Auckland Region climate change projections and impacts

Prepared for Auckland Council, Council Controlled Organisations, and District Health Boards

Revised January 2018

Prepared by:
Petra Pearce (Climate Scientist)
Rob Bell (Principal Scientist – Coastal and Estuarine Processes)
Helen Bostock (Marine Geologist)
Trevor Carey-Smith (Climate Scientist)
Daniel Collins (Hydrologist)
Nava Fedaeff (Climate Scientist)
Ayushi Kachhara (Air Quality Technician)
Gregor Macara (Climate Scientist)
Brett Mullan (Principal Scientist – Climate Variability)
Ryan Paulik (Hazards Analyst)
Elizabeth Somervell (Air Quality Scientist)
Abha Sood (Climate Scientist)
Andrew Tait (Principal Scientist – Climate)
Sanjay Wadhwa (GIS Analyst)
John-Mark Woolley (Climate Research Scientist)

For any information regarding this report please contact:

Petra Pearce
Climate Scientist
Weather and Climate Applications
+64-9-375 2052
petra.pearce@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:	2018021AK
Report date:	January 2018
NIWA Project:	ARC17103
Auckland Council Technical report:	TR2017/030-2

ISSN 2230-4525 (Print)
ISSN 2230-4533 (Online)
ISBN 978-1-98-855520-1 (Print)
ISBN 978-1-98-855521-8 (PDF)

This report should be referenced using the following citation:
Pearce, P., Bell, R., Bostock, H., Carey-Smith, T., Collins, D., Fedaeff, N., Kachhara, A., Macara, G., Mullan, B., Paulik, R., Somervell, E., Sood, A., Tait, A., Wadhwa, S., Woolley, J.-M. (2018). Auckland Region climate change projections and impacts. Revised January 2018. Prepared by the National Institute of Water and Atmospheric Research, NIWA, for Auckland Council. Auckland Council Technical Report, TR2017/030-2.

Quality Assurance Statement		
	Internally reviewed by:	Dr Andrew Lorrey Group Manager – Weather & Climate Applications NIWA Auckland
	Externally reviewed by:	Professor James Renwick School of Geography, Environment and Earth Sciences Victoria University of Wellington
	Formatting checked by:	Petra Pearce Climate Scientist – NIWA Auckland
	Approved for release by:	Dr Sam Dean Chief Scientist – Climate, Atmosphere & Hazards NIWA Wellington

Contents

Tables

Figures

Executive summary

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

Auckland Council and Council Controlled Organisations commissioned NIWA to analyse projected climate changes for the Auckland Region and potential impacts of climate change on some of Auckland's environments and sectors. This report addresses expected changes for 21 different climate variables out to 2120, and draws heavily on climate model simulations from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. Potential climate change impacts on important environments and sectors in the Auckland Region are discussed.

Future climate changes are likely to be significant and will impact the entire Auckland Region. Using a mid-range projection, Auckland's temperature is expected to increase by about 0.6°C by 2040 (compared to the late 20th century), 1.2°C by 2090, and 1.4°C by 2110. However, uncertainty about future concentrations of greenhouse gases in the atmosphere, and differences in the way each climate model responds to those concentrations, mean warming projections span a wide range: 0.5-1.2°C by 2040, 0.3-3.3°C by 2090, and 0.4-4.0°C by 2110. Changes to extreme temperatures are likely, with the number of hot days (days > 25°C) in Auckland projected to double by the early 22nd century under a mid-range climate change scenario and more than triple under a business-as-usual scenario. The entire Auckland Region is projected to be frost-free by 2110 under a business-as-usual climate change scenario.

The seasonal distribution of rainfall is projected to change markedly in Auckland. It is likely that spring rainfall will decline and autumn rainfall will increase, but annual total rainfall may not change significantly. Extreme rainfall is likely to increase in the Auckland Region because a warmer atmosphere can hold more moisture. In addition, drought is projected to become more common and more severe in Auckland due to changing rainfall patterns and temperature increases. Winds are projected to decrease in the region. There is also uncertainty about the number and characteristics of ex-tropical cyclones which may affect Auckland.

These changes are likely to have significant impacts on different environments and sectors within the Auckland Region. Rainfall and temperature changes may result in drier soils and changes to river flow (both low flows and floods), as well as an increase in the occurrence of slips. Uptake of increasing atmospheric CO_2 by the oceans is causing ocean acidification, impacting ocean productivity and the development of marine species. Increasing sea surface temperature is likely to encourage non-native marine species to establish and proliferate in Auckland. Sea-level rise will have major impacts on Auckland's coastal communities, infrastructure and habitats. Changes to air quality in response to climate change are likely to impact the health of Aucklanders. Indigenous biodiversity will be affected both directly by climate changes (e.g. drought and increased temperature) and indirectly by pests and habitat loss. Auckland's biodiversity, primary industries and communities may be at risk from future biosecurity issues such as plant and animal pests as well as disease vectors such as mosquitos.

1 Introduction

Auckland Council, Auckland Transport, Panuku Development and Watercare Services commissioned the National Institute of Water and Atmospheric Research (NIWA) to undertake a review of climate change projections for the Auckland Region (Figure 1-1). This work follows the publication of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report in 2013 and 2014, and the New Zealand climate change report published by the Ministry for the Environment in 2016 (Mullan et al., 2016). The contents of this technical report include analysis of climate projections for the Auckland Region in greater detail than the national-scale analysis. Regional-scale climate projection maps have been provided for 21 different climate variables – more than what was included for the national-scale report.

This technical report describes climate changes which may occur over the coming century in the Auckland Region. Consideration about future change incorporates knowledge of both natural variations in the climate and changes that may result from increasing global concentrations of greenhouse gases that are contributed to by human activities. Climatic variables discussed in this report include temperature, rainfall, wind, potential evapotranspiration deficit, soil moisture, storminess, wind, solar radiation, and humidity. Hydrologic variables (average, high and low stream flows and soil moisture) are also discussed, as are oceanic changes and possible changes in sea level. Commentary on climate change impacts and implications for some of Auckland's different environments and sectors are provided, including air quality, wildfire, indigenous biodiversity, and biosecurity. Key messages boxes summarise the main points for each section ahead of the details.

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

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

A short report and video which summarise information from this full technical report are available at http://www.knowledgeauckland.org.nz.

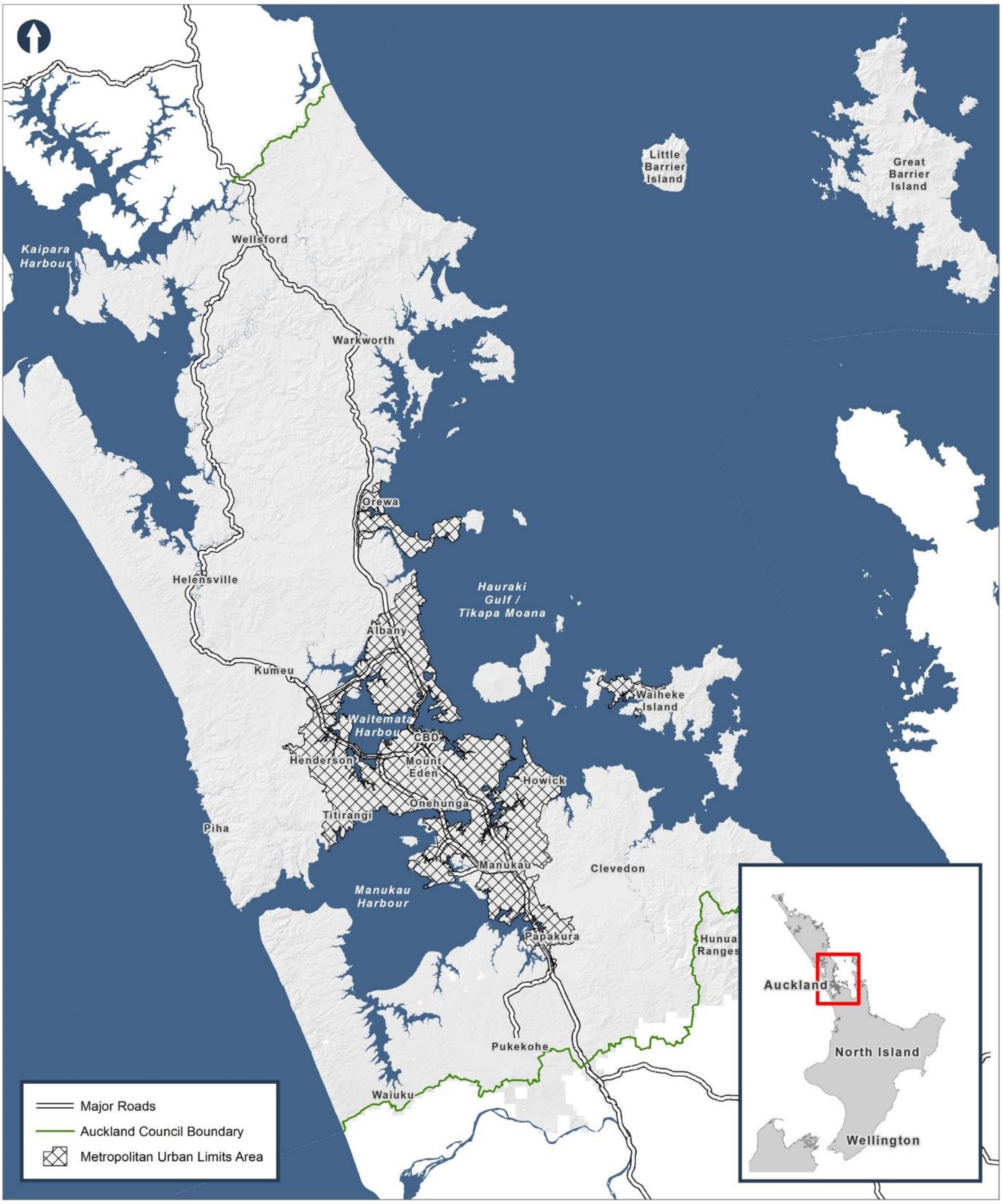

Figure 1-1: The Auckland Region governed by Auckland Council.

1.1 Global climate change

Key messages

- The global climate system is warming and many of the recently observed climate changes are unprecedented.
- Global mean sea level has risen over the past century.
- It is extremely likely human influences on greenhouse gas emissions have been the dominant cause of recent climate change.
- Continued increases in greenhouse gas emissions will cause further warming and impacts on all parts of the global climate system.

This section summarises some key findings from the 2013 and 2014 IPCC Fifth Assessment Reports (AR5) as a context for the information about past and future climate changes for the Auckland Region that follow in this report. Additional information from the IPCC reports is summarised in Appendix I.

Warming of the global climate system is unequivocal, and since the 1950s, many of the observed climate changes are unprecedented over short and long timescales (decades to millennia) (IPCC, 2013a). These changes include warming of the atmosphere and ocean, diminishing of ice and snow, sea-level rise, and increases in the concentration of greenhouse gases in the atmosphere. Climate change is already influencing the intensity and frequency of many extreme weather and climate events globally. Shifts in average temperatures will result in proportionally large increases for extreme temperatures (Figure 1-2). The Earth's atmosphere has warmed by 0.85 (0.65-1.06) °C on average over the period 1880-2012. The rate of sea-level rise since the mid-19th century has been larger than the mean rate of change during the previous two millennia. Over the period 1901-2010, global mean sea level rose by 0.19 (0.17-0.21) m.

The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years (Lüthi et al., 2008). Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions (IPCC, 2013a). The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification. Due to the influence of greenhouse gases on the global climate system, it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century (IPCC, 2013a).

Continued emissions of greenhouse gases will cause further warming and changes in all parts of the climate system, and limiting climate change will require substantial and sustained reductions of greenhouse gas emissions. The most recent set of future climate change scenarios utilised by the IPCC are called Representative Concentration Pathways (RCPs).

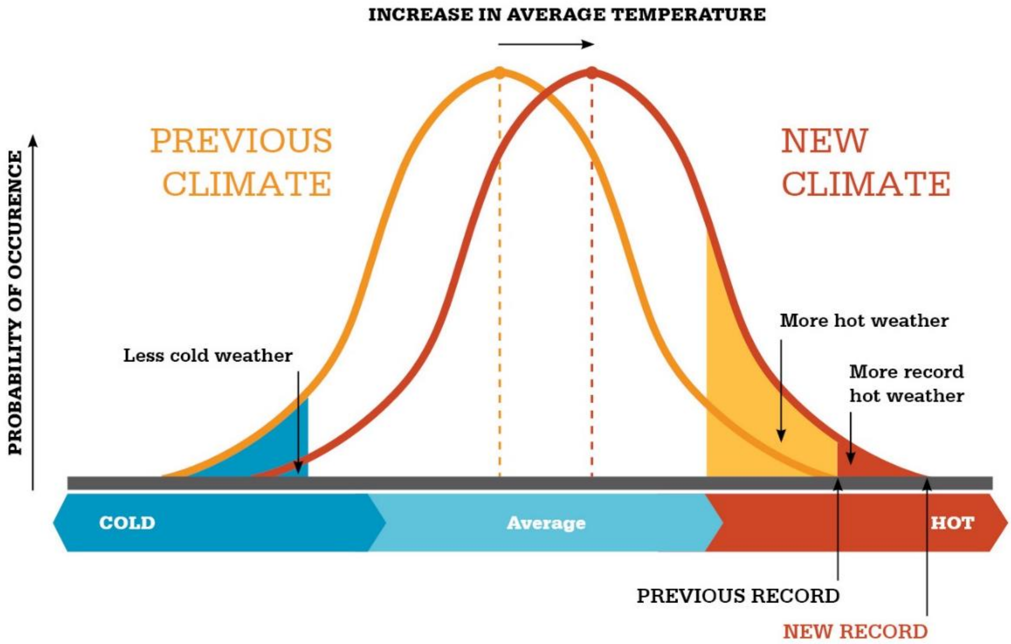

Figure 1-2: Schematic showing how small shifts in average temperature result in large changes in extreme temperatures. From www.climatecommission.gov.au

1.2 Representative Concentration Pathways

Key messages

- Future climate change projections are considered under four emissions scenarios, called Representative Concentration Pathways (RCPs) by the Intergovernmental Panel on Climate Change (IPCC).
- The four RCPs project different climate futures based on future greenhouse gas concentrations, determined by economic, political and social developments during the 21st century.
- RCP2.6 is a mitigation scenario requiring removal of greenhouse gases from the atmosphere, RCP4.5 and RCP6.0 are mid-range scenarios where greenhouse gas concentrations stabilise by 2100, and RCP8.5 is a 'business as usual' scenario with increasing greenhouse gas emissions into the future.
- Projections for Auckland's future climate are presented for RCP4.5 and RCP8.5 in this report.

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

This range of uncertainty has been dealt with by the IPCC through consideration of 'scenarios' that describe concentrations of greenhouse gases in the atmosphere. The wide range of scenarios are associated with possible economic, political, and social developments during the 21st century, and via consideration of results from several different climate models for any given scenario. In the 2013 IPCC Fifth Assessment Report, the atmospheric greenhouse gas concentration component of these scenarios are called Representative Concentrations Pathways (RCPs). These are abbreviated as RCP2.6, RCP4.5, RP6.0, and RCP8.5, in order of increasing radiative forcing by greenhouse gases (i.e. the change in energy in the atmosphere due to greenhouse gas emissions). These pathways are identified by their approximate total (accumulated) radiative forcing at 2100 relative to pre-industrial conditions at 1750 (i.e. RCP2.6 has a total radiative forcing by 2100 of approximately 2.6 W/m^2). RCP2.6 leads to very low anthropogenic greenhouse gas concentrations (requiring removal of CO_2 from the atmosphere, also called the 'mitigation' scenario), RCP4.5 and RCP6.0 are two 'stabilisation' scenarios (where greenhouse gas emissions and therefore radiative forcing stabilises by 2100) and RCP8.5 has very high greenhouse gas concentrations (the 'business as usual' scenario, where radiative forcing is 8.5 W/m^2 at 2100 and increases beyond 2100). Therefore, the RCPs represent a range of 21st century climate policies. Figure 1-3 shows the total global mean radiative forcing for each RCP to 2300 and Figure 1-4 shows the projected global temperature anomaly and CO_2 emissions associated with each RCP into the future.

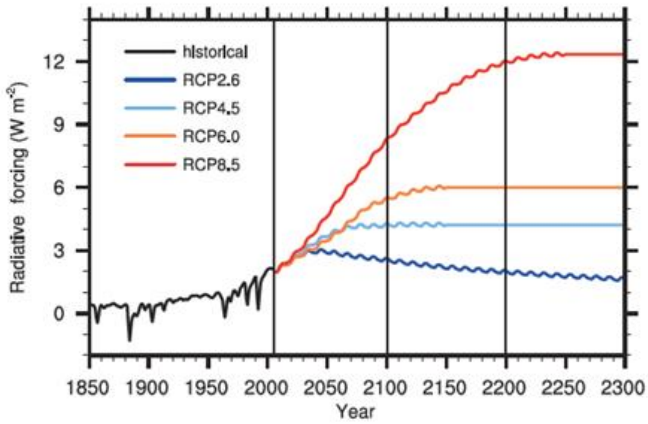

Figure 1-3: Total global mean radiative forcing to 2300 for the four RCP scenarios. From IPCC (2013a).

