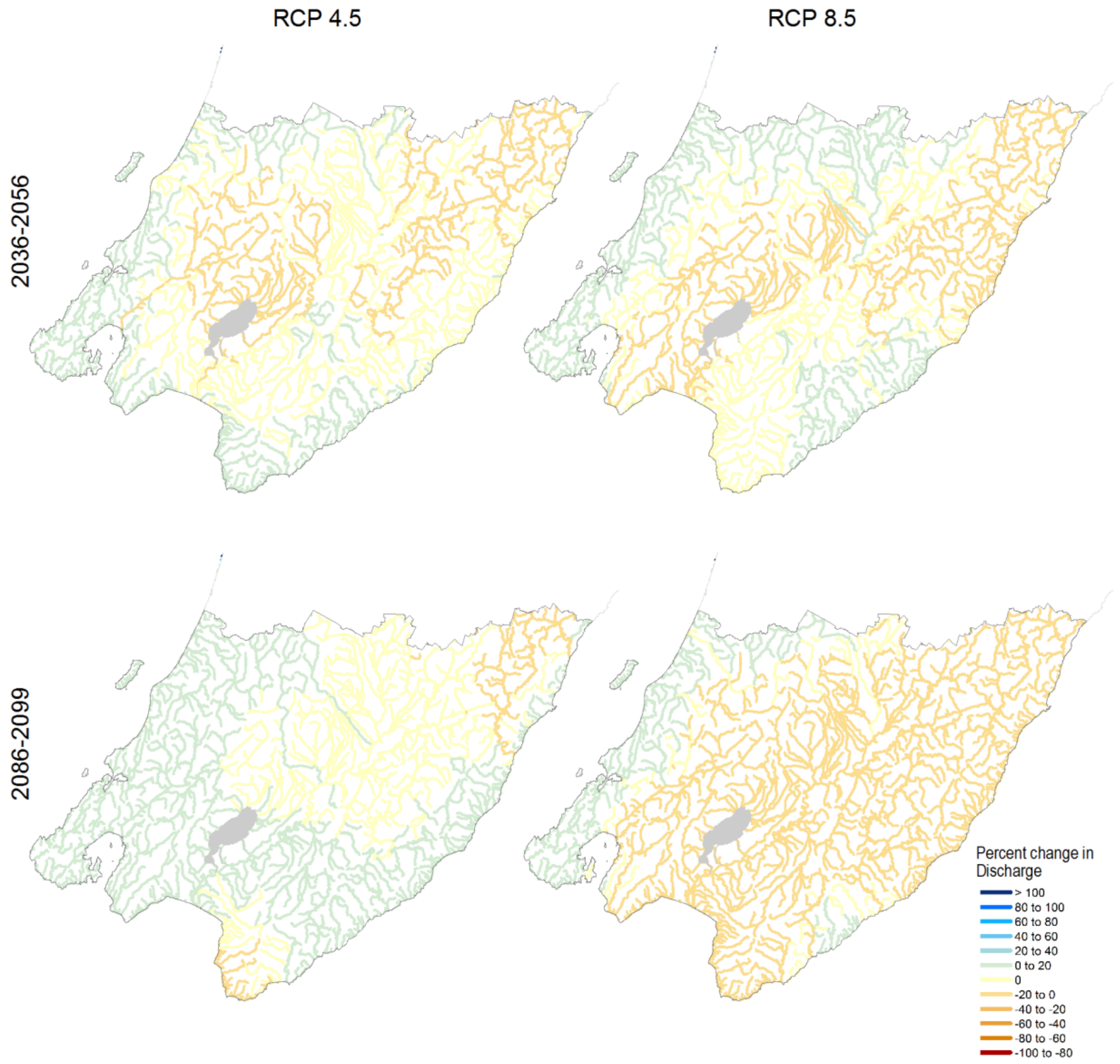

Figure 6-14: Multi-model median changes in mean discharge (%).

6.5.2 Mean annual low flow (MALF)

The mean annual low flow is defined as the mean of the lowest 7-day average flows in each year of a projection period. Median changes in the MALF are presented in Figure 6-15. Changes exhibit a different spatial pattern than the change in mean discharge, indicating a change in the frequency distribution of different flows at each river reach. Across all time slices and emissions scenarios, MALF decreases across the whole Wellington Region, with some small exceptions (Kapiti Island and a few rivers on the west coast show small increases in MALF). The most extreme decreases are projected for the eastern half of the region (up to 60% decrease in some areas), and MALF decreases more with time and increasing emissions for eastern parts of the region.

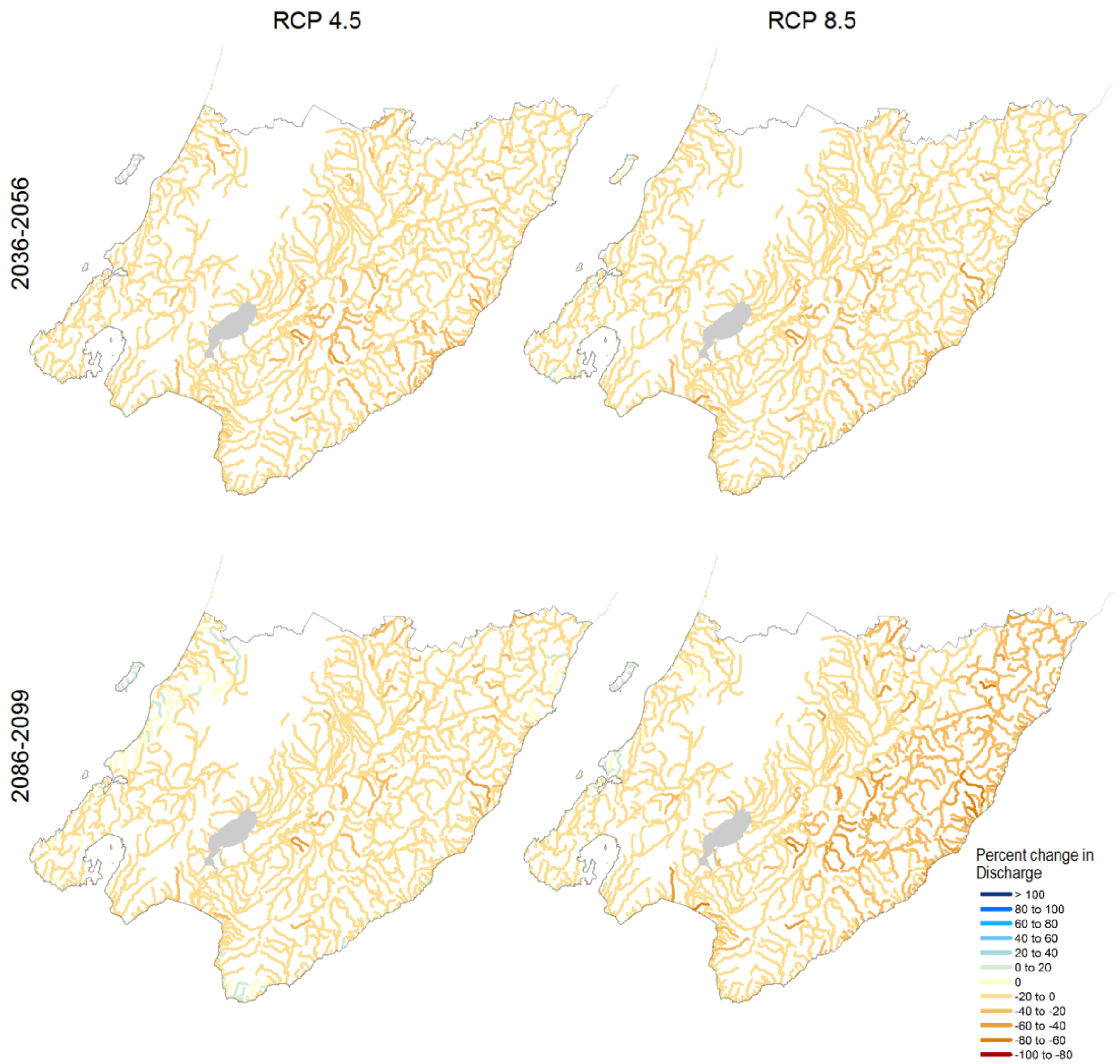

Figure 6-15: Multi-model median changes in mean annual low flow, MALF (%).

6.5.3 Mean annual flood (MAF)

The mean annual flood is the average of the maximum flood discharges experienced in a particular river over a time period, which should have a recurrence interval of once every 2.33 years. Median changes in the mean annual flood (MAF) are presented in Figure 6-16. For most of the Wellington Region outside the Tararua and Rimutaka Ranges, MAF increases at both time slices under both emissions scenarios. At mid-century, under RCP4.5 the largest increases are for the area to the west of Wellington City (up to 60% increase) and decreases are projected for much of the northern part of the region (up to 20% decrease), and for RCP8.5 most of the region experiences increases in MAF (mostly up to 20% increase, but some areas up to 40% increase). By the end of the century, higher MAF is expected for most of the region, particularly for the southeast (east of Lake Wairarapa) (up to 60% increase) under RCP4.5 and the west and east coasts under RCP8.5. Some changes in MAF are projected to be large (>100% increase) under RCP 8.5 by end-century, particularly to the west of Wellington City and along the Kapiti Coast.