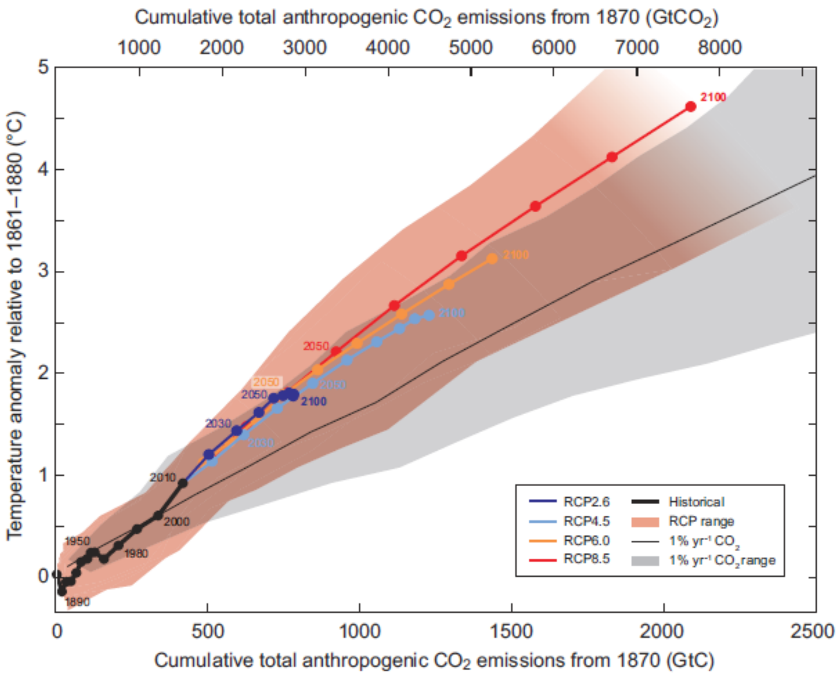

Figure 1-4: Global mean surface temperature increase as a function of cumulative global CO2 emissions from various lines of evidence. Multi-model results from a hierarchy of climate-carbon cycle models for each RCP until 2100 are shown with coloured lines and decadal means (dots). Some decadal means are labelled for clarity (e.g., 2050 indicating the decade 2040−2049). Model results over the historical period (1860 to 2010) are indicated in black. The coloured plume illustrates the multi-model spread over the four RCP scenarios and fades with the decreasing number of available models in RCP8.5. The multi-model means and range simulated by CMIP5[1] models, forced by a CO_2 increase of 1% per year (1% yr^{-1} CO_2 simulations), is given by the thin black line and grey area. For a specific amount of cumulative CO_2 emissions, the 1% per year CO_2 simulations exhibit lower warming than those driven by RCPs, which include additional non-CO_2 forcings. Temperature values are given relative to the 1861−1880 base period, emissions relative to 1870. Decadal averages are connected by straight lines. From IPCC (2013a).

[1] Coupled Model Inter-comparison Project, Phase 5, which involved coordinating and archiving climate model simulations based on shared model inputs by modelling groups from around the world. This project involved many experiments with coupled atmosphere-ocean global climate models, most of which were reported on in the IPCC Fifth Assessment Report, Working Group I. The CMIP5 dataset includes projections using the Representative Concentration Pathways. https://cmip.llnl.gov/cmip5/

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. RCPs are based on a combination of integrated assessment models, simple climate models, atmospheric chemistry and global carbon cycle models. Table 1-1 shows the projected global mean surface air temperature for each RCP.

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

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

The full range of projected globally-averaged temperature increases for all scenarios for 2081-2100 (relative to 1986-2005) is 0.3 to 4.8°C (Figure 1-5**).** Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit inter-annual-to-decadal variability and will not be regionally uniform. As global temperatures increase, it is virtually certain that there will be more hot and fewer cold temperature extremes over most land areas. It is very likely that heat waves will occur with a higher frequency and duration. Furthermore, the contrast in rainfall between wet and dry regions and wet and dry seasons will increase. Along with increases in global mean temperature, mid-latitude and wet tropical regions will experience more intense and more frequent extreme rainfall events by the end of the 21st century. The global ocean will continue to warm during the 21st century, influencing ocean circulation and sea ice extent.

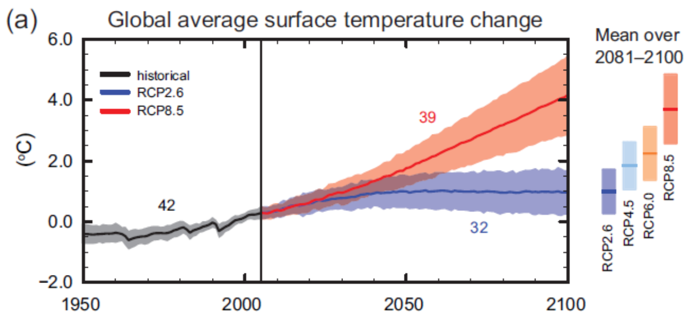

Figure 1-5: CMIP5 multi-model simulated time series from 1950-2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled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

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 continental ice sheets. For all scenarios, the total range of projected sea level rise for 2081-2100 (relative to 1986-2005) is 0.26-0.98m. 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. More information about sea level rise projections is given in Section 8.3.

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

The RCPs presented by the IPCC in the Fifth Assessment Report are different to the SRES emissions scenarios used in the IPCC Fourth Assessment Report (e.g. A1B, A2, etc.) (IPCC, 2013a). Although some of the SRES scenarios involved storylines that embraced sustainability and environmental protection, they did not explicitly incorporate climate change mitigation (i.e. controls on carbon emissions). In contrast, the RCPs from the Fifth Assessment Report consider climate change mitigation policies to limit emissions. To compare the RCPs with the SRES scenarios, RCP4.5 and SRES B1 scenarios are comparable, RCP6.0 lies between the SRES B1 and A1B scenarios, and the RCP8.5 scenario has comparable forcing to SRES A2 by 2100. RCP2.6 is not comparable to any of the SRES scenarios.

In this report, global climate model outputs based on two RCPs (RCP4.5 and RCP8.5) have been downscaled to produce future projections of climate for the Auckland Region. The rationale for choosing these two scenarios was to present a 'business-as-usual' scenario if greenhouse gas emissions continue unabated (RCP8.5) and a scenario which could be realistic if global action is taken towards mitigating climate change (RCP4.5). RCP6.0 was not chosen for the stabilisation scenario as no projections for this RCP are available beyond 2100. Although projections mapped in this report are for the RCP4.5 and RCP8.5 scenarios, GIS data of climate projections for all four RCPs have been provided to Auckland Council where data permitted.

1.3 Downscaling methodology

Key messages

- Climate model simulation data from the IPCC Fifth Assessment has been used to produce climate projections for New Zealand and Auckland.
- Six climate models were chosen by NIWA for dynamical downscaling. These models were chosen because they produced the most accurate results when compared to historical climate and circulation patterns in the New Zealand and southwest Pacific region. They were chosen as they were as varied as possible in the parent global model so they would span the likely range of model sensitivity.
- Downscaled climate change projections are at a 5 km x 5 km resolution over New Zealand.
- Climate projection maps present the average of the six downscaled models.
- Climate projections are presented as a 20-year average for three future periods: 2031-2050 (termed '2040'); 2081-2100 (termed '2090'); and 2101-2120 (termed '2110'). All maps show changes relative to the baseline climate of 1986-2005 (termed '1995').

NIWA has used climate model simulation data from the IPCC Fifth Assessment to update climate change scenarios for New Zealand through both regional climate model (dynamical) and statistical downscaling processes. The dynamical and statistical downscaling processes are described in detail in a 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 in this report, and statistical downscaling results are also presented for mean temperature and rainfall projections.

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

The six GCMs chosen for dynamical downscaling were BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISS-E2-R, HadGEM2-ES and NorESM1-M. These models had simulations that contained hourly precipitation results from 1970 through to 2100. The native resolution of the RCM is 27 km and there are known biases in the precipitation fields derived from this model. These projections (aside from some of the extreme rainfall, relative humidity, wind, and solar radiation projections) have a bias-corrected version applied to these data at 5 km x 5 km resolution with a daily time-step. The 5 km grid corresponds to the Virtual Climate Station Network (VCSN) grid[2]. Figure 1-6 shows a schematic for the dynamical downscaling method used in this report.

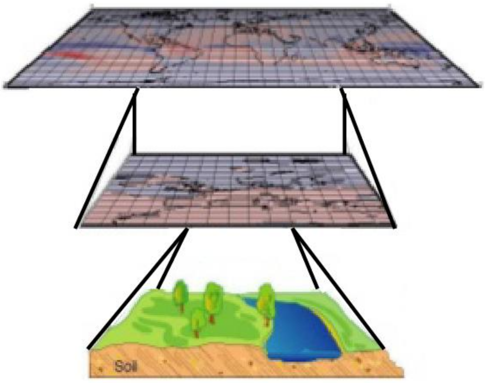

Figure 1-6: Schematic showing dynamical downscaling method used in this report.

Statistical downscaling uses statistical relationships (or sometimes simple interpolation) to relate the large-scale climate simulation outputs (which are gridded) to regional, catchment or local station scales. Several different models are used to simulate future New Zealand climate (six, mentioned above, for dynamical downscaling and up to 41 for statistical downscaling).

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

Climate projections are presented as a 20-year average for three future periods: 2031-2050 (termed '2040'), 2081-2100 (termed '2090') and 2101-2120 (termed '2110'). All maps show changes relative to the baseline climate of 1986-2005 (termed '1995'), as used by IPCC. Hence the projected changes at 2040, 2090 and 2110 should be thought of as 45-year, 95-year, and 115-year projected trends. Note that the projected changes use 20-year averages, which will not entirely remove effects of natural variability.

Downscaled climate projection data is presented as 5 km x 5 km square pixels over the Auckland Region. The projections mapped in this report contain some pixels around the coast of the Auckland Region where no projection data are displayed, resulting in some small gaps in the projection data at the coast (Figure 1-7). Data were downscaled only where low resolution cells in the climate model consisted of land coverage and where they overlapped high resolution cells on land. In most cases, interpolating over mixed sea and land points creates artificial biases, for example lower temperatures, so the data in that cell is removed (i.e. the blue squares inside the land boundary in

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

Figure 1-7). For display purposes in the maps for this report, NIWA has undertaken interpolation to continue the climate projections to the coast. The nearest neighbour interpolation method was used to do this where the empty coastal cell was assigned the value of the nearest neighbouring cell. This method was agreed upon by Auckland Council.

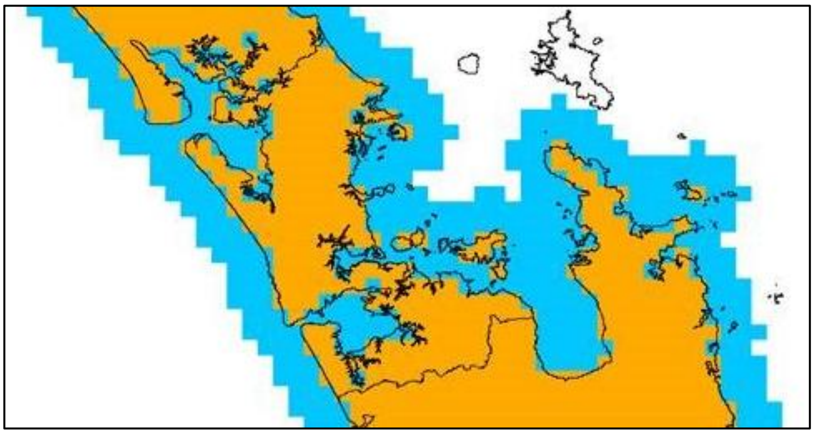

Figure 1-7: Missing land pixels (blue squares inside the land boundary) in the Auckland Region climate projections.

The degree of model agreement has been calculated for most of the climate variables in this report. This was calculated by analysing the direction of change of each individual model (of the six models above) for each RCP, time slice, and season/year. Where 5/6 or 6/6 models agreed on the direction of change, this was determined to have ‘good’ model agreement, and is therefore reported in the appropriate section. Individual model results were not available for the following variables: growing degree-days, rain days, heavy rain days, and windy days as these variables were not generated for the national-scale guidance (Mullan et al., 2016); they have been generated especially for regional reports.

1.4 Natural factors causing fluctuation in climate patterns over New Zealand

Key messages

- Natural variability is an important consideration in addition to the underlying climate change signal.
- El Niño-Southern Oscillation is the most dominant mode of inter-annual climate variability and it impacts Auckland primarily through changing wind, temperature and rainfall patterns.
- The Interdecadal Pacific Oscillation affects Auckland through drier conditions during the positive phase and wetter conditions during the negative phase.
- The Southern Annular Mode affects Auckland through higher temperatures during the positive phase and lower temperatures during the negative phase.
- Natural variability will continue to affect the year-to-year climate of Auckland into the future.

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

1.4.1 The effect of El Niño and La Niña

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

During El Niño, easterly trade winds weaken and warm water 'spills' eastward across the equatorial Pacific, accompanied by higher rainfall than normal in the central-east Pacific. La Niña produces opposite effects, and is typified by an intensification of easterly trade winds, retention of warm ocean waters over the western Pacific. ENSO events occur on average 3 to 7 years apart, typically becoming established in April or May and persisting for about a year thereafter.

During El Niño events, the weakened trade winds cause New Zealand to experience a stronger than normal south-westerly airflow. This generally brings lower seasonal temperatures to the country and drier than normal conditions to the north and east of New Zealand, including Auckland (Salinger and Mullan, 1999) (Figure 1-8). During La Niña conditions, the strengthened trade winds cause New Zealand to experience more north-easterly airflow than normal, higher-than-normal temperatures (especially during summer), and wetter conditions in the north and east of the North Island, including Auckland (Figure 1-8).

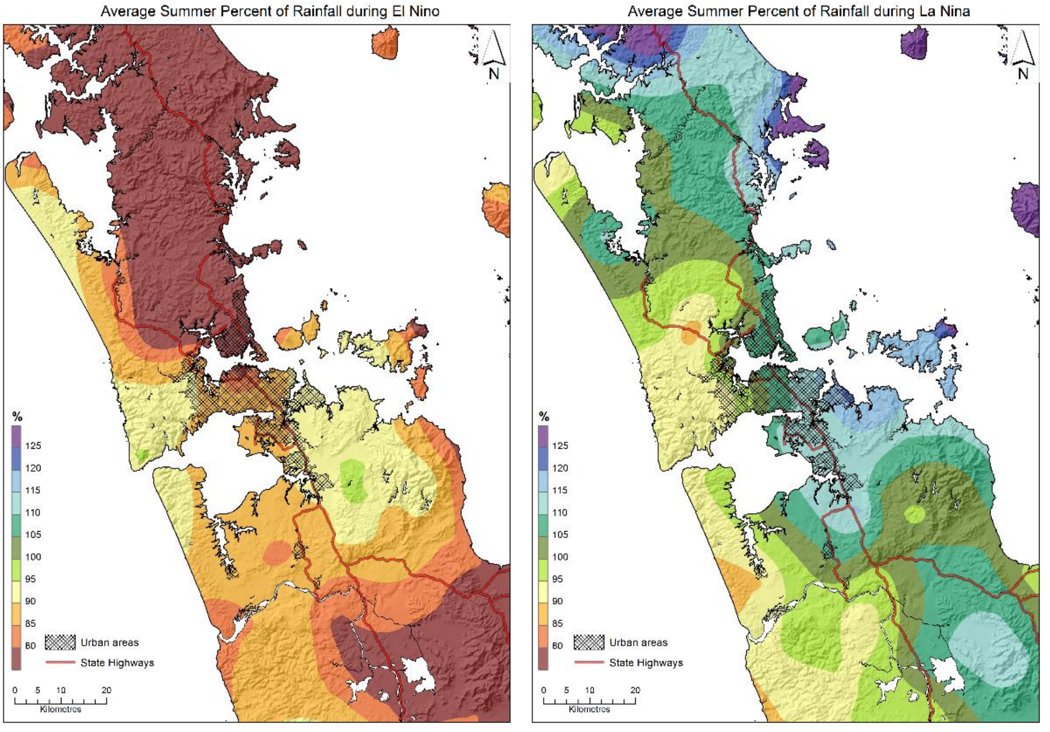

Figure 1-8: Average summer percentage of normal rainfall during El Niño (left) and La Niña (right) in Auckland. El Niño composite uses the following summers: 1963/64, 1965/66, 1968/69, 1969/70, 1972/73, 1976/77, 1977/78, 1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98, 2002/03. La Niña composite uses the following summers: 1964/65, 1970/71, 1973/74, 1975/76, 1983/84, 1984/85, 1988/89, 1995/96, 1998/99, 1999/2000, 2000/01. This figure was last updated in 2005. © NIWA.