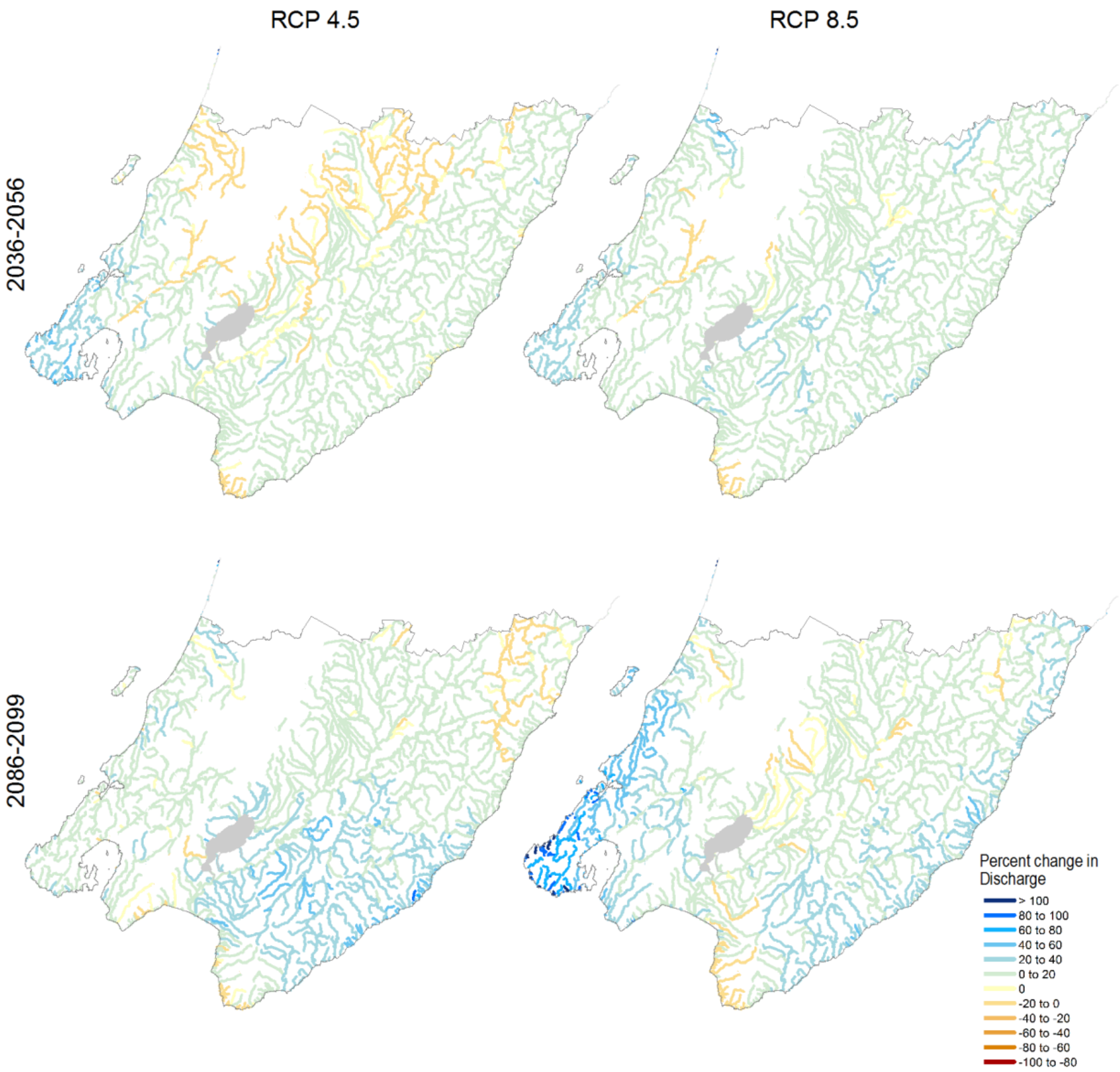

Figure 6-16: Multi-model median changes in mean annual flood, MAF (%).

6.5.4 Uncertainty in hydrological projections

It is important to note that there is high uncertainty in flood projections, and in river flow projections in general. Although the median results shown in the maps above may indicate large increases or decreases in flow statistics (calculated as the average across the 20-year time slice considered), the range of model results (within the ensemble) is large. This is partly due to New Zealand's natural climatic (and therefore flow) variability which the climate change signal is superimposed upon.

Regarding future flood events, modelling these is very complex and an on-going area of research investigation.

There is no direct relationship between increases in extreme rainfall (e.g. 99th percentile daily rain increases throughout the Wellington Region in the 21st century, see Section 4.2.6) and future flood magnitudes. River flows and flood events are very sensitive to not only changes in rainfall and heavy rainfall amounts, but also to where the rain falls in the catchment, what the antecedent conditions (e.g. soil moisture, vegetation cover) are, how the rainfall is temporally distributed over the event, and at what time of year the event occurs. Flood modelling yields results that vary significantly, depending on the climate model, scenario used and time slice considered. This means that for many catchments there is often no clear signal in terms of changes in the frequency and magnitude of future flows and floods characteristics. A further uncertainty here is that the differences in hydrological metrics between the time periods may not be attributable to climate change alone, or even predominantly. Natural variability (e.g., IPO) also has an effect and may dominate climate change effects, but this has not been analysed in this study.

However, while the signal is unclear, the risk of significant change to flood flows is high. Ongoing research and model refinement is needed to reduce this uncertainty. However, given the potentially high risk, users of future flood flow information should take a precautionary and adaptive approach to flood management.

The implications for water resources and hazard management varies with the hydrological changes. In most cases water demand is projected to increase, but the opportunity to abstract water in these areas is generally expected to decline, putting greater pressure on water resource management and agricultural productivity. The flood hazard is projected to remain about the same or increase; in some areas the increases are substantial. Increased flood exposure is projected for areas with minimal increases in water shortage as well as severe increases, potentially compounding the challenges faced by local agricultural activities.

6.5.5 Impacts on hill country erosion

Hill country erosion is a significant issue for higher-elevation parts of the Wellington Region, particularly those areas used for primary industries such as agriculture, horticulture and forestry. Hill country erosion has downstream effects including river sedimentation which can have impacts on flooding magnitude and frequency, water quality, and aquatic habitats. Major erosion events may cause significant economic stress for people and businesses within the Wellington Region.

Basher et al. (2012) studied the impacts of climate change on erosion, using projections from the IPCC's Fourth Assessment Report. They concluded that the main features of climate change that will affect erosion are:

- Changes in rainfall patterns (annual and extremes) (see Section 4.2)
- Increases in temperature affecting plant water use and soil water balance (see Section 4.1 and 4.5)
- Increased windiness and incidence of drought (see Section 4.5 and 4.6)

Climate and erosion are clearly linked through water movement into and through the soil, the soil water balance, and slope hydrology. Projected increases in extreme rainfalls (Section 4.2.6) will play a critical role in determining the effect of climate change. Hillslope erosion processes (e.g. shallow landslides, earthflows, gully, and sheet erosion) are likely to be influenced by climate change.

Shallow rapid landslides are usually triggered by a rainfall event, and as such they are likely to change in frequency with climate change depending on changes to extreme and annual rainfall, rainfall variability, ex- and extra-tropical cyclone variability, and wind.

Gully erosion and sheet erosion is related to high annual and storm rainfalls, so any increase in rainfall with climate change (either of annual totals or extreme events) can be expected to increase these types of erosion. Sheet erosion is also common on areas of bare ground within pasture that is heavily grazed or affected by drought.

Wind erosion is common in areas with loose sediment and depleted vegetation. Wind erosion is likely to change with changes in windiness and soil moisture content (including rainfall).

The Wairarapa coast was identified by Basher et al. (2012) as having high potential for earthflow erosion. Section 4.4.1 shows that the Wairarapa coast is likely to experience increases in extreme daily rainfall which may exacerbate earthflow erosion.

Increases in strong winds for the Wellington region are projected (Section 4.5), which may lead to an increase in the potential for wind erosion in susceptible areas. Coastal sand dunes are particularly susceptible to wind erosion.

6.6 Wildfire

New Zealand's native species evolved under conditions of highly infrequent natural fire, and are generally poorly adapted to survive fire and recover in its wake (Ogden et al., 1998). Fires have a negative effect on biodiversity through encouraging weed spread and reducing the margins of habitat fragments.

Fire risk is projected to increase in the future, due to the following conditions (Pearce et al., 2010):

- Warmer temperatures, stronger winds, lower rainfall and more drought for some areas will exacerbate fire risk
- The fire season will probably be longer through starting earlier and finishing later
- More thunderstorms and lightning will increase ignitions
- Fuel will be easier to ignite (because of drying)
- Drier and windier conditions will result in faster fire spread and greater areas burned
- More severe fire weather and fire danger is likely throughout eastern districts of the Wellington Region.

For Seasonal Severity Rating (SSR)[12], the 16-model average projection shows a 40-50% increase for most of the Wellington Region (except for a ~30% increase on the Kapiti Coast) by the 2040s

[12] 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

compared to the 1980-1999 (Pearce et al., 2010). The number of days of Very High and Extreme (VH+E) forest fire danger is projected to increase by 50-100% for Wellington City and the west coast of the Region, and between 100-150% for the remainder of the Region, for the 2040s compared to the historical period. The historical number of VH+E forest fire danger days for Wellington Airport is 16.8, and this is projected to increase to 32.4 days in the 2040s. The increase for Paraparaumu Airport is projected to be a change from 2.0 days in the historical period to 3.8 days in the 2040s. Similar patterns were observed for the 2090s, with SSR projected to be 40-50% higher than the historical period for the entire Wellington Region, and the number of days of Very High and Extreme forest fire danger to increase to 100-150% higher than present for the whole region. The number of VH+E days for Wellington Airport for the 2090s is projected to increase to 32.7 days and for Paraparaumu the increase is to 4.6 days.

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. (2010) for more information on the projections of Seasonal Severity Rating and Very High and Extreme forest fire danger days in New Zealand.

Afforestation with exotic tree species, one of the most popular climate change mitigation strategies, may increase the fire hazard in the Wellington Region. Exotic tree plantations may lead to a higher risk of wildfire than from pasture or native shrubland or forest (exotic conifer and gum plantations create the equivalent of North American and Australian forests, respectively) (McGlone and Walker, 2011).

6.7 Soil temperature projections and the potential impact on the growing season of pasture

Soil temperature determines seed germination and growth of wild and agricultural plants, and impacts climate through both geophysical and carbon-cycle feedbacks. However, predictions of soil temperature changes have received relatively little attention; the IPCC Fifth Assessment Report does not report soil temperature projections, but focuses instead on surface air temperatures (Phillips et al., 2014, Jungqvist et al., 2014). In addition, many studies on soil temperature are for boreal forests and focus on permafrost melting (Houle et al., 2012, Jungqvist et al., 2014, Zhang et al., 2005), which is less relevant to New Zealand climates.

Soil temperatures are projected to warm in the future, albeit at a slower rate than air temperatures. The relationship between soil temperature and air temperature is complex because changes in vegetation, precipitation, soil moisture, and other climate variables (e.g. solar radiation and humidity) may influence water and energy fluxes on the surface and in the soil, and therefore modulate the relationship between soil and air temperatures (Zhang et al., 2005). As such, the atmospheric warming trend cannot be simply applied to project soil temperature change.

One impact of soil warming is likely to be an acceleration of germination timing, as well as controlling rates of decomposition of soil organic matter and nutrient assimilation by plants (Jungqvist et al., 2014, Houle et al., 2012). Orwin et al. (2015) suggested that warming has variable effects on mycorrhizal fungi, which are relied upon for nutrient uptake by most primary sector plant species. Melillo et al. (2002) found that soil warming increased the availability for mineral nitrogen to plants for a mid-latitude forest (Massachusetts, USA), where soils are typically nitrogen-limited.

Warming has varied impacts on soils, as detailed in Figure 6-17 (Orwin et al., 2015). For pastoral industries, assuming water is not limiting, Figure 6-17b (intensive grazing) shows that warming alone has the most significant impacts on increasing aboveground quantity of pasture biomass, pathogens, denitrification and NH_3 (ammonia) emissions. For extensive grazing, Figure 6-17c shows that warming has the most significant impacts on aboveground quantity and nitrogen mineralisation, with flow-on effects to provisioning services. To summarise, warming may increase pasture biomass aboveground and nitrogen mineralisation (which makes organic nitrogen available to plants in an inorganic form) but also increase pathogens, denitrification (which reduces soil fertility), and ammonia emissions.

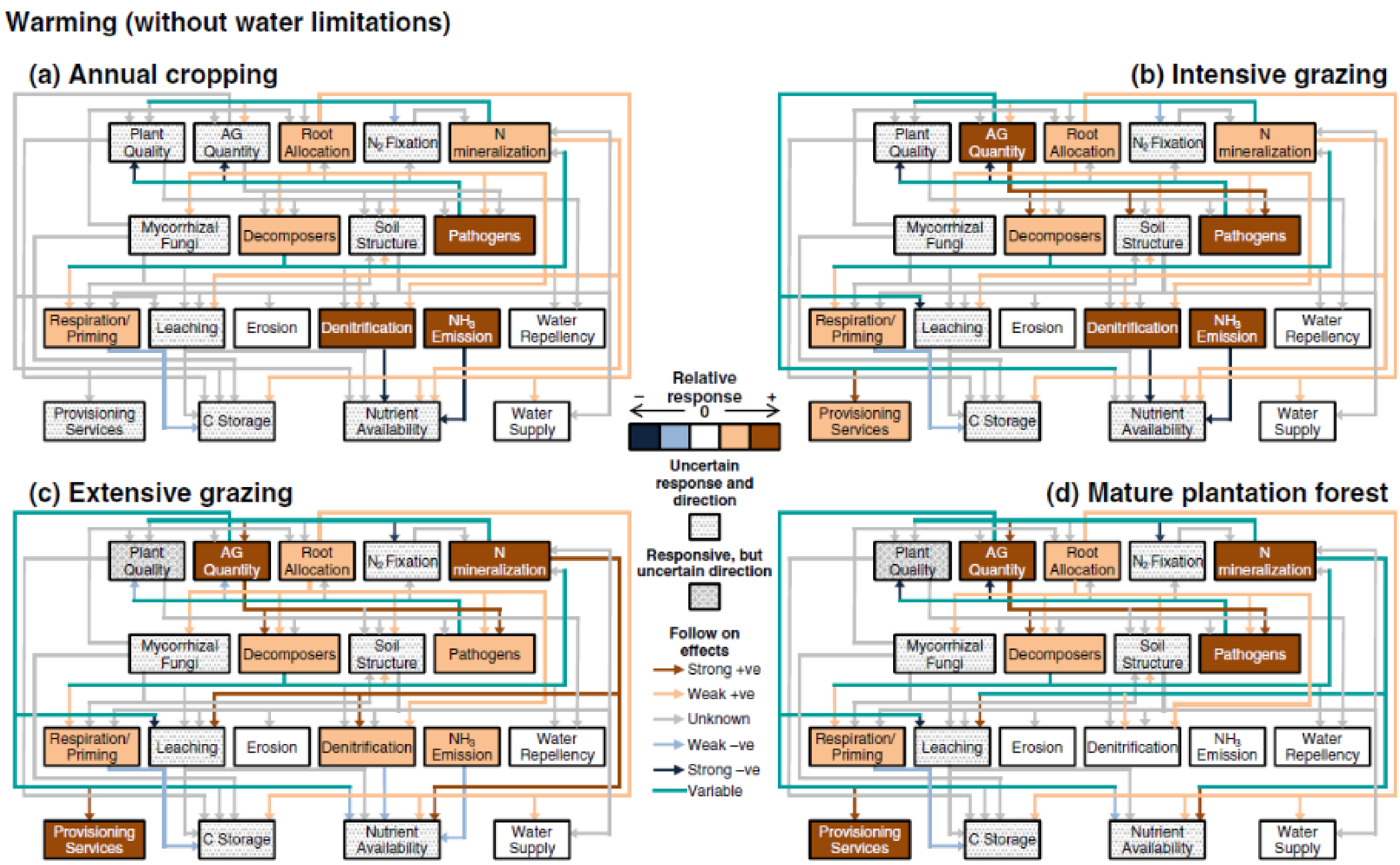

Figure 6-17: Impact of warming alone and assuming that water is not limiting, on soil processes, natural capital and service delivery in four primary sector systems. Colours of boxes indicate the direction of responses of a given variable to warming and its relative importance for that system compared to the others. Arrows indicate the impact of a change in one variable on other variables. AG = aboveground, +ve = positive, -ve = negative. After Orwin et al., 2015).

Clark et al. (2012) summarised climate change impacts on New Zealand's primary production industries, but did not explicitly mention soil temperature. However, some of the impacts of warming air temperatures are also applicable for warming soil temperatures. Generally, optimal plant growth occurs at higher temperatures and under increased concentrations of CO_2, but the strength of these effects depends on the amount of nitrogen available for plants. Changes to temperature are likely to result in increased seasonal grass and crop growth rates during winter and spring, which has flow-on effects to dairy production and calving dates, among other effects. Potential impacts on pasture include shifts in the botanical composition and forage quality on pastures, with increased weediness (Orwin et al., 2015). Higher temperatures favour C4 grasses such as kikuyu, and accelerated pasture development with associated seasonal reduction in dry matter digestibility. Warmer temperatures may also stimulate crop yields, making for faster emergence, canopy development and growth rates during winter, spring, and autumn, when most crops are inhibited by cold temperatures.

7 Considering both anthropogenic and natural changes

Much of the material in Sections 4 to 6 focuses on the projected impact on the climate and oceans of and surrounding the Wellington Region over the coming century of increases in global anthropogenic greenhouse gas concentrations. But natural variations, such as those described in Section 3.3 (associated with for example El Niño, La Niña, the Interdecadal Pacific Oscillation, the Southern Annular Mode, and "climate noise"), will also continue to occur. As noted at the beginning of Section 4, those involved in (or planning for) climate-sensitive activities in the Wellington Region will need to cope with the sum of both anthropogenic change and natural variability.

An example of this for temperature (from an overall New Zealand perspective) is shown in Figure 7-1. This figure shows annual temperature anomalies relative to the 1986-2005 base period used throughout this report. The solid black line on the left-hand side represents NIWA's 7-station temperature anomalies (i.e., the average over Auckland, Masterton, Wellington, Nelson, Hokitika, Lincoln, and Dunedin), and the dashed black line represents the 1909-2014 trend of 0.92°C/century extrapolated to 2100. All the other line plots and shading refer to the air temperature averaged over the region 33-48°S, 160-190°W, and thus encompasses air temperature over the surrounding seas as well as land air temperatures over New Zealand. Post-2014, the two line plots show the annual temperature changes (for the 'box' average) under RCP 8.5 (orange) and RCP 2.6 (blue); a single model (the Japanese '*miroc5*' model, see Mullan et al. 2016) is selected to illustrate the interannual variability. (Note that a single illustrative model (*miroc5*) has been used in Figure 7-1 rather than the model-ensemble, which would suppress most of the interannual variability). The shading shows the range across <u>all</u> AR5 models for both historical (41 models) and future periods (23 for RCP2.6, 41 for RCP8.5).

Over the 1900-2014 historical period, the 7-station curve lies within the 41-model ensemble, in spite of the model temperatures including air temperature over the sea, which is expected to warm somewhat slower than over land (Mullan et al., 2016). For the future 2015-2100 period, the RCP2.6 ensemble shows very little warming trend after about 2030, whereas the RCP8.5 ensemble 'takes off' to be anywhere between +2°C and +5°C by 2100. The *miroc5* model is deliberately chosen to sit in the middle of the ensemble, and illustrates well how interannual variability dominates in individual years: the *miroc5* model under RCP8.5 is the warmest of all models in the year 2036 and the coldest of all models in the year 2059, but nonetheless has a long-term trend that sits approximately in the middle of the ensemble.

Figure 7-1 should not be interpreted as a set of specific predictions for individual years. But it illustrates that although we expect a long term overall upward trend in temperatures (at least for RCP8.5), there will still be some relatively cool years. However 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 emission scenarios) is likely to be warmer than anything we currently experience.