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

1.4.2 The effect of the Interdecadal Pacific Oscillation

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

1.4.3 The effect of the Southern Annular Mode

The Southern Annular Mode (SAM) represents the variability of circumpolar atmospheric jets that encircle the Southern Hemisphere that extend out to the latitudes of New Zealand. The SAM is often coupled with ENSO, and both phenomena affect New Zealand's climate in terms of westerly wind strength and storm occurrence (Renwick and Thompson, 2006). In its positive phase, the SAM is associated with relatively light winds and more settled weather over New Zealand, with stronger westerly winds further south towards Antarctica. In the Auckland Region, the positive SAM phase is generally associated with higher than normal daily maximum temperatures. 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 Auckland Region, lower than normal daily maximum temperatures are observed during the negative phase of the SAM.

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

1.4.4 The influence of natural variability on climate change projections

It is important to consider anthropogenic climate change in the context of natural variability. An example of this for temperature (from an overall New Zealand perspective) is shown in Figure 1-9. The solid black line on the left-hand side represents NIWA's 7-station temperature anomalies[3] (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 New Zealand region. Post-2014, the two line plots show the annual temperature changes for the New Zealand region under RCP8.5 (orange) and RCP2.6 (blue); a single model is selected to illustrate the inter-annual variability (note that a single illustrative model (*miroc5*) has been used in Figure 1-9 rather than the model-ensemble, which would suppress most of the inter-annual variability). The shading shows the range across all IPCC AR5 models for both historical and future periods.

Over the 1900-2014 historical period, the 7-station curve lies within the model ensemble (purple shading). For the future 2015-2100 period, the RCP2.6 ensemble (blue shading) shows very little warming trend after about 2030, whereas the RCP8.5 ensemble (orange shading) 'takes off' to be anywhere between +2°C and +5°C by 2100. The *miroc5* model (red line/blue line) is deliberately chosen to sit in the middle of the ensemble, and illustrates well how inter-annual variability dominates in individual years. The *miroc5* model under RCP8.5 (red line) is the warmest of all models in the year 2036 and the coldest of all models in the year 2059, but nonetheless, it has a long-term trend that sits approximately in the middle of the ensemble.

Figure 1-9 should not be interpreted as a set of specific predictions for individual years. However, it illustrates that although we expect a long term overall upward trend in temperatures (at least for RCP8.5), there will still be some relatively cool years. For this 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.

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

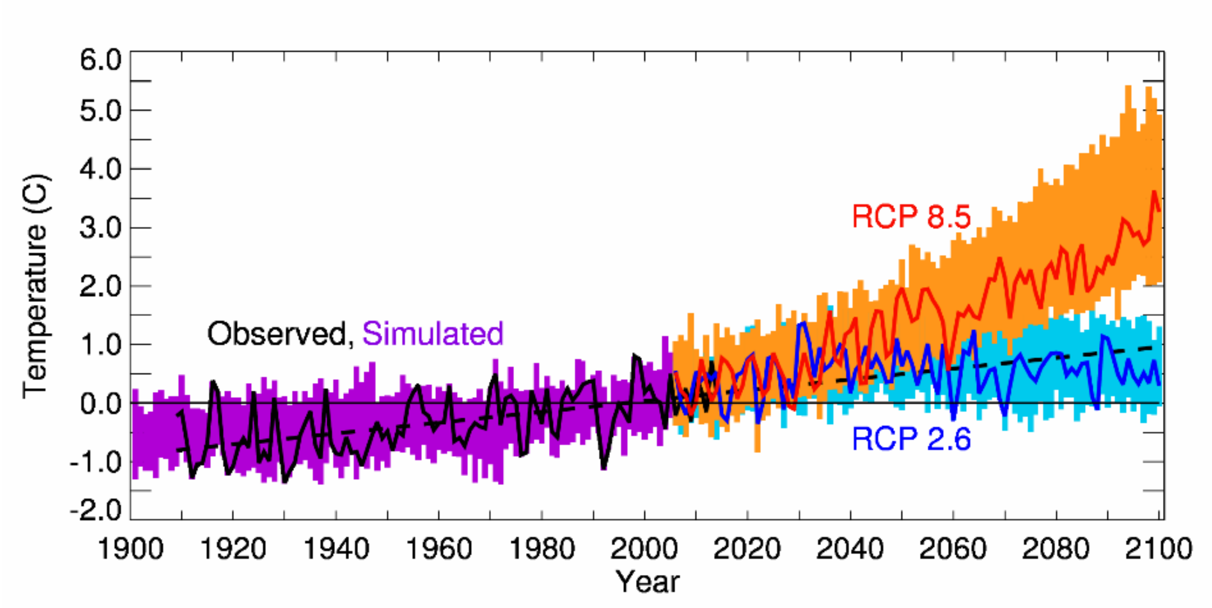

Figure 1-9: New Zealand Temperature - historical record and an illustrative schematic projection illustrating future year-to-year variability. (See text for full explanation). From Mullan et al. (2016).

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

2 Present-day and future climate of the Auckland Region

Auckland experiences a temperate subtropical climate (Chappell, 2013). In general, the climate of the region reflects the general prevailing westerly flow over New Zealand, which includes eastward-moving low pressure (cyclonic) systems interspersed with high pressure (anticyclonic) weather systems. Summers tend to be warm and humid, while winters are relatively mild, and most parts of the region receive only a few frosts each year. Rainfall is typically plentiful all year round, with sporadic very heavy falls. Dry spells may occur during the summer months, but they are usually not long-lived. Most parts of Auckland receive around 2000 hours of bright sunshine per year. Sometimes Auckland experiences extreme events that cause flooding and wind damage, which may be of tropical origin. More detailed information about the present climate of the Auckland Region can be found in Chappell (2013) and Chappell (2014).

The future climate of the Auckland Region will be influenced by a combination of the effects of anthropogenic climate change (increasing global concentrations of greenhouse gases) 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 1.4. The following Sections 3 to 7 outline the present-day climate of Auckland and projected changes due to anthropogenic climate change.

3 Temperature

Key messages

- The Auckland Region is projected to warm considerably into the future.
- Warming is projected under all climate change scenarios, for all climate models, throughout Auckland.
- Most of Auckland is projected to experience over 70 more hot days per year (days > 25°C) by 2110 under RCP8.5 (up from ~20 at present), and 30-40 more hot days per year under RCP4.5.
- The number of cold nights/frosts (< 0°C) is projected to decline everywhere in Auckland.
- The number of growing degree-days is projected to increase throughout the region, which may impact plant growth.

Temperature variables presented include mean temperature, mean maximum and mean minimum temperature, diurnal (daily) temperature range, hot days (maximum temperature >25°C), cold nights/frosts (minimum temperature <0°C), and growing degree-days. For all variables, present-day conditions are summarised and future projections are presented for RCP4.5 and RCP8.5 at 2040, 2090 and 2110.

3.1 Mean temperature

Key messages

- Mean temperature has increased over the 20th and early 21st century in Auckland, and this trend will continue.
- By 2110, mean annual temperature for the Auckland Region is projected to increase by 1.4°C for RCP4.5 and by 3.3°C for RCP8.5.
- Warming is projected for the entire Auckland Region, but less warming is projected for the Waitakere Ranges in general.
- The season with the most warming projected is autumn, and the seasons with the least warming projected are winter and spring.

3.1.1 Present

Temperature varies with elevation, with the lowest median annual average temperatures of the Auckland Region experienced at the highest elevations in the Hunua Ranges and Waitakere Ranges (Figure 3-1). Annual temperatures are highest closer to the east coast, on the Auckland Isthmus, around the Manukau Harbour, and on the Hauraki Gulf islands. There is seasonal variation in median average temperatures but the spatial pattern remains the same as for median annual average temperatures (Figure 3-2). There is significant year-to-year variability in Auckland's temperature. Figure 3-3 shows the average annual temperature for Auckland from 1910 to 2016, with a trend of about 1.6°C increase in annual mean temperature during that time. This trend is statistically significant above the 95% confidence level. There are substantial differences between years, with some having mean temperatures over 2.0°C different to adjacent years.

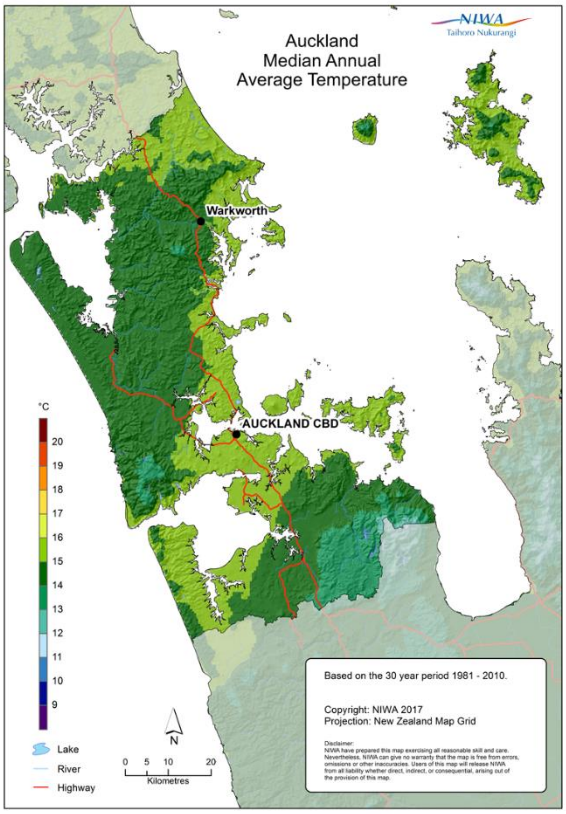

Figure 3-1: Median annual average temperature for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

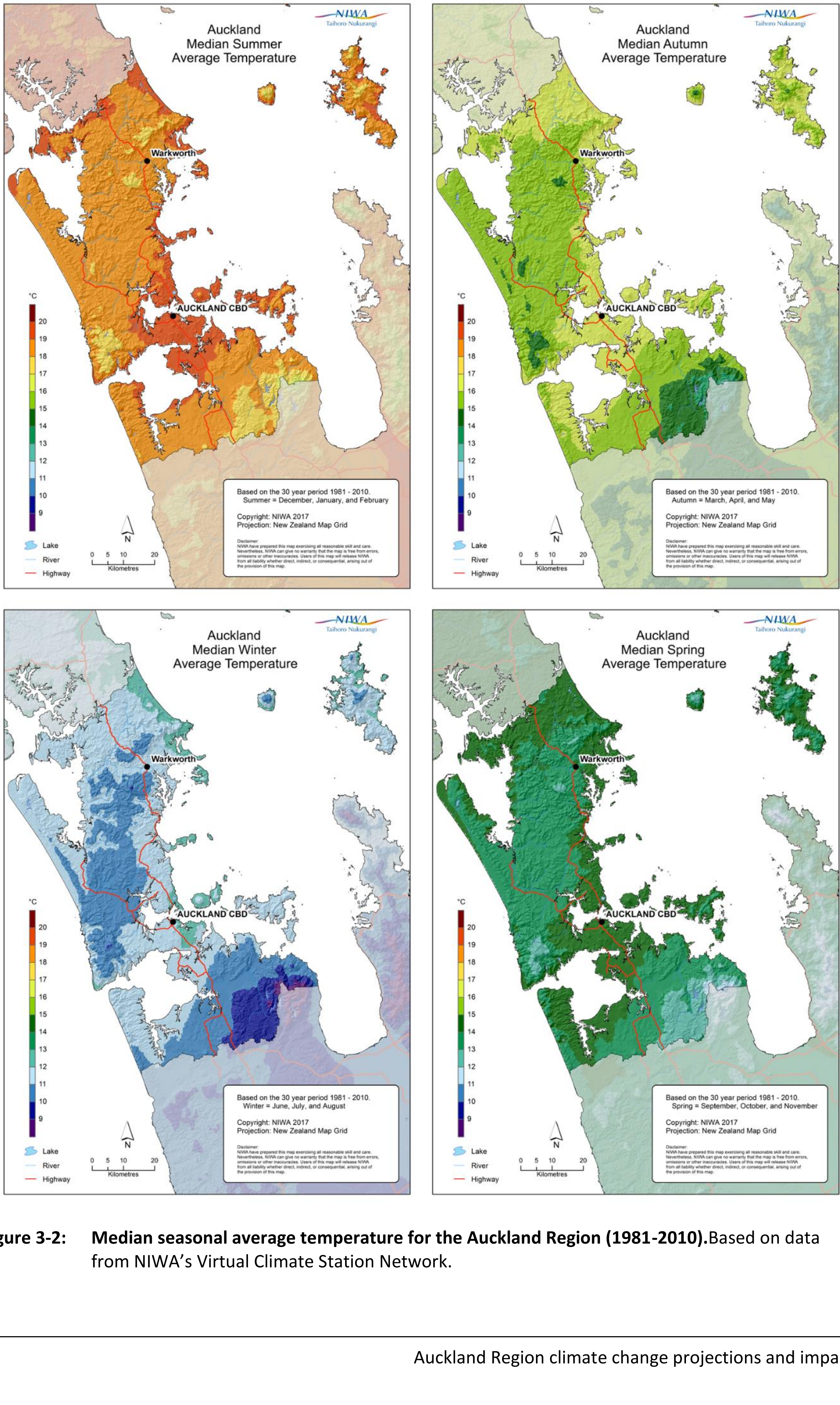

Figure 3-2: Median seasonal average temperature for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

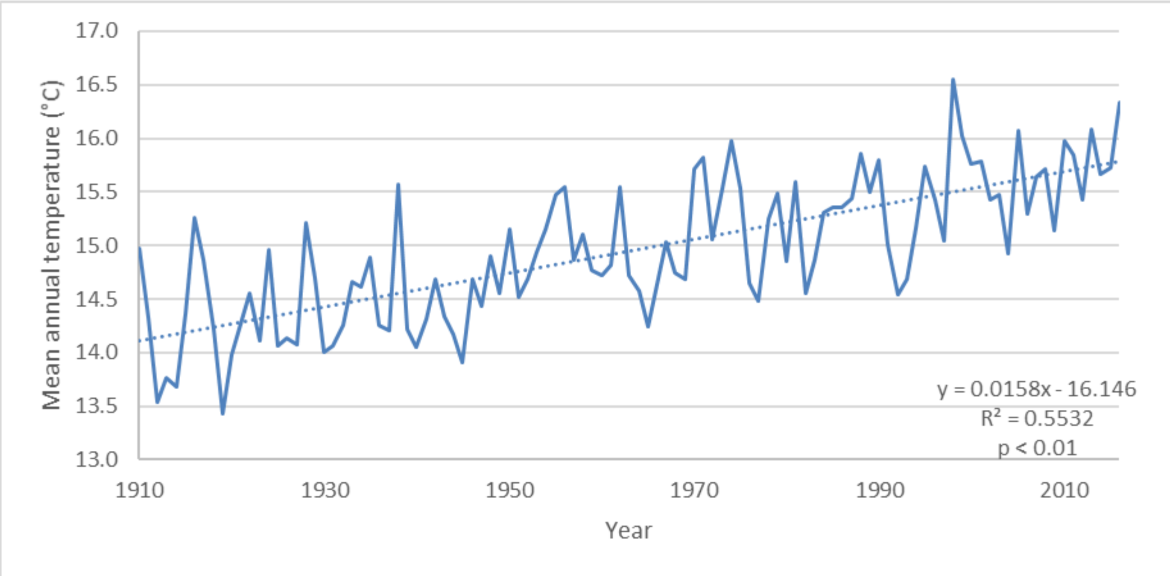

Figure 3-3: Mean annual temperature for Auckland, 1910-2016. This site is part of the 'seven station'[4] series, and these data are homogenised. Trend is approximately +0.16°C/decade.

3.1.2 Future

The seasonal and annual patterns of projected temperature changes over the Auckland Region for 2040 based on the RCP4.5 scenario are shown in Figure 3-4. Figure 3-5 shows corresponding patterns for 2090 and Figure 3-6 shows the projected changes for 2110. Figure 3-7 shows the seasonal and annual patterns of projected temperature increase for 2040 for the RCP8.5 scenario, Figure 3-8 shows the corresponding patterns for 2090, and Figure 3-9 shows projected changes for 2110. The ensemble-average of six dynamically downscaled climate models is presented.