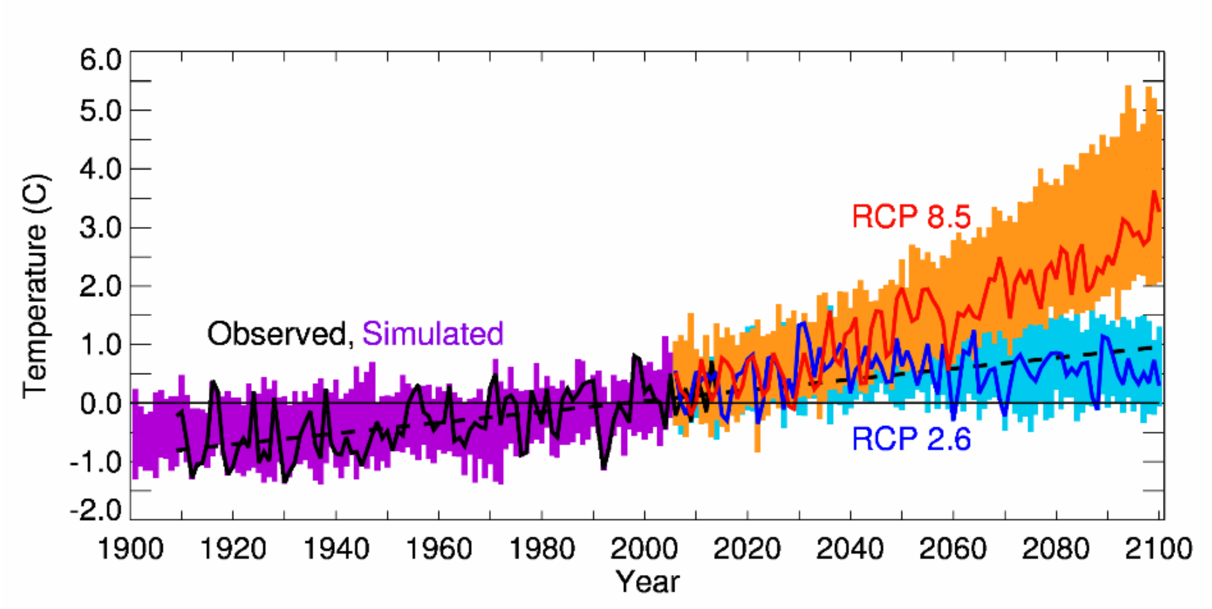

Figure 7-1: New Zealand Temperature - historical record and an illustrative schematic projection illustrating future year-to-year variability. (See text for full explanation). After Mullan et al. (2016).

For rainfall, the fact that we have recently moved into a positive phase of the Interdecadal Pacific Oscillation (Figure 3-21) may depress the impacts of anthropogenic climate change over the next decade or so. From Section 3.3.1, it can be seen that periods of positive SOI (e.g. La Niña) may on average experience slightly above normal rainfall in the Wairarapa during summer, pushing rainfall in the opposite direction as expected from anthropogenic factors (Section 4.2). A subsequent further reversal of the IPO in 20-30 years' time could have the opposite effect, enhancing part of the anthropogenic (drying) trend in rainfall for a few decades.

As discussed in Section 3.3, the IPO and the El Niño/La Niña cycle have an effect on New Zealand sea level. So the sea levels we experience over the coming century will also result from the sum of anthropogenic trend and natural variability.

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

8 Current and future climate change research projects in New Zealand

One major body of work currently being undertaken in New Zealand is the Deep South National Science Challenge (www.deepsouthchallenge.co.nz). The objective of the Deep South Challenge is to understand the role of the Antarctic and Southern Ocean in determining New Zealand's climate and future environment. Working with communities and industry, the challenge will bring together new research approaches to determine the impacts of a changing climate on New Zealand's climate-sensitive economic sectors, infrastructure and natural resources to guide planning and policy. This will be underpinned by improved knowledge and observations of climate processes in the Southern

Ocean and Antarctica, and will include development of a world-class earth systems model to predict New Zealand's climate. The Deep South Challenge first phase projects will run until 2019.

Another large research project being undertaken in New Zealand is the Weather@home project (www.climateprediction.net/weatherathome), run in New Zealand by NIWA in collaboration with the University of Oxford, the UK Met Office, the University of Melbourne and the University of Tasmania. Weather@home works by participants volunteering spare processing power on their computers to run global and regional climate models. This enables the climate models to be run many thousands of times, far more than would be possible with conventional computing resources. The model results can be used for attribution studies, to understand how specific events (e.g. droughts, floods, storms etc.) are changing over time, and the change in likelihood of a particular event due to climate change. Rosier et al. (2016) ran the Weather@home experiment for a significant rainfall event in Northland in 2014, and found that the risk of such events have likely increased due to anthropogenic influences on climate.

The Climate Changes, Impacts and Implications (CCII) project (www.ccii.org.nz) is a 4-year project (2012-2016) designed to address the following question: "What are the predicted climatic conditions and assessed/potential impacts and implications of climate variability and trends on New Zealand and its regional biophysical environment, the economy and society, at projected critical temporal steps up to 2100?" The CCII project will ultimately provide new climate change projections and advancements in understanding their impacts and implications for New Zealand's environment, economy and society.

Mullan et al. (2016) addressed the IPCC AR5 projections for New Zealand's atmospheric climate. Other climate change-related reports are currently in preparation or recently completed by NIWA include:

- Impacts of climate change on river flows for agricultural use, lead author Daniel Collins, to be released by the Ministry for Primary Industries in mid-2017;
- Coastal hazards and climate change: Guidance for local government, lead author Rob Bell, to be released by the Ministry for the Environment in mid-2017;
- Climate change impacts on river flows, driven by the Regional Climate Model precipitation and other changes described by Mullan et al. (2016), lead author Daniel Collins, to be released by the Ministry for the Environment in late 2017;
- Return periods of extreme precipitation, used extensively for engineering applications. The next version of NIWA's High Intensity Rainfall System (HIRDS) is to be released in late 2017;
- Regional climate drivers and their impacts on the Wellington Region, lead author Nava Fedaeff, to be released by Greater Wellington Regional Council in early 2018 (note that this is not a climate change report).
- Our Future Climate New Zealand tool, which can be used to produce New Zealand climate change projection maps and graphs for different variables and climate models. Accessed at www.ofcnz.niwa.co.nz.

- Climate change impacts on inflows to the Ruamahanga groundwater management zone, NIWA report prepared for GWRC in 2016, lead author Christian Zammit (Zammit and Yang, 2016).

9 Conclusions

The climate is changing. It is internationally accepted that further changes will result from increasing amounts of anthropogenically-produced greenhouse gases in the atmosphere. The forcing from anthropogenic greenhouse gas contributions to the global atmosphere is the dominant driver of climate conditions, and will continue to become more dominant in the future if there is no slowdown in production (IPCC, 2013). In addition, the climate will also vary from year to year and decade to decade owing to natural processes such as El Niño. It is unlikely that natural variability will have the same mitigation potential for local climate conditions as it has in the past. Climate change effects over the next decades are predictable with some certainty, and will vary from place to place. This report has addressed those future changes for the Wellington Region, as well as providing information on past changes and temporal variability, and synthesising future impacts of climate change on certain sectors in the region.

Future changes to the Wellington Region's climate are likely to be significant. The climate of the Wairarapa is likely to become more extreme, with a large increase in hot days, increases in drought potential (PED), and declining low river flows. Changes to the western part of the Wellington Region are generally more moderate in terms of temperature, but extreme rainfalls are likely to increase. Sea-level rise will have an impact on much of the region, especially where urban areas and infrastructure are very close to the coast.

Climate change will affect different sectors in the Wellington Region. Changing pest distributions due to changes to temperature will affect the region's biodiversity and primary industries, and increasing risk of drought, particularly in the Wairarapa, will impact the productivity of agriculture and horticulture. River flows are projected to change, with mean and low flows declining in much of the region but some flood flows increasing. This will impact on freshwater biodiversity as well as water use for industry.

Climate change projects such as the Deep South National Science Challenge will continue to research the potential future impacts of climate change on the New Zealand region.

10 Acknowledgements

Sanjay Wadhwa is thanked for providing the hydrological maps. Sara Mikaloff-Fletcher and Graham Rickard are acknowledged for their work on the marine ESM outputs and figures. We acknowledge the useful feedback provided by Greater Wellington Regional Council during the preparation of this report.

11 Glossary of abbreviations and terms

AR5	5th Assessment Report of IPCC – published in 2013/14 covering three Working Group Reports and a Synthesis Report (previous assessment report in 2007 was the AR4)
EEZ	Exclusive Economic Zone – the area of ocean from 12 to 200 nautical miles off New Zealand's coastline, around 4.3 million km^2. This is the zone which New Zealand has sovereign rights regarding the exploration and use of marine resources.
ENSO	El Niño–Southern Oscillation – a 2–5 year climate cycle that affects mainly the Pacific and Indian Oceans
Downscaling	Downscaling is a method that derives local- to regional scale (10 to 100 km) information from larger-scale models or data analyses. Two main methods exist: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the driving model remains an important limitation on the quality of the downscaled information. (IPCC, 2013)
IPCC	Intergovernmental Panel on Climate Change – a scientific and intergovernmental body under the auspices of the United Nations.
IPO	Inter-decadal Pacific Oscillation – a 20–30 year climate cycle that affects the wider Pacific Ocean area, which last change in phase occurring in 1999.
MSL	Mean sea level – the average sea level over periods of months to several years. Baseline MSL for IPCC sea-level rise projections is the average over the period 1986–2005.
RCM	Regional climate model - a numerical climate prediction model run over a limited geographic domain (here around New Zealand), and driven along its lateral atmospheric boundary and oceanic boundary with conditions simulated by a global climate model (GCM). The RCM thus downscales the coarse resolution GCM, accounting for higher resolution topographical data, land-sea contrasts, and surface characteristics.
RCP	Representative concentration pathway – four scenarios of future radiative forcings from greenhouse gases.
SLR	Sea-level rise
SRES	Special Report on Emissions Scenarios (SRES) was published by the IPCC in 2000. The greenhouse gas emissions scenarios described in this report were used in the IPCC Third Assessment Report (2001) and IPCC Fourth Assessment Report (2007).
SST	Sea surface temperature

VCSN	Virtual Climate Station Network - a set of New Zealand climate data based on a 5 km by 5 km grid across the country. Data has been interpolated from ‘real’ climate station records (Tait et al., 2006).

12 Appendix

The purpose of this appendix to the NIWA 2017 climate change report for Greater Wellington Regional Council (GWRC) is to clarify climate change extreme rainfall parameters for long return periods as requested by the Council.

1. Clarify that the 99th percentile of daily rainfall, although referred to as 'extreme' in the report, is **not** extreme in the context of flood protection design, where an average recurrence interval of at least 100 years, or longer, and usually for shorter rainfall duration (less than daily), is required (i.e., AEP of 1% or less).

Question: How is the 99th percentile of daily rainfall defined and what does it mean in relation to other extreme rainfall measures?

Answer:

The 99th percentile of daily rainfall projections shows how the magnitude of the top 1% of daily rainfall events is projected to change in the future under different climate change scenarios. It is calculated by sorting daily rainfall amounts on all 'rain-days' (amounts > 1 mm) in a 20-year period, and identifying the 99th percentile of rain days. Figure 4-37 maps the percentage change in this 99th percentile value between the climatological base period 1986-2005, and a selected future period. The spatial patterns projected for the 99th percentile daily rainfall in Figure 4-37 should not be assumed to be the same for larger, more rare rainfall events.

A simple way to interpret what the 99th percentile of daily rainfall means is as follows: Wellington receives approximately 100 rain days per year. So, the top 1% of rain days would be the wettest day of the year, on average. This is not a particularly 'extreme' measure of rainfall as it has an Annual Exceedance Probability (AEP) of about 100% (i.e. an event of this size happens approximately once per year).

The approximate 24 hour rainfall total for a 1 in 100 year event (AEP 1%) is about 160 mm for both Kelburn and Masterton, according to HIRDS v3.

Projections for more rare, extreme rainfall events, such as those with an average recurrence interval (ARI) of 100 years (AEP 1%) or more are not considered in this report outside of the tables produced using HIRDS v3. Such extreme value analysis was outside the scope of the NIWA 2016 report prepared for Ministry for the Environment, on which the Greater Wellington report was based. Instead, NIWA is carrying out this analysis under an Envirolink 'tools' project to update our High Intensity Rainfall Design System (HIRDS, https://hirds.niwa.co.nz/).

The HIRDS v4 release is expected late in 2017. An updated appendix to this report or separate report on extreme rainfall projections could be provided to GWRC when the HIRDS v4 results are available.

2. Clarify how table 4-7, page 97 of the NIWA report was produced, and stress that the recommended augmentation factors vary depending on the recurrence interval. Emphasise what the recommended augmentation factor most applicable to the 99th percentile of daily rainfall shown in figure 4.37 would be. The table only shows a minimum of 2 year recurrence interval so the recommended factor for 1 year interval is unknown.

Question: How were the augmentation factors in Table 4-7 produced and are they consistent with the 99th percentile rainfall projections (Figure 4-37)?

Answer:

The augmentation factors for how extreme rainfall varies with atmospheric warming in this report were taken from the Ministry for the Environment (2008) climate change guidance manual for local government in New Zealand. The augmentation factors for the shortest duration (10-minutes), and for the longest recurrence interval (100 years), are based on the theoretical increase in the amount of water held in the atmosphere for a 1°C increase in temperature (the Clausius-Clapeyron relation). Factors for longer durations, and more frequent recurrence intervals, were estimated from the limited regional climate model data available at the time. It was noted (MfE, 2008) that the augmentation factors could vary geographically by a large amount, but there was little consistency between models.

Figure 4-37 in the Greater Wellington report shows an average precipitation increase of between 10 and 15% for the 99th percentile daily rainfall for RCP8.5. This is consistent with an augmentation factor of around 4% in Table 4-7, corresponding to an ARI of 1 year and a duration of 24 hours, and a temperature increase by 2090 under RCP8.5 of about 2.5-3.0°C.

HIRDS v4, scheduled for release in late 2017, will make use of a much larger data set of climate model results, including many thousands of simulations from a crowd-computing project (http://www.climateprediction.net/weatherathome/australia-new-zealand-heat-waves/) known as 'ClimatePrediction.net' or 'Weather@Home'. It is expected that HIRDS v4, will explicitly take account of large uncertainty in the augmentation factors, including augmentation factors considerably more than 8% per degree warming. Other recent research (Carey-Smith et al., 2010) also finds that augmentation factors for New Zealand extreme rainfall can be much larger than 8%.

3. Clarify that the words low range (table 4.9), mid-range (table 4.10) and higher-end (table 4.11) in the NIWA report refer to the AR4 guidance that was given in the last MFE report (MFE 2008), and that more accurate information is available, such as the global warming figures from AR5 (global averages) and the temperature maps presented in the NIWA report. Therefore, clarify what a reasonable choice of warming to multiply by the augmentation factor (8%) would be in light of a greater level of warming expected after the AR5.

Question: Why are the temperature increases of 1, 2, and 3°C used in Table 4-9 to 4-11 rather than warming from different emissions scenarios?

Answer:

Any degree of warming can be put into HIRDS v3 to extract depth-duration-frequency tables for a certain location for that amount of warming. In this report, NIWA chose to use 1, 2, and 3°C as examples of how extreme rainfall may change with different degrees of warming. GWRC engineers can do this same exercise in HIRDS v3 with any degree of warming that they prefer for any point in the Wellington Region, depending on which emissions scenario they would like to plan for (http://hirds.niwa.co.nz). Note however that the format of HIRDS may change with the v4 update coming in late 2017.

NIWA recommends that the selected temperature increase reflects the change in the New Zealand region, not the average global warming. The average New Zealand annual temperature increase would be the most appropriate. Northern Hemisphere continents are likely to experience much larger temperature increase than New Zealand, but it is the air reaching New Zealand (and its moisture content) that is relevant for local precipitation extremes.

4. Clarify why the period 1986-2005 was chosen as base reference for the models, and the international standardisation of this period. Offer some guidance as to how to fit this with data sets that have different periods, when choosing the amount of global warming likely to be experienced from present.

Question: Why is 1986-2005 chosen as the historical base period for the climate change projections to be relative to? Why not a more recent period?

Answer:

1986-2005 is the base period used in the IPCC Fifth Assessment Report and as such is considered a standard historical period to use for climate change projections. The Fifth Assessment Report was published in 2013 and the modelled projections used a historical period that ended a few years prior (i.e. 2005). NIWA's 2016 report to the Ministry for the Environment adopted the same base period.

However, a 20-year period is too short to estimate return periods of extreme rainfall, and HIRDS uses longer periods depending on how much data is available. When calculating augmentation factors for future extremes, it is not justified to 'discount' any warming that has already taken place since 2005. After all, the 'current' rainfall depth-duration-frequency statistics (Tables 4-8 and 4-12) do not apply to the year 2016. The current statistics also have large uncertainties, which can be found from the HIRDS tables. Remember that the augmentation factors are essentially 'scenarios' that should be used for sensitivity analyses, as recommended in Chapter 5 of MfE (2008).

5. Clarify if a spatially uniform augmentation factor for flood protection is still the best approach without any further specific studies. Alternatively suggest/recommend how the matter could be explored further (e.g. via a potential full new report to study this issue)

Question: Is a spatially uniform augmentation factor of 8% per degree of warming for flood protection still the best approach? Does the NIWA report recommend it to be changed?

Answer:

HIRDS v4 is due to be released very soon (late 2017), and so NIWA will be able to provide more information once this is released. Preliminary results from HIRDS v4 indicate that a spatially uniform augmentation factor is appropriate for New Zealand, but the augmentation factors presented in HIRDS v4 may differ significantly from those in HIRDS v3. They are likely to have a scenario approach rather than a factor per degree of warming. The Wellington Region does not show much spatial variation in the HIRDS v3 tables of current extreme rainfall (compare Tables 4-8 and 4-12), in spite of the mean annual rainfalls being quite different (Figure 3-4). As mentioned before, the NIWA report did not update the most extreme categories of rainfall analysis, or recommendations, compared to what was already available.

Reference

Carey-Smith, T., Dean, S., Vial, J., & Thompson, C. 2010. Changes in precipitation extremes for New Zealand: climate model predictions. *Weather and Climate*, 30, 23-48.

Appendix prepared by: Petra Pearce, NIWA Climate Scientist, and Brett Mullan, NIWA Principal Scientist – Climate Variability.

Date: 12 October 2017

Signed:

13 References

ANDERSON, B., MACKINTOSH, A., STUMM, D., GEORGE, L., KERR, T., WINTER-BILLINGTON, A. & FITZSIMONS, S. 2010. Climate sensitivity of a high-precipitation glacier in New Zealand. *Journal of Glaciology,* 56**,** 114-128.

AQUALINC 2008. Projected effects of climate change on water supply reliability in mid-Canterbury. Report number C08120/1. Prepared for the Ministry of Agriculture and Forestry, 45p.

BARNES, E. A. & POLVANI, L. 2013. Response of the mid-latitude jets and of their variability to increased greenhouse gases in the CMIP5 models. *Journal of Climate,* 26**,** 7117-7135.

BARRON, M., PECH, R., CHRISTIE, J. E., TAIT, A., BYROM, A. & ELLIOT, G. 2016. Climate change impacts and implications: an integrated assessment in the alpine case study. Synthesis report: RA2 Alpine Case Study. The beech forests of New Zealand. Climate Change Impacts and Implications for New Zealand to 2100. MBIE contract C01X1225. 19p.

BASHER, L., ELLIOTT, S., HUGHES, A., TAIT, A., PAGE, M., ROSSER, B., MCIVOR, I., DOUGLAS, G. & JONES, H. 2012. Impacts of climate change on erosion and erosion control methods - A critical review. MPI Technical Paper No: 2012/45, 216pp.

BATES, N. R., ASTOR, Y. M., CHURCH, M. J., CURRIE, K., DORE, J. E., GONZALEZ-DAVILA, M., LORENZONI, L., MULLER-KARGER, F., OLAFSSON, J. & SANTANA-CASLANO, J. M. 2014. A time-series view of changing ocean chemistry due to ocean uptake of anthropogenic CO2 and ocean acidification. *Oceanography,* 27**,** 126-141.