As shown by Figure 3-4, projected future warming in the Auckland Region at 2040 under the RCP4.5 scenario is between 0.50-1.00˚C, with the least warming projected for the northern Auckland Region. Autumn and summer are the seasons projected to undergo the most warming, and spring and winter undergo the least warming. Figure 3-5 shows mean seasonal and annual temperature change under RCP4.5 at 2090. A similar pattern is shown to Figure 3-4, but the magnitude of warming is larger – annual warming is projected to be 1.00-1.50°C compared with present. The season with the most warming is autumn, with southeast parts of the region projected to experience increases of 1.50-1.75°C. Figure 3-6 shows mean seasonal and annual temperature change under RCP4.5 at 2110. Most of the Auckland Region is projected to warm by 1.50-1.75°C, with some northern and western areas warming by 1.25-1.50°C. Autumn is the season which projects the most warming – most of the region is projected to warm by 1.75-2.00°C. Winter and spring undergo the least warming.

Figure 3-7 shows projected warming for the Auckland Region under RCP8.5 at 2040. At the annual scale, warming of 0.75-1.00°C is projected throughout the region. Autumn is projected to see warming of 1.00-1.25°C almost everywhere in the region. By 2090 under RCP8.5 (Figure 3-8), more significant warming is observed over the entire Auckland Region. Spring and winter are projected to experience the least amount of warming (most areas < 2.75°C of warming) and autumn exhibits the most warming over the whole region (> 3°C warming in most areas). At the annual scale, warming of 2.50-3.00°C is projected for the region, with the most warming projected for southeast and north-central areas. For 2110 under RCP8.5 (Figure 3-9), the entire Auckland Region is projected to

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

experience warming of > 3.00°C, with most areas projecting warming of 3.25-3.50°C. Autumn is the season that is projected to warm the most with 3.75°C or more of warming projected for most parts of the region.

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

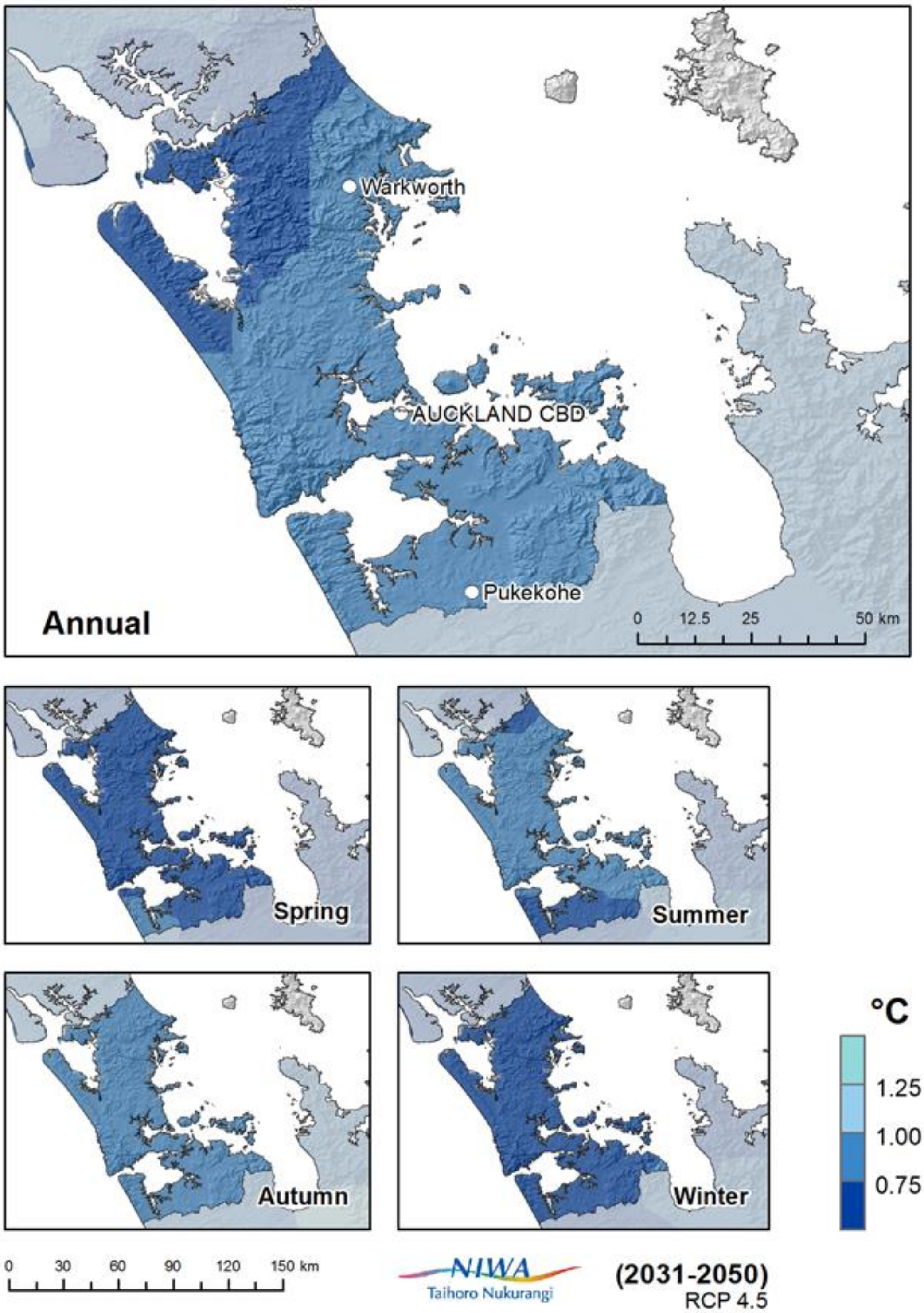

Figure 3-4: Projected annual and seasonal mean temperature changes at 2040 (2031-2050 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

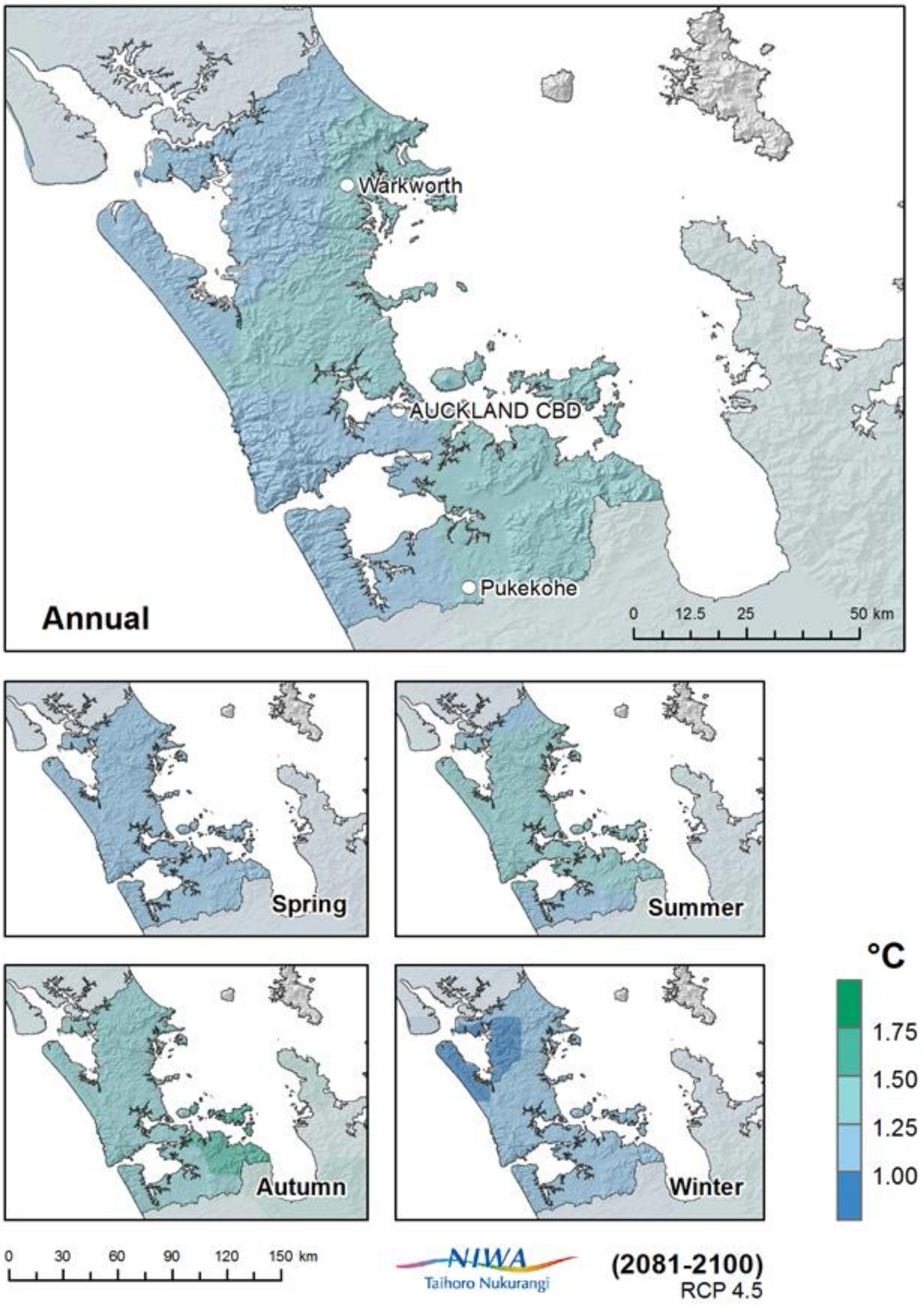

Figure 3-5: Projected annual and seasonal mean temperature changes at 2090 (2081-2100 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

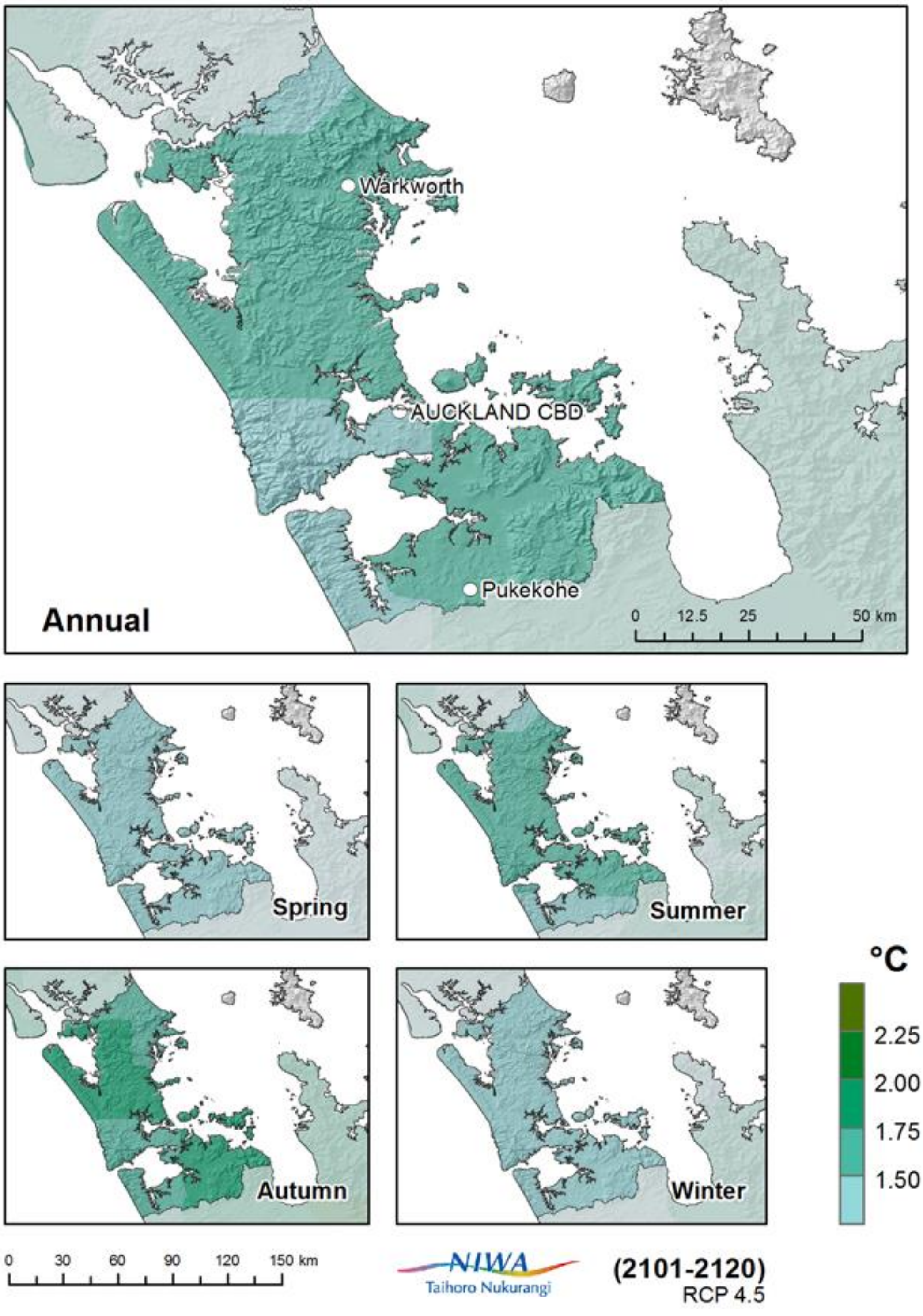

Figure 3-6: Projected annual and seasonal mean temperature changes at 2110 (2101-2120 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

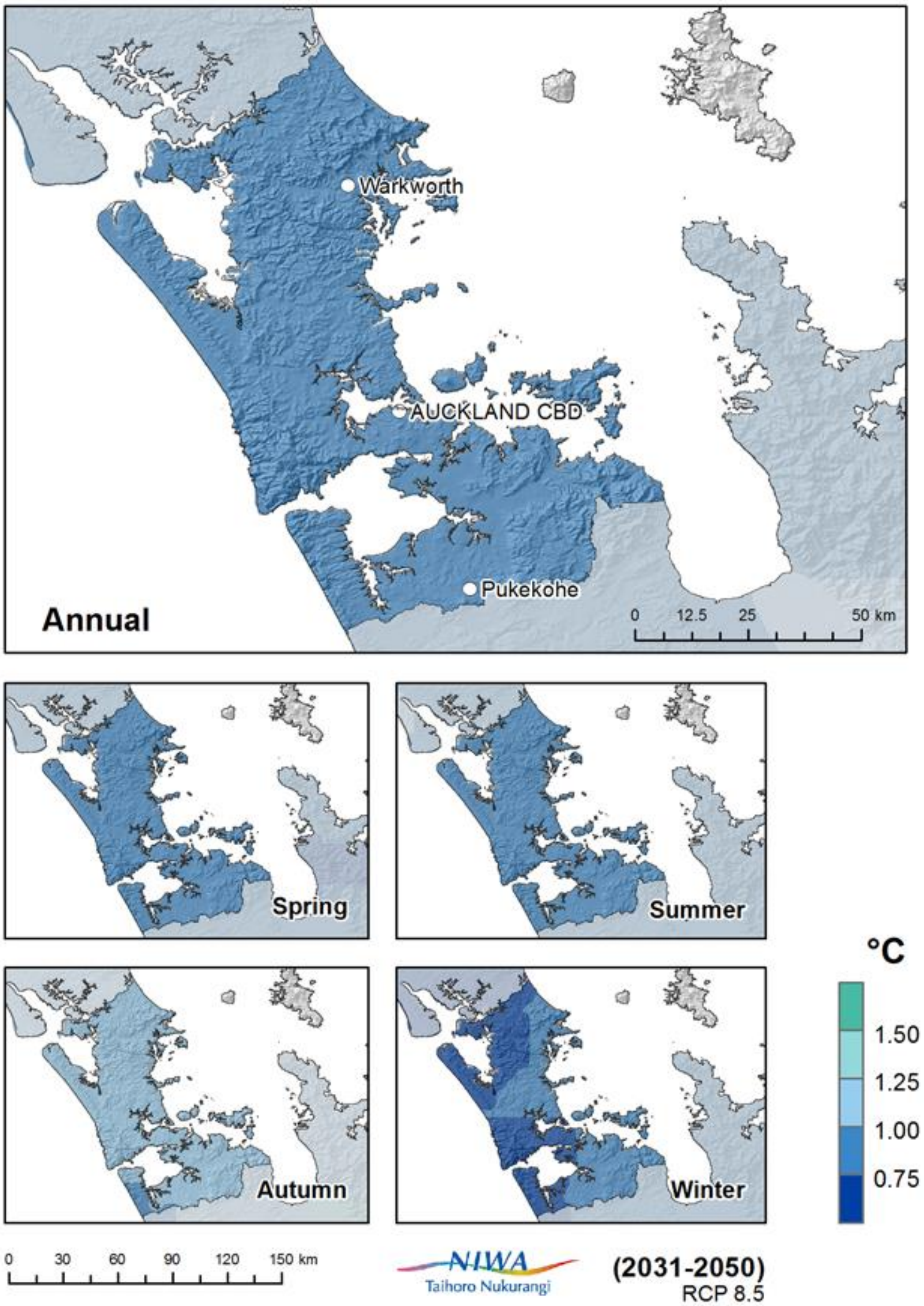

Figure 3-7: Projected annual and seasonal mean temperature changes at 2040 (2031-2050 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