BEAVAN, R. J. & LITCHFIELD, N. J. 2012. Vertical land movement around the New Zealand coastline: implications for sea-level rise. GNS Science report, retrieved from www.kapiticoast.govt.nz/contentassets/a933446e8c094de8a946d20b9f36a1de/vertical-land-movement-around-the-nz-coastline.pdf.

BECKEN, S., HENDRICKX, J. & ZAMMIT, C. 2014. Developing climate change maps for Tourism: Essential Information or Awareness raising? *Journal of Travel Research,* DOI: 10.1177/0047287514528286.

BELL, R. G. & HANNAH, J. 2012. Sea-level variability and trends: Wellington Region. NIWA Client Report HAM2012-043, 74 pp.

BOPP, L., RESPLANTY, L., ORR, J., DONEY, S., DUNNE, J., GEHLEN, M. & ET AL 2013. Multiple stressors of ocean ecosystems in the 21st Century: Projections with CMIP5 models. *Biogeosciences,* 10**,** 6225-6245.

BOYD, P., LAROCHE, J., GALL, M., FREW, R. & MCKAY, R. M. L. 1999. Role of iron, light and silicate in controlling algal biomass in Subantarctic waters SE of New Zealand. *Journal of Geophysical Research,* 104**,** 13395-13408.

CASTINEL, A., FORREST, B. & HOPKINS, G. 2014. Review of disease risks for New Zealand shellfish aquaculture: perspectives for management. Prepared for Ministry of Business, Innovation and Employment. Cawthron Institute Report No. 2297, 31p.

CHAPPELL, P. R. 2014. The climate and weather of Wellington. NIWA Science and Technology Series: 65, 44 pp.

CHRISTIE, J. E. 2014. Adapting to a changing climate: a proposed framework for the conservation of terrestrial native biodiversity in New Zealand. Department of Conservation, Wellington, 23 p.

CHURCH, J. A., CLARK, P. U., CAZENAVE, A., GREGORY, J. M., JEVREJEVA, S., LEVERMANN, A., MERRIFIELD, M. A., MILNE, G. A., NEREM, R. S., NUNN, P. D., PAYNE, A. J., PFEFFER, W. T., STAMMER, D. & UNNIKRISHNAN, A. S. 2013a. Sea-level rise by 2100. *Science,* 342**,** 1445.

CHURCH, J. A., CLARK, P. U., CAZENAVE, A., GREGORY, J. M., JEVREJEVA, S., LEVERMANN, A., MERRIFIELD, M. A., MILNE, G. A., NEREM, R. S., NUNN, P. D., PAYNE, A. J., PFEFFER, W. T., STAMMER, D. & UNNIKRISHNAN, A. S. 2013b. Sea Level Change. *In:* STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M., ALLEN, S., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. &

MIDGLEY, P. M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

CHURCH, J. A. & WHITE, N. J. 2011. Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics,* 32**,** 585-602.

CLARK, A., MULLAN, B. & PORTEOUS, A. 2011. Scenarios of Regional Drought under Climate Change. Wellington: NIWA Report WLG2010-32 for Ministry of Agriculture and Forestry.

CLARK, A., NOTTAGE, R., WILCOCKS, L., LEE, J. M., BURKE, C., KALAUGHER, E., ROCHE, J., BEUKES, P., LIEFFERING, M., NEWTON, P. C. D., LI, F. Y., VIBART, R., TEIXEIRA, E. I., BROWN, H. E., FLETCHER, A. L., HERNANDEZ-RAMIREZ, G., SOLTANI, A., VILJANEN-ROLLINSON, S., HORROCKS, A., JOHNSTONE, P., CLOTHIER, B., HALL, A., GREEN, S., DUNNINGHAM, A., KIRSCHBAUM, M., MEASON, D., PAYN, T., COLLINS, D., WOODS, R., ROUSE, H. L., DUNCAN, M., SNELDER, T. & COWIE, B. 2012. *Impacts of climate change on land-based sectors and adaptation options. Technical report to the Sustainable Land Management and Climate Change Adaptation Technical Working Group,* Wellington, Ministry for Primary Industries.

CLARK, P. U., SHANKUN, J. D., MARCOTT, S. A., MIX, A. C., EBY, M., KULP, S., LEVERMANN, A., MILNE, G. A., PFISTER, P. L., SANTER, B. D., SCHRAG, D. P., SOLOMON, S., STOCKER, T. F., STRAUSS, B. H., WEAVER, A. J., WINKELMANN, R., ARCHER, D., BARD, E., GOLDNER, A., LAMBECK, K., PIERREHUMBERT, R. T. & PLATTNER, G.-K. 2016. Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change,* 6**,** 360-369.

COAKLEY, S. M., SCHERM, H. & CHAKRABORTY, S. 1999. Climate change and plant disease management. *Annual Review of Phytopathology,* 37**,** 399-426.

COLLINS, D. 2016. Physical changes to New Zealand's freshwater ecosystems under climate change. Freshwater conservation under a changing climate, Wellington.

COLLINS, D., WOODS, R., ROUSE, H. L., DUNCAN, M., SNELDER, R. & COWIE, B. 2012. Chapter 8 Water resources: Water resource impacts and adaptation under climate change. Impacts of Climate Change on land-based sectors and adaptation options. Technical report to the Sustainable Land Management and Climate Change Adaptation Technical Working Group, pp 347-386.

CRUZ, J., PECH, R., SEDDON, P., CLELAND, S., NELSON, D., SANDERS, M. & MALONEY, R. 2013. Species-specific responses by groundnesting Charadriiformes to invasive predators and river flows in the braided Tasman River of New Zealand. *Biological Conservation,* 167**,** 363-370.

DANGENDORF, S., MARCOS, M., MULLER, A., ZORITA, E., RIVA, R., BERK, K. & JENSEN, J. 2015. Detecting anthropogenic footprints in sea level rise. *Nature Communications,* 6.

DANGENDORF, S., RYBSKI, D., MUDERSBACH, C., MULLER, A., KAUFMANN, E., ZORITA, E. & JENSEN, J. 2014. Evidence for long-term memory in sea level. *Geophysical Research Letters,* 41**,** 5530-5537.

DEAN, S., ROSIER, S., CAREY-SMITH, T. & STOTT, P. A. 2013. The role of climate change in the two-day extreme rainfall in Golden Bay, New Zealand, December 2011. *Bulletin of the American Meteorological Society,* 94**,** 561-563.

DEATH, R. 2008. Effects of floods on aquatic invertebrate communities. *In:* LANCASTER, J. & BRIERS, R. A. (eds.) *Aquatic insects: challenges to populations.* UK: CAB International.

DEATH, R., BOWIE, S. & O'DONNELL, C. 2016. Vulnerability of freshwater ecosystems due to climate change. *In:* ROBERTSON, H., BOWIE, S., DEATH, R. & COLLINS, D. (eds.) *Freshwater conservation under a changing climate. Proceedings of a workshop hosted by the Department of Conservation, 10-11 December 2013, Wellington.* Christchurch: Department of Conservation.

DEATH, R., FULLER, I. C. & MACKLIN, M. G. 2015. Resetting the river template: the potential for climate-related extreme floods to transform river geomorphology and ecology. *Freshwater Biology,* 54**,** 2037-2050.

DECONTO, R. M. & POLLARD, D. 2016. Contribution of Antarctica to past and future sea-level rise. *Nature,* 531**,** 591-597.

DERRAIK, J. G. B. & SLANEY, D. 2007. Anthropogenic environmental change, mosquito-borne diseases and human health in New Zealand. *Ecohealth,* 4**,** 72-81.

DIAMOND, H. J., LORREY, A. M., KNAPP, K. R. & LEVINSON, D. H. 2012. Development of an enhanced tropical cyclone tracks database for the southwest Pacific from 1840 to 2010. *International Journal of Climatology,* 32**,** 2240-2250.

DOWDY, A. J., MILLS, G. A., TIMBAL, B. & WANG, Y. 2013. Changes in the risk of extra-tropical cyclones in eastern Australia. *Journal of Climate,* 26**,** 1403-1417.

FRUSHER, S. D., HOBDAY, A. J., JENNINGS, S. M., CREIGHTON, C., D'SILVA, D., HAWARD, M., HOLBROOK, N. J., NURSEY-BRAY, M., PECL, G. T. & VAN PUTTEN, E. I. 2014. The short history of research in a marine climate change hotspot: from anecdote to adaptation in south-east Australia. *Reviews in Fish Biology and Fisheries,* 24**,** 593-611.

GIRONA, J., MATA, M., DEL CAMPO, J., ARBONES, A., BARTA, R. & MARSAL, J. 2006. The use of midday leaf water potential for scheduling deficit irrigation in vineyards. *Irrigation Science,* 24**,** 115-127.

GOODHUE, N. G., ROUSE, H. L., RAMSAY, D., BELL, R. G., HUME, R. M. & HICKS, D. M. 2012. Coastal adaptation to cliamte change: mapping a New Zealand coastal sensitivity index. A report prepared as part of the Coastal Adaptation to Climate Change Project under contract (CO1XO802) to MBIE, NIWA, Hamilton, New Zealand. 43p.

GRIFFITHS, G. M. 2006. Changes in New Zealand daily rainfall extremes. *Weather and Climate,* 27**,** 3-44.

HANNAH, J. & BELL, R. G. 2012. Regional Sea Level Trends in New Zealand. *Journal of Geophysical Research: Oceans,* 117**,** 1-7.

HARE, J. R., HOLMES, K. M., WILSON, J. L. & CREE, A. 2009. Modelling exposure to selected temperature during pregnancy: the limiatations of squamate viviparity in a cool-climate environment. *Biological Journal of the Linnean Society,* 96**,** 541-552.

HENDRIKX, J., HREINSSON, E. O., CLARK, M. P. & MULLAN, A. B. 2012. The potential impact of climate change on seasonal snow in New Zealand: part I - an analysis using 12 GCMs. *Theoretical and Applied Climatology,* 110**,** 607-618.