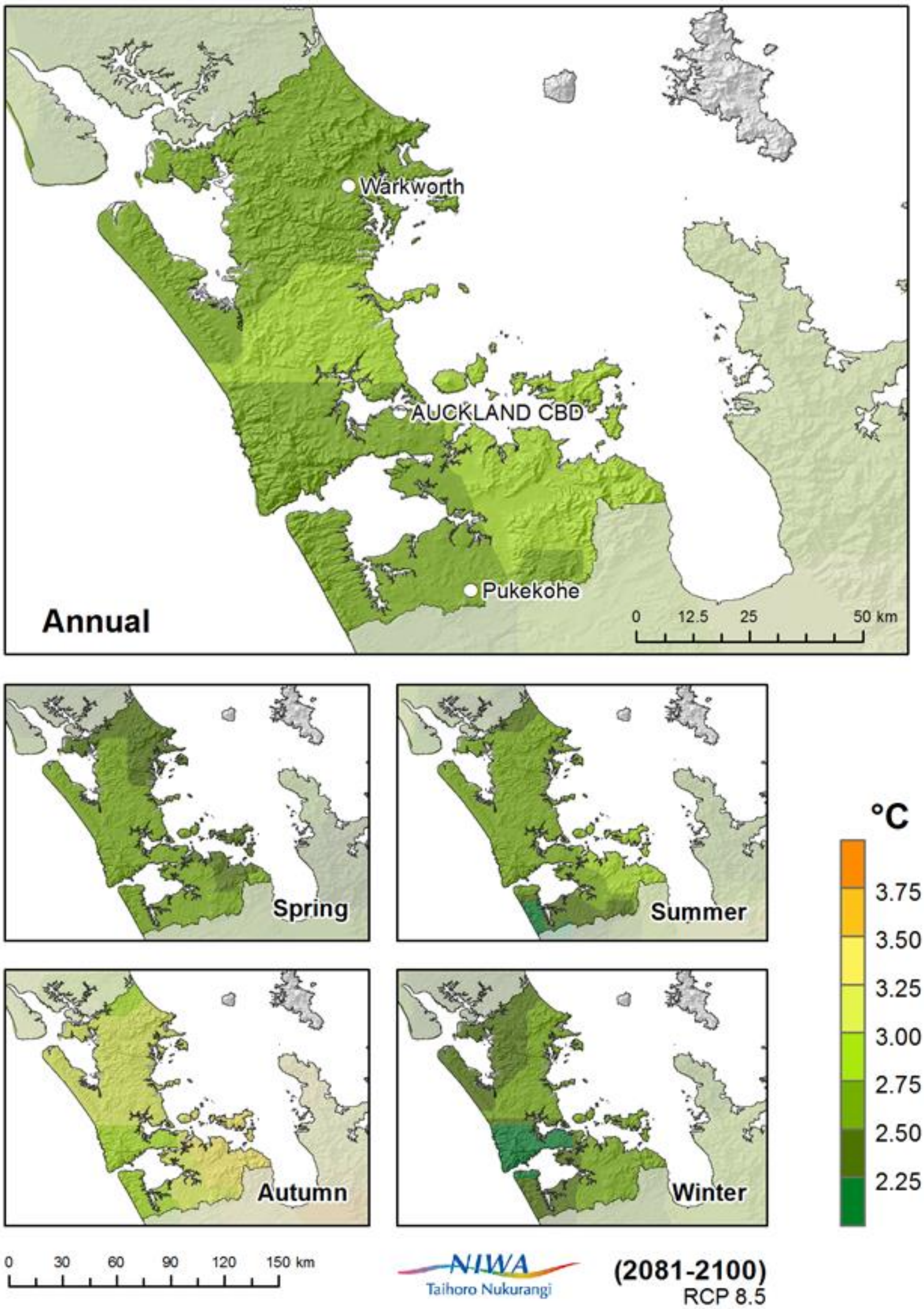

Figure 3-8: Projected annual and seasonal mean temperature changes at 2090 (2081-2100 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

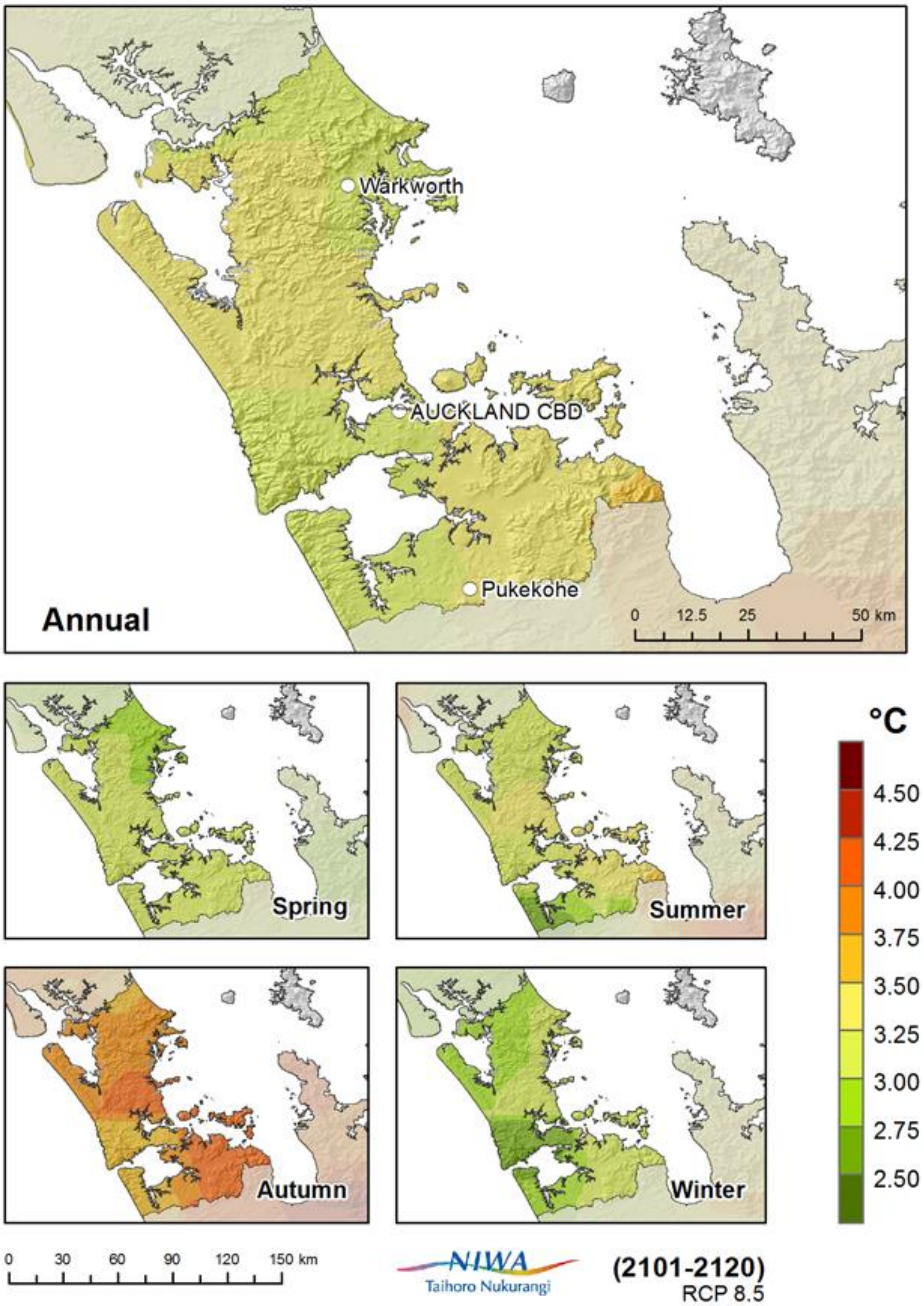

Figure 3-9: Projected annual and seasonal mean temperature changes at 2110 (2101-2120 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

Some models indicate less warming while others show a faster rate of warming (IPCC, 2013b). The full range of model-projected warming for the Auckland Region as a whole based on statistical downscaling methods, is given in Table 3-1, while Table 3-2 shows the results from dynamical downscaling methods (the maps in this report present dynamical downscaled projections). The seasonal and annual ensemble average projection (the number outside the brackets) in Table 3-1 is the average temperature increase based on all 23 models for RCP2.6, 37 models for RCP4.5, 18 models for RCP6.0, and 41 models for RCP8.5 as analysed by NIWA (for 2040 and 2090; there are fewer model results available for 2110). The bracketed numbers give the range of results (5th and 95th percentile) for each RCP for each season and the annual projection. For Table 3-2, the ensemble average projection is given outside the brackets (six dynamically downscaled models) and the bracketed numbers give the range (minimum and maximum) for each RCP for each season and the annual projection.

By 2040 (the central year of the 2031-2050 interval, with the anomaly calculated relative to 1986-2005), annual average temperatures for Auckland are projected to increase by between about 0.7°C (RCP2.6) and 0.9°C (RCP4.5) (Table 3-1). Summer, autumn and winter have similar projections for warming across the region, 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 3.1°C (RCP8.5). Like 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 scenarios show increased warming at 2090 relative to 2040. At 2110, projected warming has increased for RCP4.5 and RCP8.5 but has stayed the same as 2090 for RCP2.6.

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 shows a positive shift (i.e. change to warmer conditions) for all RCPs.

The dynamical downscaled mean temperature projections in Table 3-2 are consistent with the statistical downscaled projections in Table 3-1, in that warming is projected everywhere, and the results for each RCP and each time slice, season, and annual scale are similar. Dynamical downscaled results generally show a lower projected increase in mean temperature because these projections have been bias-corrected (Section 1.3).

Table 3-1: Projected changes in seasonal and annual mean temperature (in °C) for the Auckland Region for 2031-2050 (2040), 2081-2100 (2090), and 2101-2120 (2110) as derived from statistical downscaling. Changes are relative to the baseline period, 1986-2005 (1995). The 1995 period shows average temperatures over the whole Auckland Region. 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). No results are shown for RCP6.0 at 2110 because only two models in the NIWA CMIP5 archive have data available beyond 2100 for this RCP. From Mullan et al. (2016).

Period	RCP	Summer	Autumn	Winter	Spring	Annual
1995		18.7	15.8	11.1	14.0	14.9
2040	RCP2.6	0.8 (0.3, 1.3)	0.8 (0.3, 1.1)	0.7 (0.4, 1.0)	0.7 (0.4, 1.0)	0.7 (0.4, 1.0)
	RCP4.5	1.0 (0.5, 1.5)	0.9 (0.4, 1.4)	0.9 (0.6, 1.2)	0.8 (0.4, 1.1)	0.9 (0.5, 1.2)
	RCP6.0	0.9 (0.4, 1.6)	0.9 (0.5, 1.2)	0.8 (0.4, 1.2)	0.8 (0.3, 1.1)	0.8 (0.4, 1.2)
	RCP8.5	1.1 (0.5, 1.6)	1.1 (0.7, 1.5)	1.1 (0.6, 1.5)	0.8 (0.4, 1.2)	0.8 (0.3, 1.1)
2090	RCP2.6	0.7 (0.2, 1.4)	0.7 (0.4, 1.4)	0.7 (0.4, 1.2)	0.6 (0.3, 1.2)	0.7 (0.4, 1.3)
	RCP4.5	1.5 (0.8, 2.6)	1.5 (0.9, 2.1)	1.5 (0.9, 2.0)	1.3 (0.8, 1.8)	1.4 (0.9, 2.1)
	RCP6.0	2.0 (1.2, 3.6)	1.9 (1.1, 2.8)	1.9 (1.2, 2.6)	1.7 (1.1, 2.3)	1.9 (1.2, 2.8)
	RCP8.5	3.3 (2.3, 5.1)	3.2 (2.2, 4.4)	3.0 (2.3, 4.0)	2.8 (2.1, 3.5)	3.1 (2.3, 4.3)
2110	RCP2.6	0.7 (0.0, 1.5)	0.8 (0.3, 1.4)	0.7 (0.4, 1.2)	0.7 (0.4, 1.2)	0.7 (0.4, 1.3)
	RCP4.5	1.8 (1.1, 2.9)	1.8 (1.2, 2.3)	1.6 (1.0, 2.2)	1.5 (1.0, 2.2)	1.7 (1.2, 2.3)
	RCP6.0					
	RCP8.5	4.1 (2.9, 6.1)	4.0 (3.0, 5.6)	3.6 (2.8, 4.7)	3.4 (2.7, 4.3)	3.8 (2.9, 5.2)

Table 3-2: Projected changes in seasonal and annual mean temperature (in °C) for the Auckland Region for 2031-2050 (2040), 2081-2100 (2090), and 2101-2120 (2110) as derived from dynamical downscaling. Changes are relative to the baseline period, 1986-2005. The 1995 period shows average temperatures over the whole Auckland Region. 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). No results are shown for RCP6.0 at 2110 because only one model has data available beyond 2100 for this RCP.

Period	RCP	Summer	Autumn	Winter	Spring	Annual
1995		18.7	15.8	11.1	14.0	14.9
2040	RCP2.6	0.7 (0.5, 1.0)	0.7 (0.4, 1.0)	0.6 (0.4, 0.8)	0.6 (0.4, 0.8)	0.6 (0.5, 0.9)
	RCP4.5	0.6 (0.3, 1.0)	0.7 (0.6, 0.9)	0.5 (0.4, 0.7)	0.5 (0.4, 0.7)	0.6 (0.5, 0.8)
	RCP6.0	0.7 (0.6, 1.1)	0.8 (0.6, 1.1)	0.7 (0.4, 0.8)	0.7 (0.4, 0.9)	0.7 (0.5, 1.0)
	RCP8.5	0.9 (0.7, 1.3)	1.1 (0.9, 1.4)	0.7 (0.6, 1.1)	0.8 (0.5, 1.2)	0.9 (0.7, 1.2)
2090	RCP2.6	0.6 (0.3, 1.0)	0.7 (0.3, 1.3)	0.6 (0.2, 1.0)	0.6 (0.3, 1.0)	0.6 (0.3, 1.0)
	RCP4.5	1.1 (0.6, 1.7)	1.4 (1.0, 2.0)	1.1 (0.6, 1.5)	1.1 (0.6, 1.7)	1.2 (0.7, 1.7)
	RCP6.0	1.5 (1.2, 1.8)	1.8 (1.0, 2.3)	1.5 (0.6, 1.8)	1.5 (0.6, 2.0)	1.6 (0.7, 2.0)
	RCP8.5	2.6 (2.0, 3.3)	3.1 (2.4, 3.7)	2.5 (1.9, 3.0)	2.5 (2.0, 3.0)	2.7 (2.2, 3.3)
2110	RCP2.6	0.7 (0.4, 0.8)	0.8 (0.6, 1.2)	0.7 (0.4, 0.9)	0.6 (0.4, 0.8)	0.7 (0.4, 0.9)
	RCP4.5	1.4 (1.0, 2.0)	1.7 (1.2, 2.1)	1.3 (0.9, 1.7)	1.3 (0.9, 1.7)	1.4 (1.0, 1.8)
	RCP6.0					
	RCP8.5	3.2 (2.5, 4.0)	3.9 (3.4, 4.9)	3.0 (2.6, 3.7)	3.0 (2.7, 3.6)	3.3 (2.8, 4)

3.2 Maximum and minimum temperature

Key messages

- Mean daily maximum temperature (daytime temperature; T_{max}) and mean daily minimum temperature (night time temperature; T_{min}) has increased over the 20th and early 21st century in Auckland, and this trend will continue.
- By 2110, annual T_{max} is projected to increase by 1.50-1.75°C for RCP4.5 and by 3.25-3.75°C for RCP8.5 for much of the Auckland Region.
- By 2110, annual T_{min} temperature is projected to increase by 1.25-1.75°C for RCP4.5 and by 3.00-3.5°C for RCP8.5 for much of the Auckland Region.
- Autumn is the season when both T_{max} and T_{min} increase the most.

Maximum temperatures are generally recorded in the afternoon, and therefore are also known as daytime temperatures. Minimum temperatures are generally recorded in the early hours of the morning, and therefore are also known as night time temperatures.

3.2.1 Present

The highest median annual average daily maximum (afternoon) temperatures are observed in the central Auckland Region and along the east coast, with an annual average of 19-20°C (Figure 3-10). The lowest median annual average daily maximum temperatures are observed in the higher elevations of the region, for example in the Hunua Ranges and Waitakere Ranges (17-18°C). Median summer average daily maximum temperatures are around 22-24°C for most of the region and median winter average daily maximum temperatures are 14-16°C for most of the region. There is considerable seasonal variation in the daily maximum temperatures observed across the region, but the spatial patterns remain similar, i.e. with the highest temperatures experienced in the central Auckland Region and along the east coast, and the lowest temperatures observed in the highest elevations (Figure 3-11). Annual average daily maximum temperatures have increased over the 20th and early 21st century in Auckland (Figure 3-12), and this trend is statistically significant above the 95% confidence level.

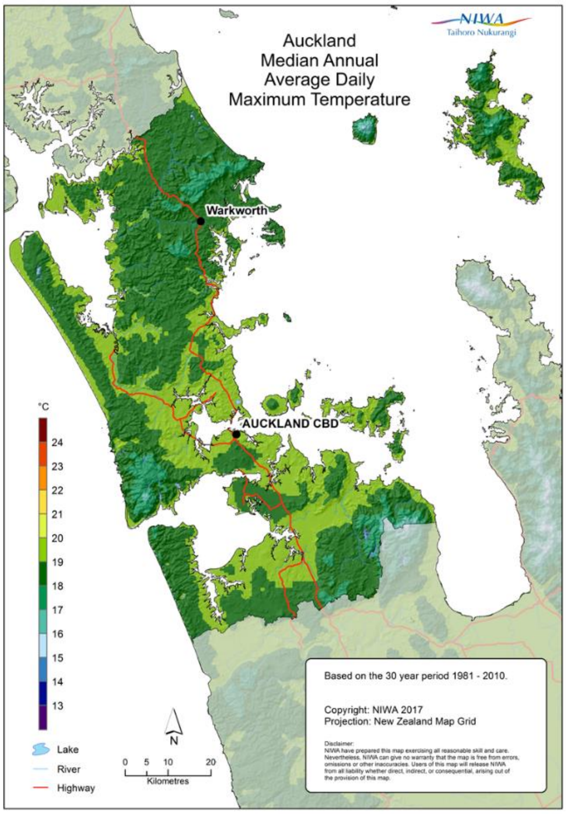

Figure 3-10: Median annual average daily maximum temperature for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

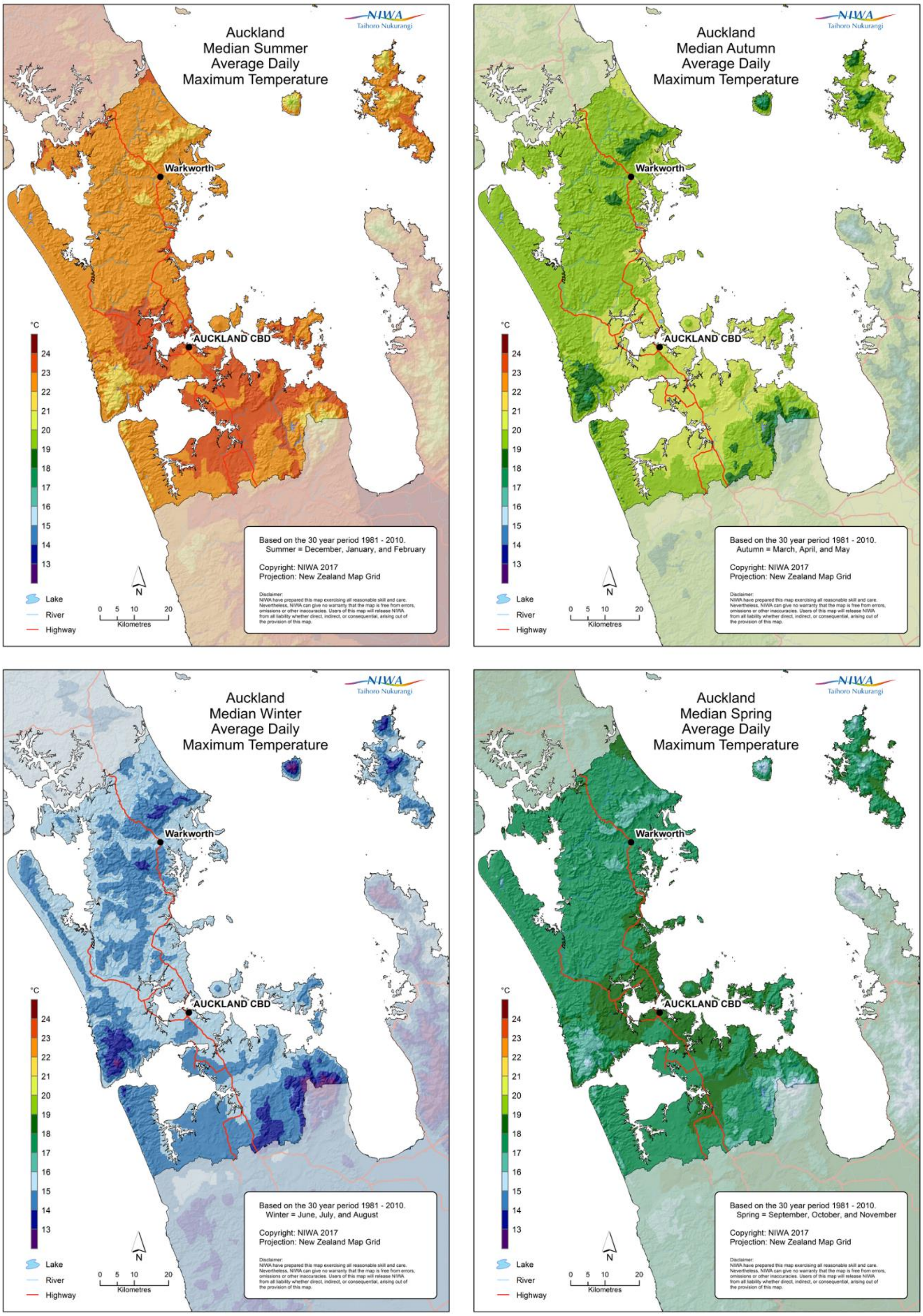

Figure 3-11: Median seasonal average daily maximum temperature for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

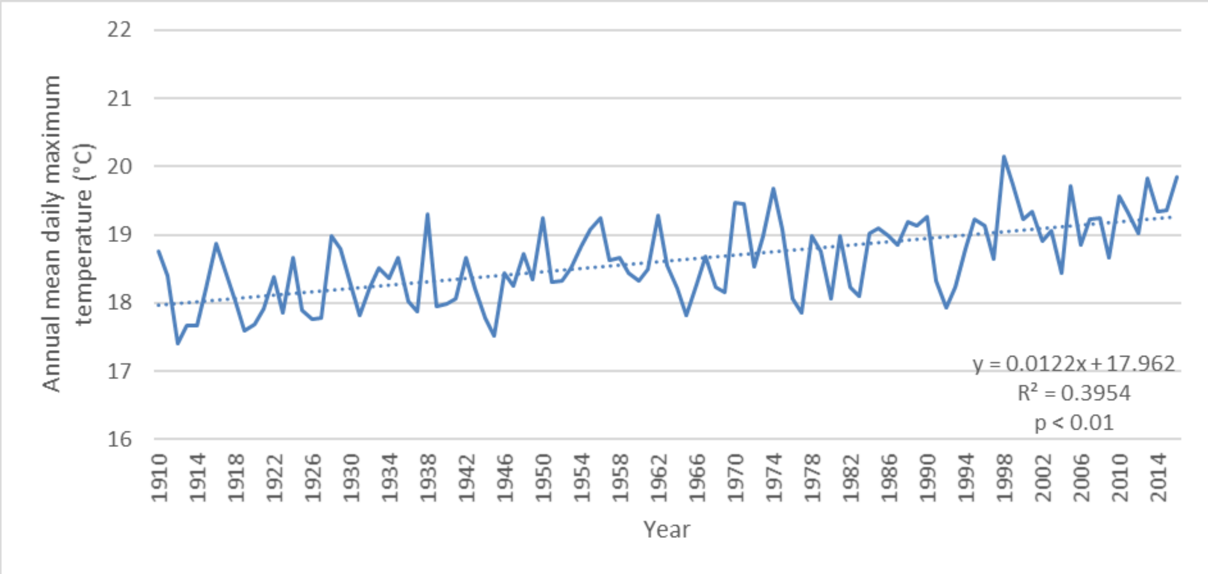

Figure 3-12: Annual mean daily maximum temperature (°C) at Auckland, 1910-2016. This data is part of New Zealand's Seven Station Temperature Series and has been homogenised. The trend indicates an increase of about 1°C per century.

The lowest annual average daily minimum temperatures are recorded in the Hunua Ranges and surrounding area, as well as in the west of the Auckland Region (8-10°C) (Figure 3-13). The highest daily minimum temperatures are observed along the east coast of the region (12-13°C). Significantly higher minimum daily temperatures are observed in summer (13-16°C) than in winter (6-10°C), but the spatial pattern remains similar to the annual temperatures (Figure 3-14). Annual mean daily minimum temperatures have increased over the 20th and early 21st century in Auckland (Figure 3-15), and this trend is statistically significant above the 95% confidence level.

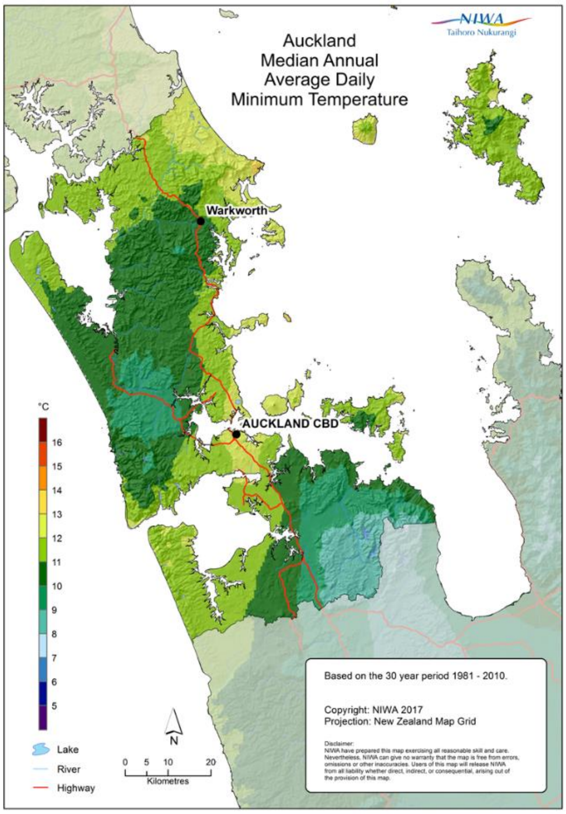

Figure 3-13: Median annual average daily minimum temperature for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

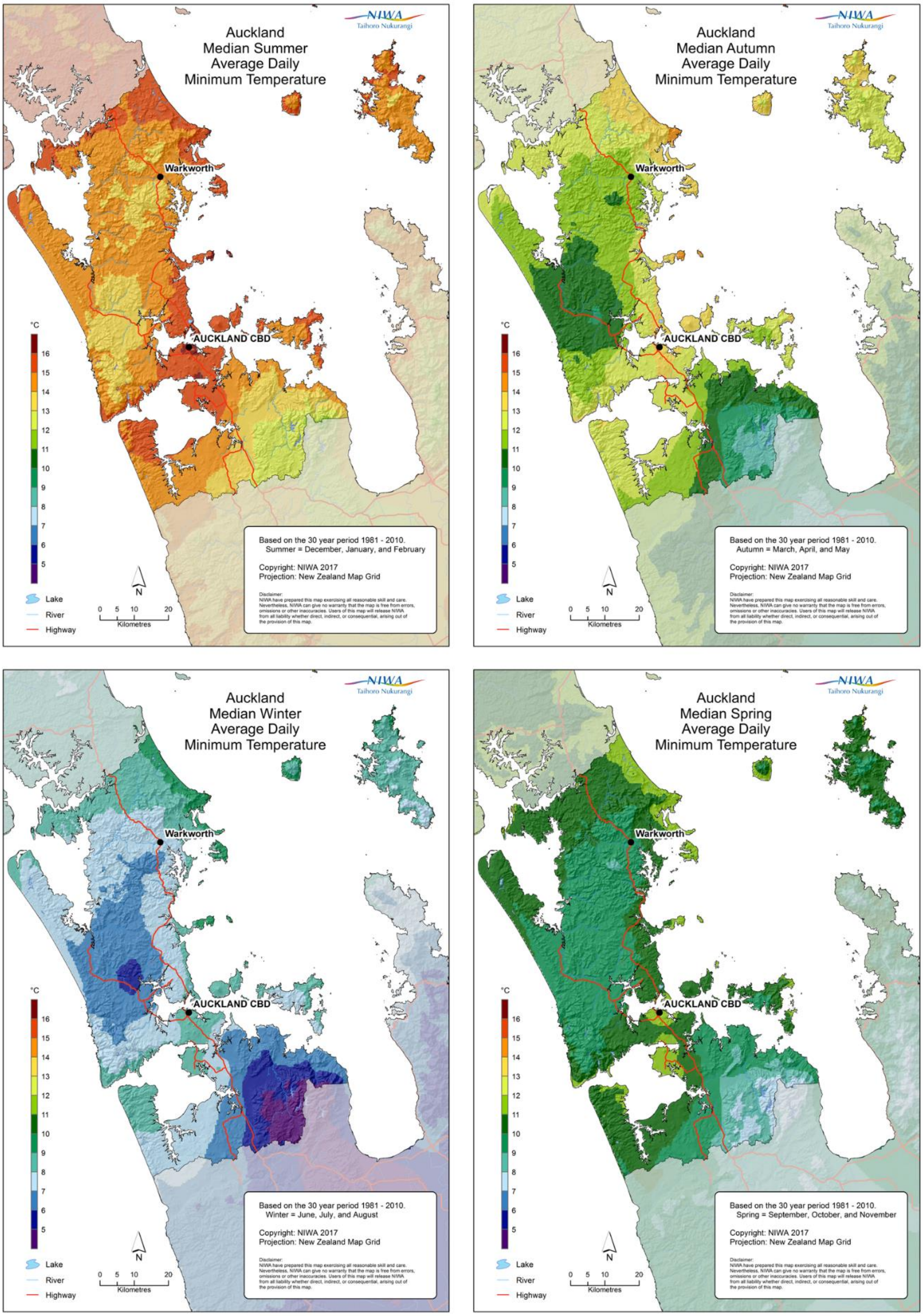

Figure 3-14: Median seasonal average daily minimum temperature for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

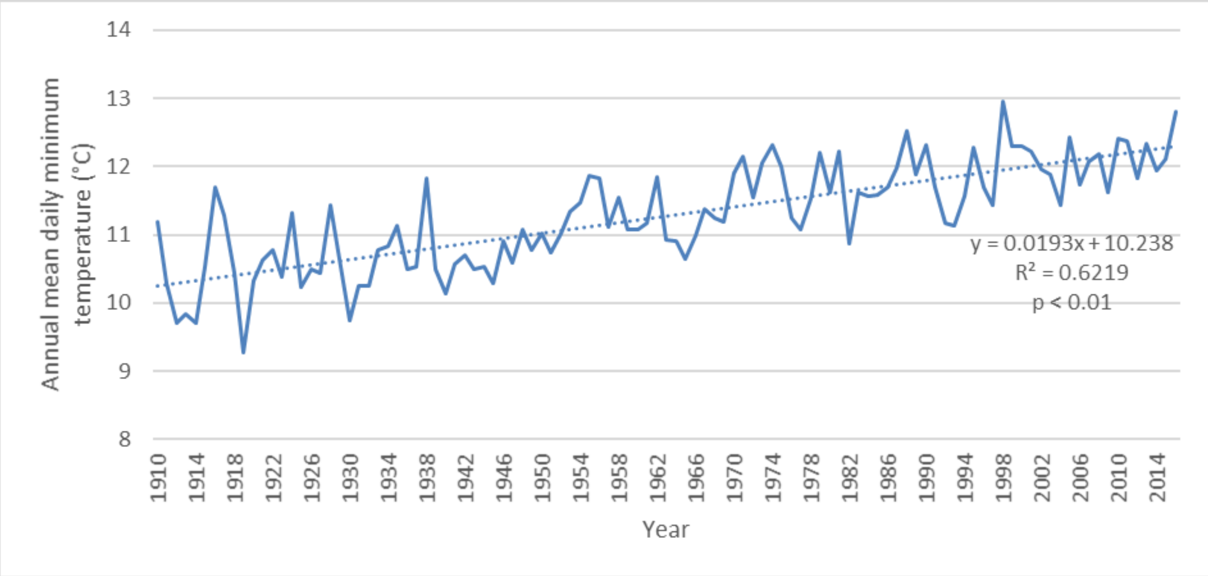

Figure 3-15: Annual mean daily minimum temperature (°C) at Auckland, 1910-2016. This data is part of New Zealand's Seven Station Temperature Series and has been homogenised. The trend indicates an increase of about 1.9°C per century.