HEWITT, J., ELLIS, J. I. & THRUSH, S. F. 2016. Multiple stressors, nonlinear effects and the implications of climate change impacts on marine coastal ecosystems. *Global Change Biology,* 22**,** 2665-2675.

HINKEL, J., LINCKE, D., VAFEIDIS, A. T., PERRETTE, M., NICHOLLS, R. J., TOL, R. S. J., MARZEION, B., FETTWEIS, X., IONESCU, C. & LEVERMANN, A. 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences,* 111**,** 3292-3297.

HOEGH-GULDBERG, O., CAI, R., POLOCZANSKA, E. S., BREWER, P. G., SUNDBY, S., HILMI, K., FABRY, V. J. & JUNG, S. 2014. The Ocean. *In:* BARROS, V. R., FIELD, C. B., DOKKEN, D. J., MASTRANDREA, M. D., MACH, K. J., BILIR, T. E., CHATTERJEE, M., EBI, K. L., ESTRADA, Y. O., GENOVA, R. C., GIRMA, B., KISSEL, E. S., LEVY, A. N., MACCRACKEN, S., MASTRANDREA, P. R. & WHITE, L. L. (eds.) *Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

HOULE, D., BOUFFARD, A., DUCHESNE, L., LOGAN, T. & HARVEY, R. 2012. Projections of future soil temperature and water content for three southern Quebec forested sites. *Journal of Climate,* 25**,** 7690-7701.

IPCC 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K. and Reisinger, A. (eds.)],* Geneva, Switzerland, IPCC.

IPCC 2013. Summary for Policymakers. *In:* STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*

Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
IPCC 2014a. *Climate Change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 151p.*
IPCC 2014b. Summary for Policymakers. *In:* EDENHOFER, O., R. PICHS-MADRUGA, Y. SOKONA, E. FARAHANI, S. KADNER, K. SEYBOTH, A. ADLER, I. BAUM, S. BRUNNER, P. EICKEMEIER, B. KRIEMANN, J. SAVOLAINEN, S. SCHLÖMER, C. VON STECHOW, T. ZWICKEL & MINX, J. C. (eds.) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.
IPCC 2014c. Summary for Policymakers. *In:* FIELD, C. B., BARROS, V. R., DOKKEN, D. J., MACH, K. J., MASTRANDREA, M. D., BILIR, T. E., CHATTERJEE, M., EBI, K. L., ESTRADA, Y. O., GENOVA, R. C., GIRMA, B., KISSEL, E. S., LEVY, A. N., MACCRACKEN, S., MASTRANDREA, P. R. & WHITE, L. L. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, NY, USA: Cambridge University Press.
JUNGQVIST, G., ONI, S. K., TEUTSCHBEIN, C. & FUTTER, M. N. 2014. Effect of climate change on soil temperature in Swedish boreal forests. *PLoS ONE,* 9**,** e93957.
KEAN, J. M., BROCKERHOFF, E. G., FOWLER, S. V., GERARD, P. J., LOGAN, D. P., MULLAN, A. B., SOOD, A., TOMPKINS, D. M. & WARD, D. F. 2015. Effects of climate change on current and potential biosecurity pests and diseases in New Zealand. Prepared for Ministry for Primary Industries, MPI Technical Paper No: 2015/25. 100p.
KOPP, R. E., HORTON, R. M., C.M., L., MITROVICA, J. X., OPPENHEIMER, M., RASUMUSSEN, D. J., STRAUSS, B. H. & TEBALDI, C. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future,* 2**,** 383-406.
KOPP, R. E., KEMP, A. C., BITTERMANN, K., HORTON, B. P., DONNELLY, J. P., GEHRELS, W. R., HAY, C. C., MITROVICA, J. X., MORROW, E. D. & RAHMSTOR, S. 2016. Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences,* 113**,** E1434-E1441.
LANE, E., GORMAN, R. G., PLEW, D. & STEPHENS, S. 2012. Assessing the storm inundation hazard for coastal margins around the Wellington region. NIWA Client Report CHC2012-073, 148 pp.
LAW, C. S., RICKARD, G. J., MIKALOFF-FLETCHER, S. E., PINKERTON, M., GORMAN, R. G., BEHRENS, E., CHISWELL, S. M., BOSTOCK, H. C., ANDERSON, O. & CURRIE, K. 2016. The New Zealand EEZ and the South West Pacific. Synthesis Report RA2, Marine Case Study. Climate Changes, Impacts and Implications (CCII) for New Zealand to 2100. MBIE Contract C01X1225. 41pp.
LEAKEY, A. D. B., AINSWORTH, E. A., BERNACCHI, C. J., ROGERS, A., LONG, S. P. & ORT, D. R. 2009. Elevated CO2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany,* 60**,** 2859-2876.
LEVITUS, S., ANTONOV, J. I., BOYER, T. P., BARANOVA, O. K., GARCIA, H. E., LOCARNINI, R. A., MISHONOV, A. V., REAGAN, J. R., SEIDOV, D., YAROSH, E. S. & ZWENG, M. M. 2012. World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010. *Geophysical Research Letters,* 39.
MANNING, M., LAWRENCE, J., KING, D. N. & CHAPMAN, R. 2014. Dealing with changing risks: a New Zealand perspective on climate change adaptation. *Regional Environmental Change,* 15**,** 581-594.
MCGLONE, M. & WALKER, S. 2011. Potential effects of climate change on New Zealand's terrestrial biodiversity and policy recommendations for mitigation, adaptation and research. *Science for Conservation,* 312**,** 1-80.
MCGLONE, M., WALKER, S., HAY, R. & CHRISTIE, J. E. 2010. Climate change, natural systems and their conservation in New Zealand. *In:* NOTTAGE, R., WRATT, D., BORNMAN, J. F. & JONES, K. (eds.)

Climate change adaptation in New Zealand: future scenarios and some sectoral perspectives. Wellington: New Zealand Climate Change Centre.
MCINTOSH, A. R., CROWL, T. A. & TOWNSEND, C. R. 1994. Size-related impacts of introduced brown trout on the distribution of native common river galaxias. *New Zealand Journal of Marine and Freshwater Research,* 28**,** 135-144.
MCINTOSH, A. R., MCHUGH, P. A., DUNN, N. R., GOODMAN, J. M., HOWARD, S. W., JELLYMAN, P. G., O'BRIEN, L. K., NYSTROM, O. & WOODFORD, D. J. 2010. The impact of trout on galaxiid fishes in New Zealand. *New Zealand Journal of Ecology,* 34.
MCMILLAN, H., JACKSON, B. & POYCK, S. 2010. Flood risk under climate change: A framework for assessing the impacts of climate change on river flow and floods, using dynamically-downscaled climate scenarios - A case study for the Uawa (East Cape) and Waihou (Northland) catchments. NIWA client report prepared for Ministry of Agriculture and Forestry, No. CHC2010-033, 63p.
MELILLO, J. M., STEUDLER, P. A., ABER, J. D., NEWKIRK, K., LUX, H., BOWLES, F. P., CATRICALA, C., MAGILL, A., AHRENS, T. & MORRISSEAU, S. 2002. Soil warming and carbon-cycle feedbacks to the climate system. *Science,* 298**,** 2173-2176.
MILLER, S. A., SMITH, G. S., BOLDINGH, H. L. & JOHANSSON, A. 1998. Effects of water stress on fruit quality attributes of kiwifruit. *Annals of Botany,* 81**,** 73-81.
MILLS, J. A., YARRALL, J. W., BRADFORD-GRIEVE, J. M., UDDSTROM, M. J., RENWICK, J. A. & MERILA, J. 2008. The impact of climate fluctuation on food availability and reproductive performance of the planktivorous red-billed gull *Larus novaehollandiae scolpulinus*. *Journal of Animal Ecology,* 77**,** 1129-1142.
MINISTRY FOR THE ENVIRONMENT 2008a. Climate Change Effects and Impacts Assessment. A Guidance Manual for Local Government in New Zealand. *In:* MULLAN, B., WRATT, D., DEAN, S., HOLLIS, M., ALLAN, S., WILLIAMS, T., KENNY, G. & MFE (eds.). Wellington: Ministry for the Environment.
MINISTRY FOR THE ENVIRONMENT 2008b. Coastal hazards and climate change. A guidance manual for local government in New Zealand. 2nd edition. Revised by Ramsay, D. and Bell, R. (NIWA). Prepared for Ministry for the Environment. viii+127 p.
MINISTRY FOR THE ENVIRONMENT 2017. Coastal hazards and climate change: Guidance for local government. Lead authors: Bell, R.; Lawrence, J.; Allan, S.; Blackett, P.; Stephens, S. Ministry for the Environment Publication ME-1292.
MITCHELL, N. J., KEARNEY, M. R., NELSON, N. J. & PORTER, W. P. 2008. Predicting the fate of a living fossil: how will global warming affect sex determination and hatching phenology in tuatara? *Proceedings of the Royal Society B - Biological Sciences,* 275**,** 2185-2193.
MULLAN, A. B., CAREY-SMITH, T., GRIFFITHS, G. M. & SOOD, A. 2011. Scenarios of storminess and regional wind extremes under climate change. NIWA Client Report for Ministry of Agriculture and Forestry, WLG2010-31.
MULLAN, A. B., PORTEOUS, A., WRATT, D. & HOLLIS, M. 2005. Changes in drought risk with climate change. NIWA report WLG2005-23 for Ministry for the Environment and Ministry of Agriculture and Fisheries, Wellington.
MULLAN, A. B., SOOD, A. & STUART, S. 2016. Climate Change Projections for New Zealand based on simulations undertaken for the IPCC 5th Assessment. Part A: Atmosphere Changes. NIWA Client Report for Ministry for the Environment, WLG2015-31. June 2016.
NEW ZEALAND HERALD. 2013. *Plug pulled on tidal turbine projects* [Online]. Available: http://www.nzherald.co.nz/sustainable-business/news/article.cfm?c_id=1503533&objectid=11148072 [Accessed 6 November 2017].
NICHOLLS, R. J., MARINOVA, N., LOWE, J. A., BROWN, S., VELLINGA, P., DE GUSMAO, D., HINKEL, J. & TOL, R. S. J. 2011. Sea-level rise and its possible impacts given a 'beyond 4C world' in the 21st century. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 369**,** 161-181.