3.2.2 Future

Projected changes in daytime maximum (T_{max}) and night time minimum (T_{min}) are presented in this section. The ensemble-average of six dynamically downscaled climate models is presented. The temperature trends are positive over the whole Auckland Region for both RCP4.5 and RCP8.5, but are neither spatially homogeneous nor of equal magnitude. T_{max} and T_{min} are documented for all seasons and three future periods (2040, 2090, and 2110) in Figure 3-16 to Figure 3-27.

Changes in T_{max} and T_{min} are positive under all three time slices and both RCPs, with larger increases with time and emissions scenario. The largest amount of warming is generally projected to occur in the southeast of the Auckland Region (Section 3.1.2).

For annual T_{max}, RCP4.5 projections show increases of 0.75-1.00°C across the region by 2040 (Figure 3-16). By 2090, the region projects increases in annual T_{max} of 1.25-1.50°C (Figure 3-17). By 2110, the projections for the region show increases in annual T_{max} of 1.50-1.75°C (Figure 3-18). Across all time slices for RCP4.5, spring, summer and autumn show similar changes in T_{max}, with winter showing slightly smaller changes than the other seasons.

For RCP8.5 at 2040, most of the region projects increases in annual T_{max} of 0.75-1.25°C (Figure 3-19). At 2090, 2.75-3.25°C increase in annual T_{max} is projected for most of the region (Figure 3-20). At 2110, most of the region projects an increase of 3.25-3.75°C (Figure 3-21). Autumn is the season where T_{max} increases the most under RCP8.5.

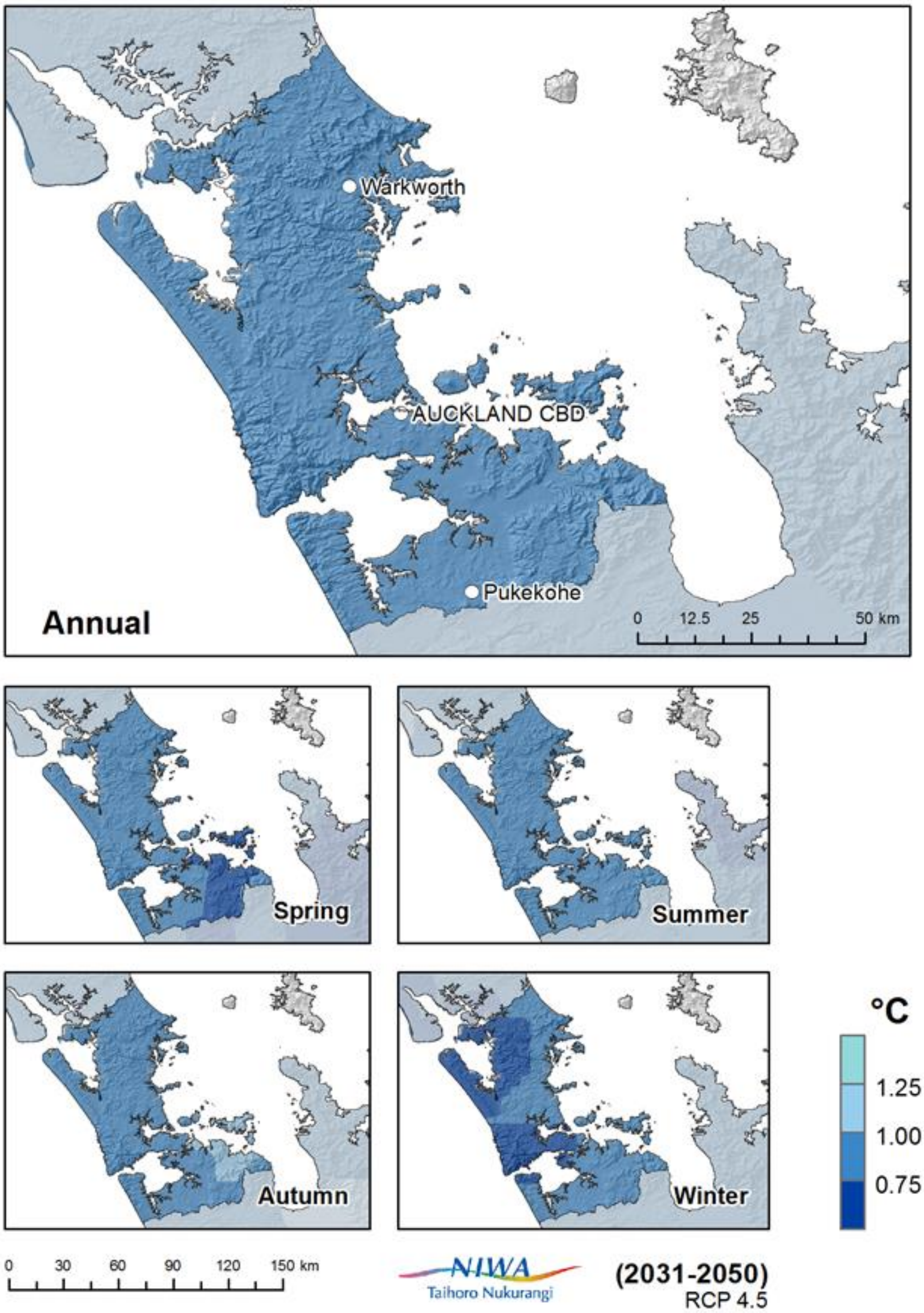

Figure 3-16: Projected annual and seasonal daily mean maximum temperature changes at 2040 (2031-2050 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

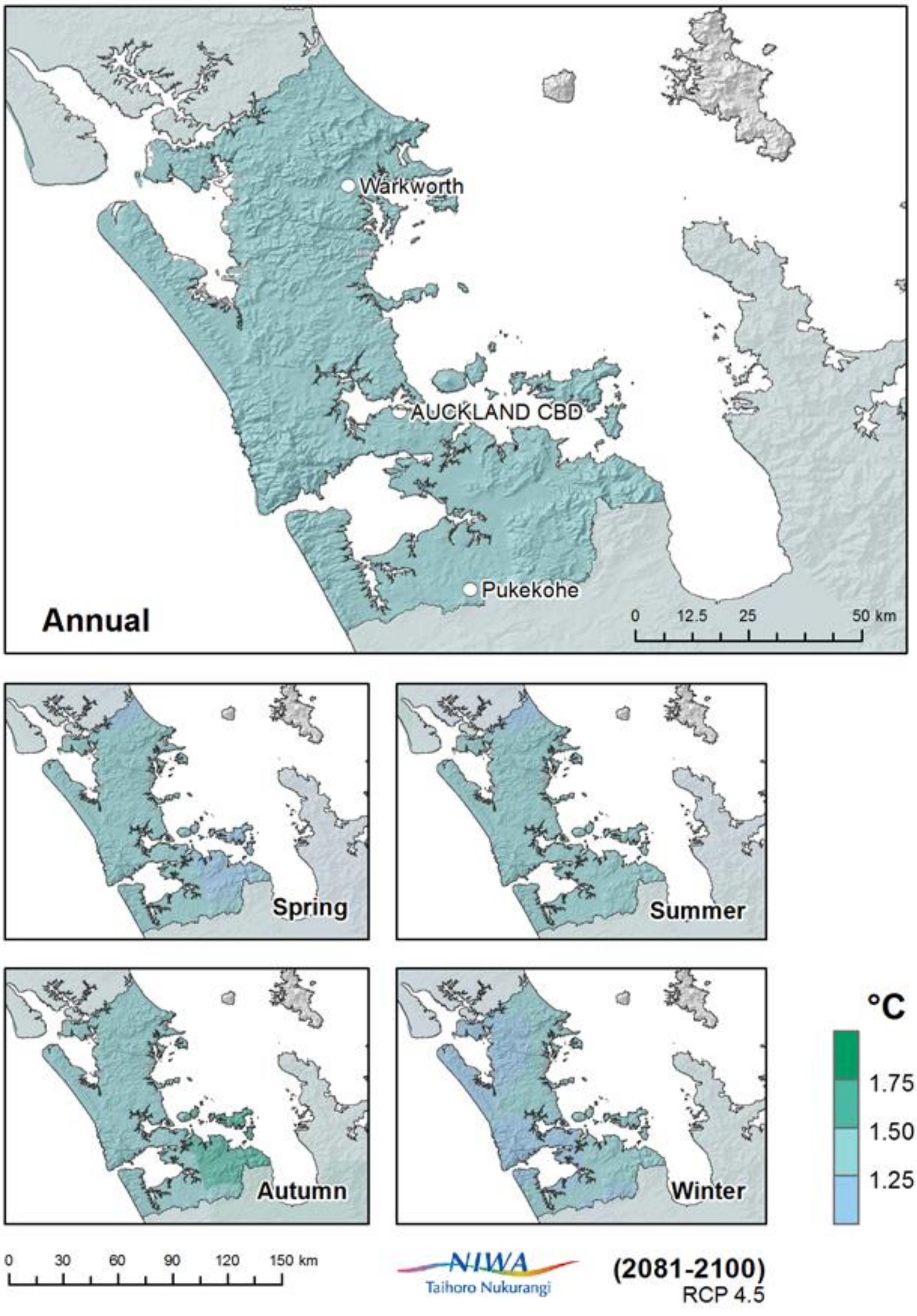

Figure 3-17: Projected annual and seasonal daily mean maximum temperature changes at 2090 (2081-2100 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

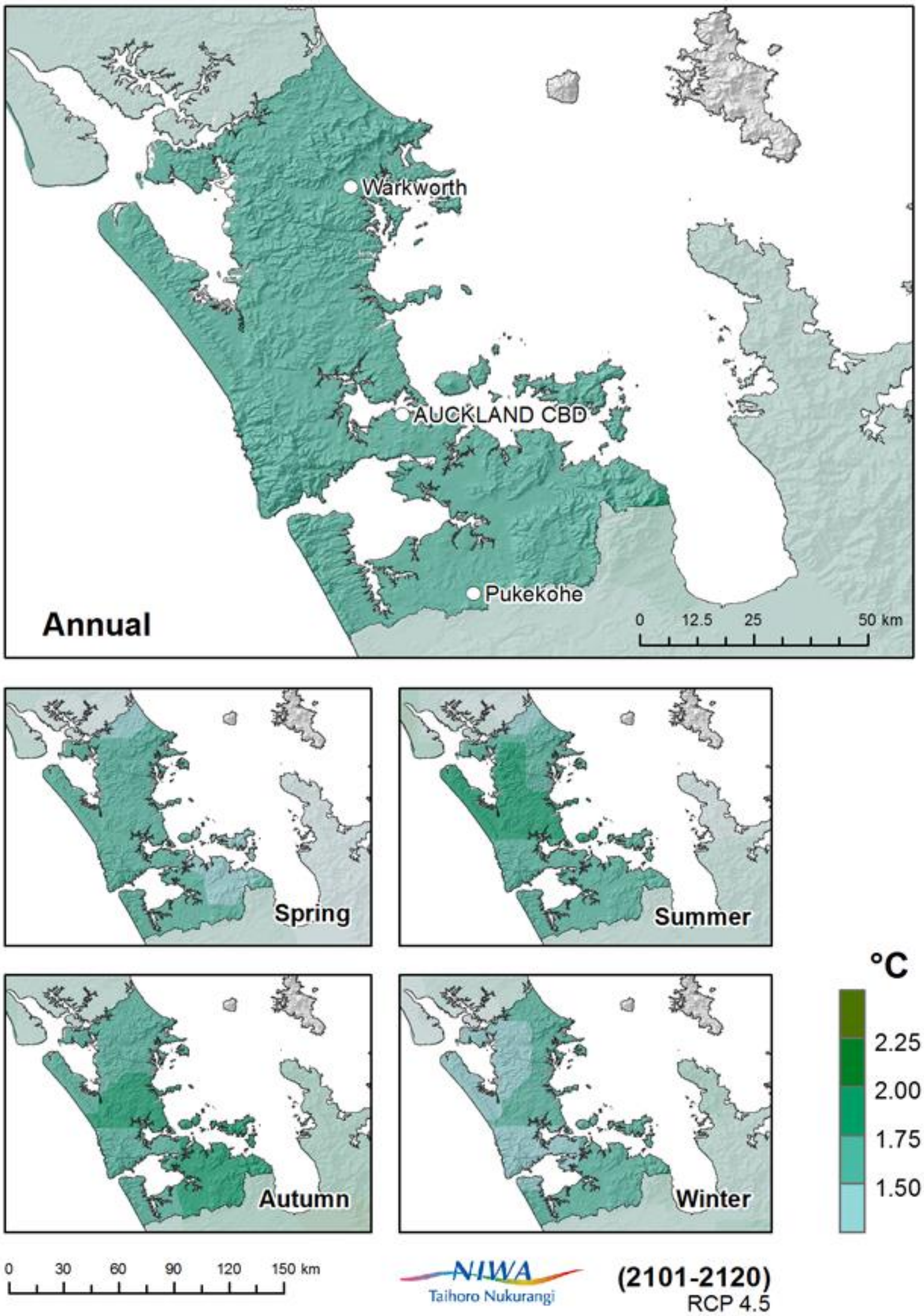

Figure 3-18: Projected annual and seasonal daily mean maximum temperature changes at 2110 (2101-2120 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

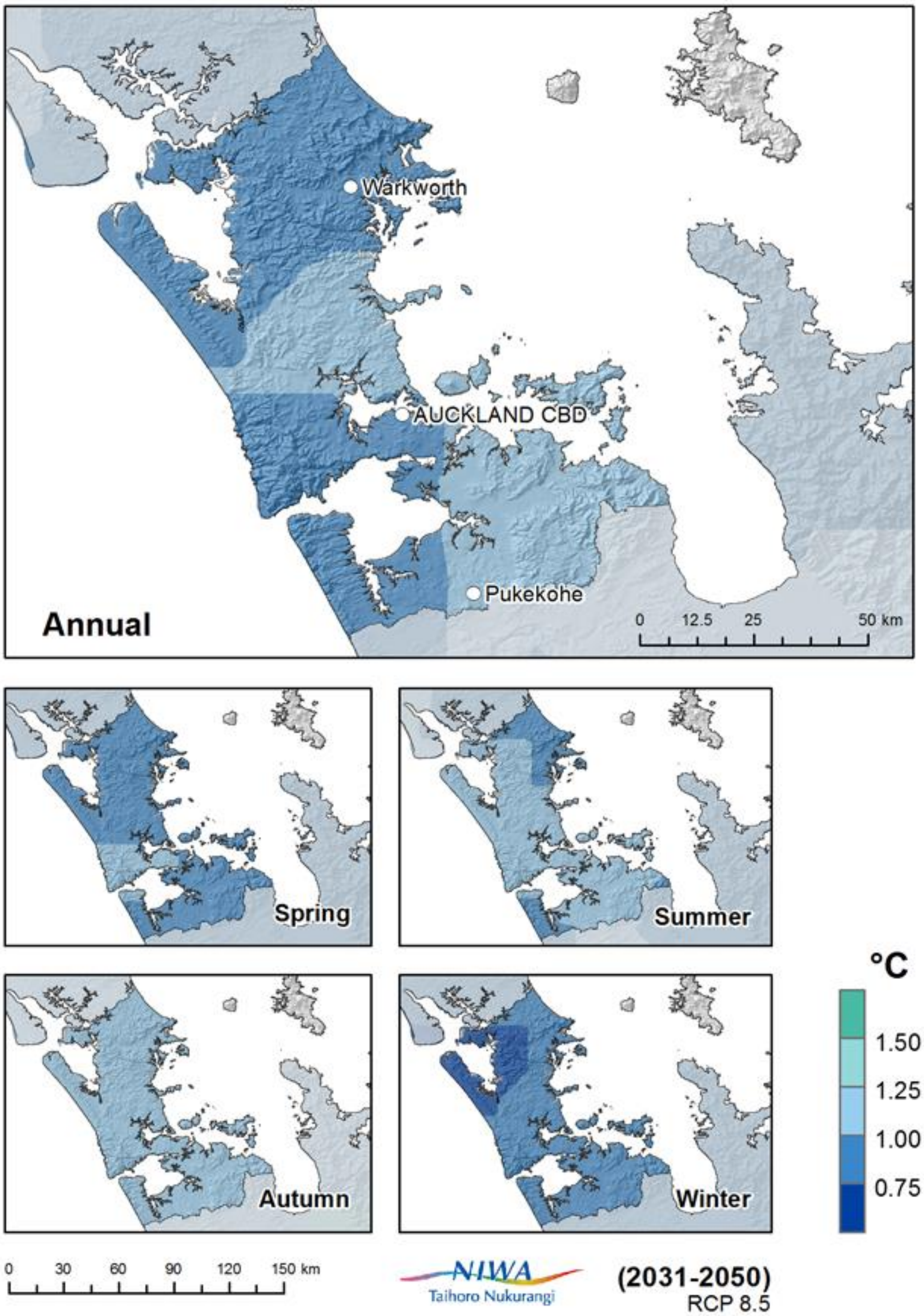

Figure 3-19: Projected annual and seasonal daily mean maximum temperature changes at 2040 (2031-2050 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