NZIER & AGFIRST CONSULTANTS NZ 2014. Value of irrigation in New Zealand: An economy-wide assessment, 55p.

OGDEN, J., BASHER, L. & MCGLONE, M. 1998. Fire, forest regeneration and links with early human habitation: evidence from New Zealand. *Annals of Botany,* 81**,** 687-696.

ORWIN, K. H., STEVENSON, B. A., SMAILL, S. J., KIRSCHBAUM, M., DICKIE, I. A., CLOTHIER, B., GARRETT, L. G., VAN DER WEERDEN, T. J., BEARE, M. H., CURTIN, D., DE KLEIN, C. A. M., DODD, M. B., GENTILE, R., HEDLEY, C., MULLAN, A. B., SHEPHERD, M., WAKELIN, S. A., BELL, N., BOWATTE, S., DAVIS, M. R., DOMINATI, E., O'CALLAGHAN, M., PARFITT, R. L. & THOMAS, S. M. 2015. Effects of climate change on the delivery of soil-mediated ecosystem services within the primary sector in temperate ecosystems: a review and New Zealand case study. *Global Change Biology,* 21**,** 2844-2860.

PARLIAMENTARY COMMISSIONER FOR THE ENVIRONMENT 2015. Preparing New Zealand for rising seas: certainty and uncertainty. Wellington: Parliamentary Commissioner for the Environment. Retrieved from: www.pce.parliament.nz/publications/preparing-new-zealand-for-rising-seas-certainty-and-uncertainty.

PEARCE, H. G., KERR, J., CLARK, A., MULLAN, A. B., ACKERLEY, D., CAREY-SMITH, T. & YANG, E. 2010. Improved estimates of the effect of climate change on NZ fire danger, Prepared for Ministry of Agriculture and Fisheries by Scion and NIWA, Scion Report No. 18087. 83p.

PEARSON, C. & HENDERSON, R. 2004. Floods and low flows. *In:* HARDING, J., MOSLEY, C., PEARSON, C. & SORRELL, B. (eds.) *Freshwaters of New Zealand.* Christchurch: New Zealand Hydrological Society and New Zealand Limnological Society.

PHILLIPS, C. L., TORN, M. S. & KOVEN, C. D. 2014. Response of soil temperature to climate change in the CMIP5 earth system models. *American Geophysical Union Fall Meeting.* San Francisco, USA.

POLOCZANSKA, E. S., BROWN, C. J., SYDEMAN, W. J., KIESSLING, W., SCHOEMAN, D. S., MOORE, P. J., BRANDER, K., BRUNO, J. F., BUCKLEY, L. B., BURROWS, M. T., DUARTE, C. M., HALPERN, B. S., HOLDING, J., KAPPEL, C. V., O'CONNOR, M. I., PANDOLFI, J. M., PARMESAN, C., SCHWING, F. B., THOMPSON, S. A. & RICHARDSON, A. J. 2013. Global imprint of climate change on marine life. *Nature Climate Change,* 3**,** 919-925.

POLOVINIA, J. J., DUNNE, J., WOODWORTH, P. A. & HOWELL, E. A. 2011. Projected expansion of the Subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. *ICES Journal of Marine Science: Journal du Conseil*.

PORTNER, H.-O., KARL, D., BOYD, P., CHEUNG, W., LLUCH-COTA, S. E., NOJIRI, Y., SCHMIDT, D. N. & ZAVIALOV, P. 2014. Ocean systems. *In:* FIELD, C. B., BARROS, V. R., DOKKEN, D. J., MACH, K. J., MASTRANDREA, M. D., BILIR, T. E., CHATTERJEE, M., EBI, K. L., ESTRADA, Y. O., GENOVA, R. C., GIRMA, B., KISSEL, E. S., LEVY, A. N., MACCRACKEN, S., MASTRANDREA, P. R. & WHITE, L. L. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

RAVEN, J., CALDEIRA, K., ELDERFIELD, H., HOEGH-GULDBERG, O., LISS, P., RIEBESELL, U., SHEPHERD, J., TURLEY, C. & WATSON, A. 2005. Ocean acidification due to increasing carbon dioxide. *The Royal Society*.

REISINGER, A., KITCHING, R. L., CHIEW, F., HUGHES, L., NEWTON, P. C. D., SCHUSTER, S. S., TAIT, A. & WHETTON, P. 2014. Australasia. *In:* BARROS, V. R., FIELD, C. B., DOKKEN, D. J., MASTRANDREA, M. D., MACH, K. J., BILIR, T. E., CHATTERJEE, M., EBI, K. L., ESTRADA, Y. O., GENOVA, R. C., GIRMA, B., KISSEL, E. S., LEVY, A. N., MACCRACKEN, S., MASTRANDREA, P. R. & WHITE, L. L. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK, and New York, NY, USA: Cambridge University Press.

RENWICK, J. A. & THOMPSON, D. 2006. The Southern Annular Mode and New Zealand climate. *Water & Atmosphere,* 14**,** 24-25.

RHEIN, M., RINTOUL, S. R., AOKI, S., CAMPOS, E., CHAMBERS, D., FEELY, R. A., GULEV, S., JOHNSON, G. C., JOSEY, S. A., KOSTIANOV, A., MAURITZEN, C., ROEMMICH, D., TALLEY, L. D. & WANG, F. 2013. *Observations: Oceans. Climate Change 2013 - The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge, Cambridge University Press.

RICKARD, G. J., BEHRENS, E. & CHISWELL, S. M. 2016. CMIP5 Earth System Models with Biogeochemistry: An assessment for the southwest Pacific Ocean. *Journal of Geophysical Research (Oceans)***,** 7857-7879, doi: 10.1002/2016JC011736.

RIDGWAY, K. R. 2007. Long term trend and decadal variability of the southward penetration of the East Australian Current. *Geophysical Research Letters,* 34.

ROBERTSON, H., BOWIE, S., DEATH, R. & COLLINS, D. (eds.) 2016. *Freshwater conservation under a changing climate. Proceedings of a workshop hosted by the Department of Conservation, 10-11 December 2013, Wellington. ,* Department of Conservation, Christchurch, 87p.

ROEMMICH, D., GILSON, J., SUTTON, P. J. H. & ZILBERMAN, N. 2016. Multidecadal change of the South Pacific Gyre circulation. *Journal of Physical Oceanography,* 46**,** 1871-1883.

ROSIER, S., DEAN, S., STUART, S., CAREY-SMITH, T., BLACK, M. & MASSEY, N. 2016. Extreme rainfall in early July 2014 in Northland, New Zealand - was there an anthropogenic influence? *Bulletin of the American Meteorological Society,* 96**,** S136-S140.

ROWE, D. K., HICKS, M. & RICHARDSON, J. 2000. Reduced abundance of banded kokopu (Galaxias fasciatus) and other native fish in turbid rivers of the North Island of New Zealand. *New Zealand Journal of Marine and Freshwater Research,* 34**,** 545-556.

ROYAL SOCIETY OF NEW ZEALAND 2016. Climate change implications for New Zealand, http://www.royalsociety.org.nz/expert-advice/papers/yr2016/climate-change-implications-for-new-zealand/, 72p.

SALINGER, M. J., RENWICK, J. A. & MULLAN, A. B. 2001. Interdecadal Pacific Oscillation and South Pacific climate. *International Journal of Climatology,* 21**,** 1705-1721.

SLANGEN, A. B. A., CHURCH, J. A., AGOSTA, C., FETTWEIS, X., MARZEION, B. & RICHTER, K. 2016. Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change,* 6**,** 701-705.

STRAUSS, B. H., KULP, S. & LEVERMANN, A. 2015. Carbon choices determine US cities committed to futures below sea level. *Proceedings of the National Academy of Sciences,* 112**,** 13508-13513.

TAIT, A., HENDERSON, R., TURNER, R. & ZHENG, X. G. 2006. Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. *International Journal of Climatology,* 26**,** 2097-2115.

THOMPSON, D. W. J., SOLOMON, S., KUSHNER, P. J., ENGLAND, M. H., GRISE, K. M. & KAROLY, D. J. 2011. Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geoscience,* 4**,** 741-749.

TURLEY, C., BLACKFORD, J. C., WIDDICOMBE, S., LOWE, D., NIGHTINGALE, P. D. & REES, A. P. 2006. Reviewing the impact of increased atmospheric CO2 on oceanic pH and the marine ecosystem. *Avoiding Dangerous Climate Change,* 8**,** 65-70.

WEATHERDON, L. V., MAGNAN, A. K., ROGERS, A. D., SUMALIA, U. R. & CHEUNG, W. 2016. Observed and projected impacts of climate change on marine fisheries, aquaculture, coastal tourism, and human health: an update. *Frontiers in Marine Science,* 3**,** 48.

WILLIS, T. J., HANDLEY, S. J., CHANG, F. H., LAW, C. S., MORRISEY, D. J., MULLAN, A. B., PINKERTON, M., RODGERS, K. L., SUTTON, P. J. H. & TAIT, A. 2007. Climate change and the New Zealand Marine Environment. NIWA Client Report NEL2007-025 for the Department of Conservation. 76 pp.

WOODWARD, G., PERKINS, D. M. & BROWN, L. E. 2010. Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B-Biological Sciences,* 365**,** 2093-2106.

ZAMMIT, C. & WOODS, R. 2011. Projected climate and river flow for the Waimakariri catchment for 2040s and 2090s. NIWA Client Report: CHCH2011-025, 52p.

ZAMMIT, C. & YANG, J. 2016. Impact of climate change on inflows to the Ruamahanga groundwater management zone, NIWA Client Report for Greater Wellington Regional Council, 2016156CH, 34pp.

ZHANG, Y., CHEN, W., SMITH, S. L., RISEBOROUGH, D. W. & CIHLAR, J. 2005. Soil temperature in Canada during the twentieth century: Complex responses to atmospheric climate change. *Journal of Geophysical Research,* 110**,** D03112.