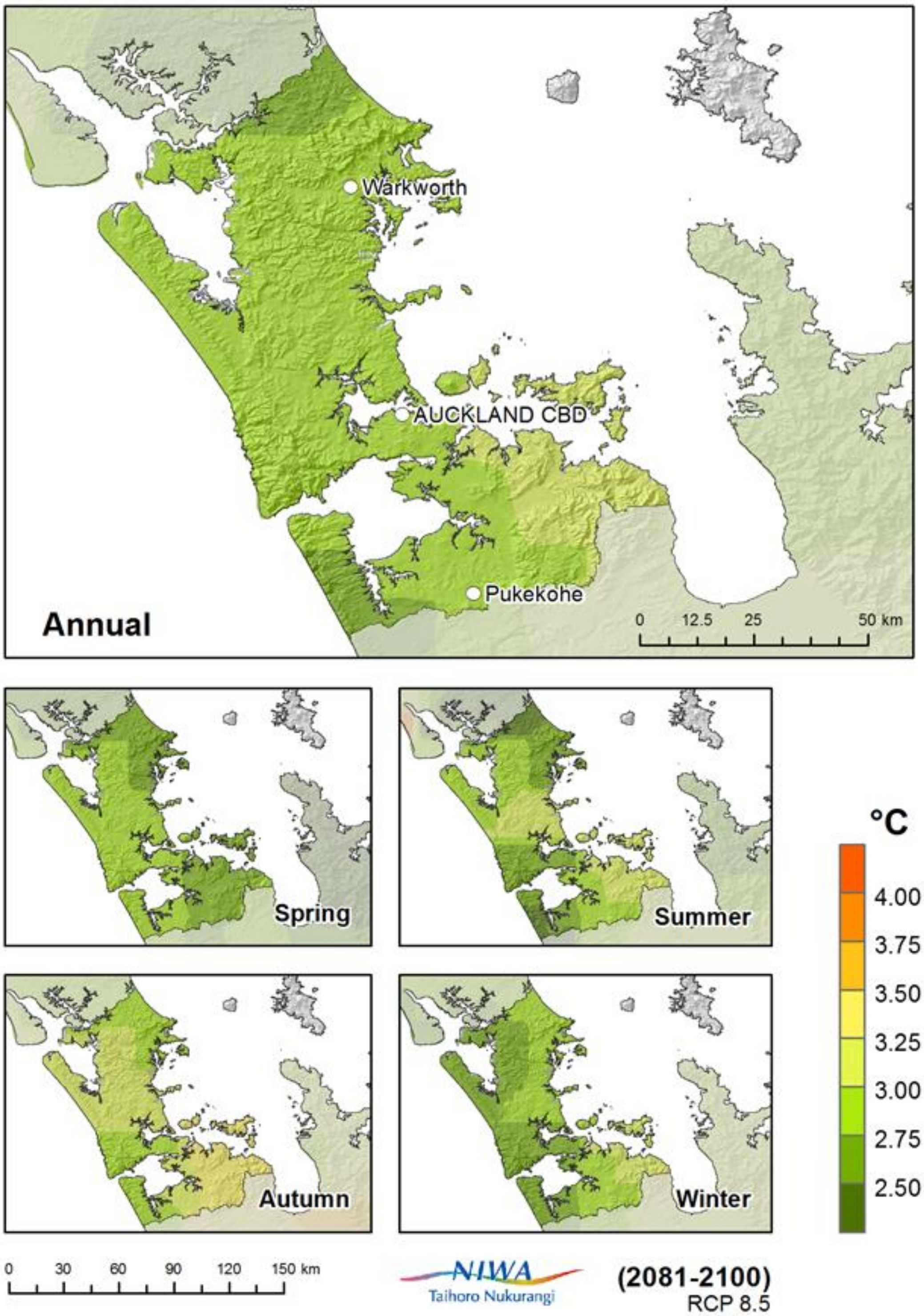

Figure 3-20: Projected annual and seasonal daily mean maximum temperature changes at 2090 (2081-2100 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

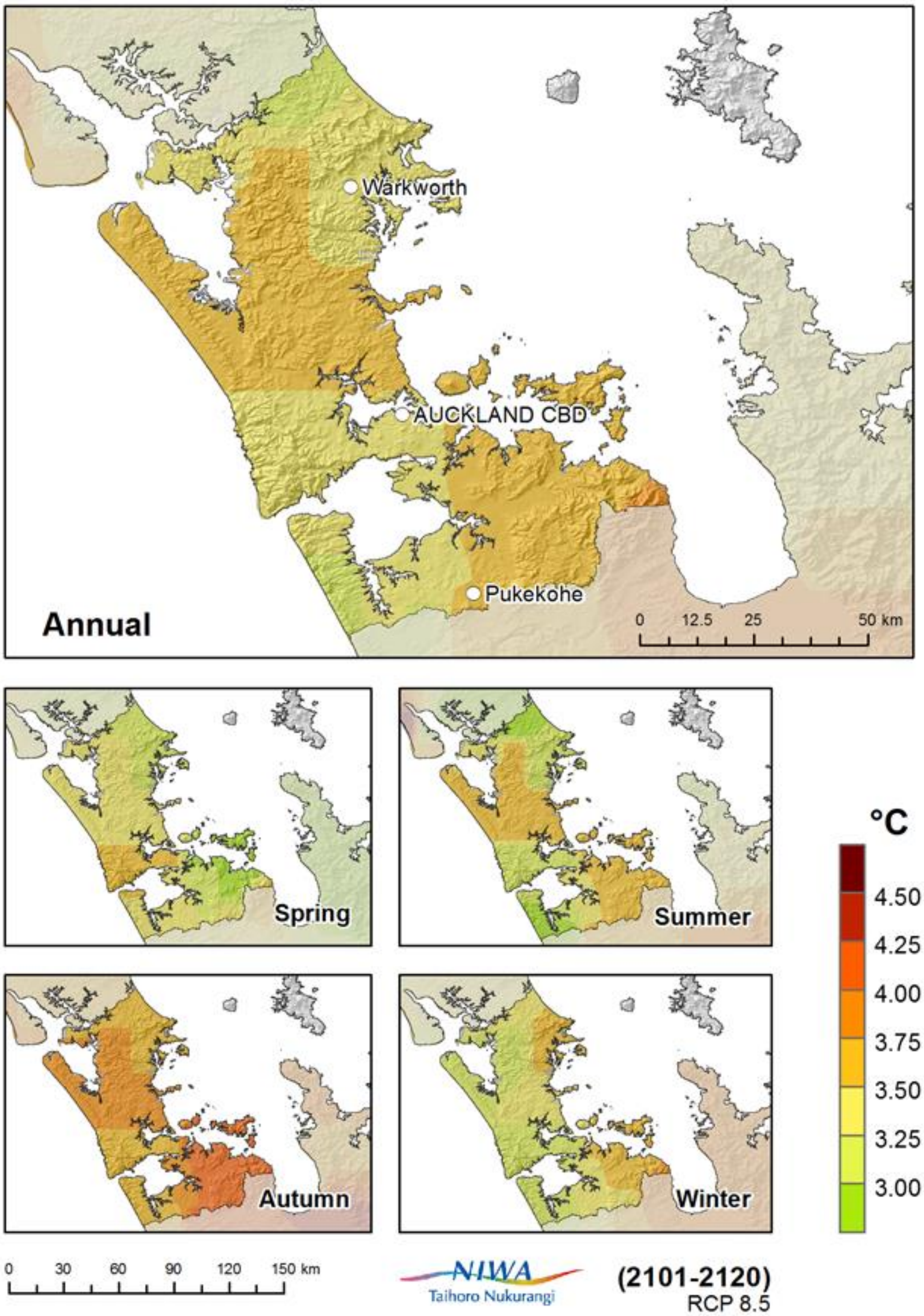

Figure 3-21: Projected annual and seasonal daily mean maximum temperature changes at 2110 (2101-2120 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

For T_{min}, RCP4.5 projections for 2040 show increases in annual T_{min} of 0.50-0.75°C for most of the region and 0.75-1.00°C in the southeast part of the region (Figure 3-22). By 2090, the whole Auckland Region is expected to experience increases in annual T_{min} of 1.00-1.25°C (Figure 3-23). By 2110 under RCP4.5, the projections indicate most parts of the region will experience an increase in annual T_{min} of 1.25-1.50°C and 1.50-1.75°C in north-central and southeast areas (Figure 3-24). For RCP4.5, autumn is the season that shows the largest increases in T_{min} across the region, for all time slices.

For RCP8.5 at 2040, annual T_{min} projections show increases of 0.75-1.00°C for the whole region (Figure 3-25). 2090 projections show most parts of the region project an increase of 2.50-2.75°C and 2.25-2.50°C in some southwest and northern areas (Figure 3-26). For 2110, RCP8.5 projections show an increase in annual T_{min} of 3.00-3.25°C for most of the region, and 3.25-3.50°C in the southeast (Figure 3-27). For RCP8.5, like for RCP4.5, autumn is the season where T_{min} projects the largest increases across the region at all time slices.

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

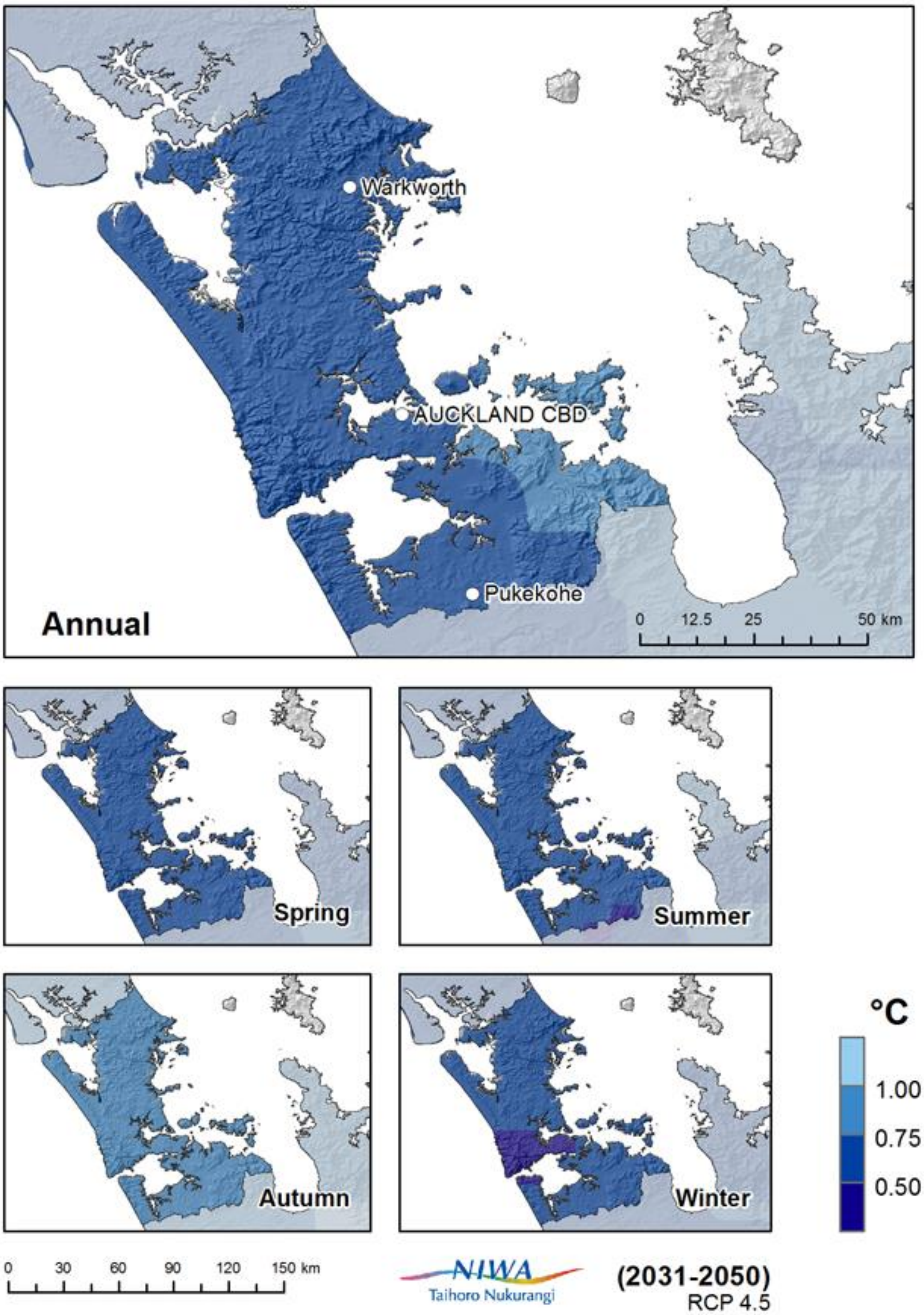

Figure 3-22: Projected annual and seasonal daily mean minimum temperature changes at 2040 (2031-2050 average) for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

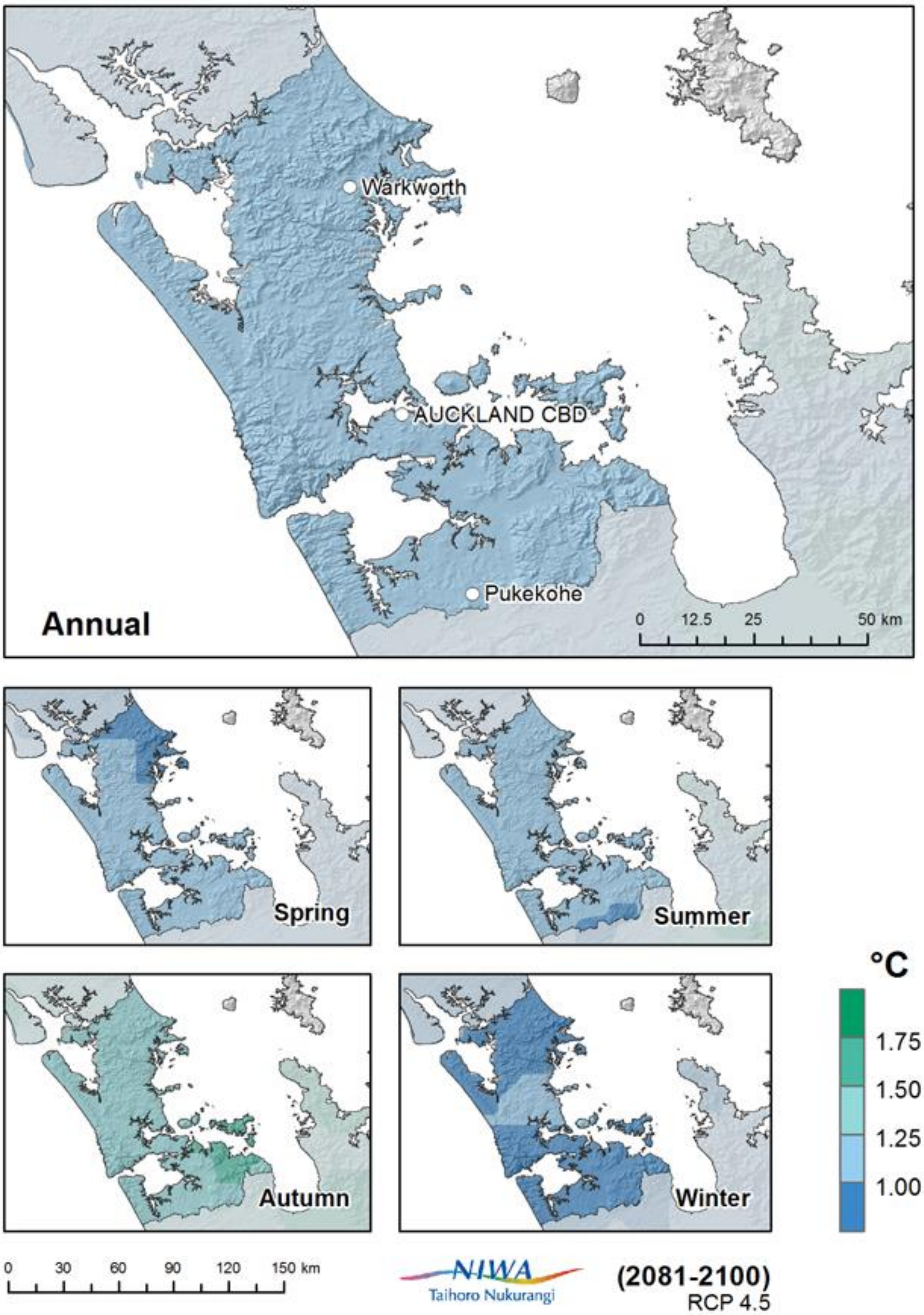

Figure 3-23: Projected annual and seasonal daily mean minimum temperature changes at 2090 (2081-2100 average) for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

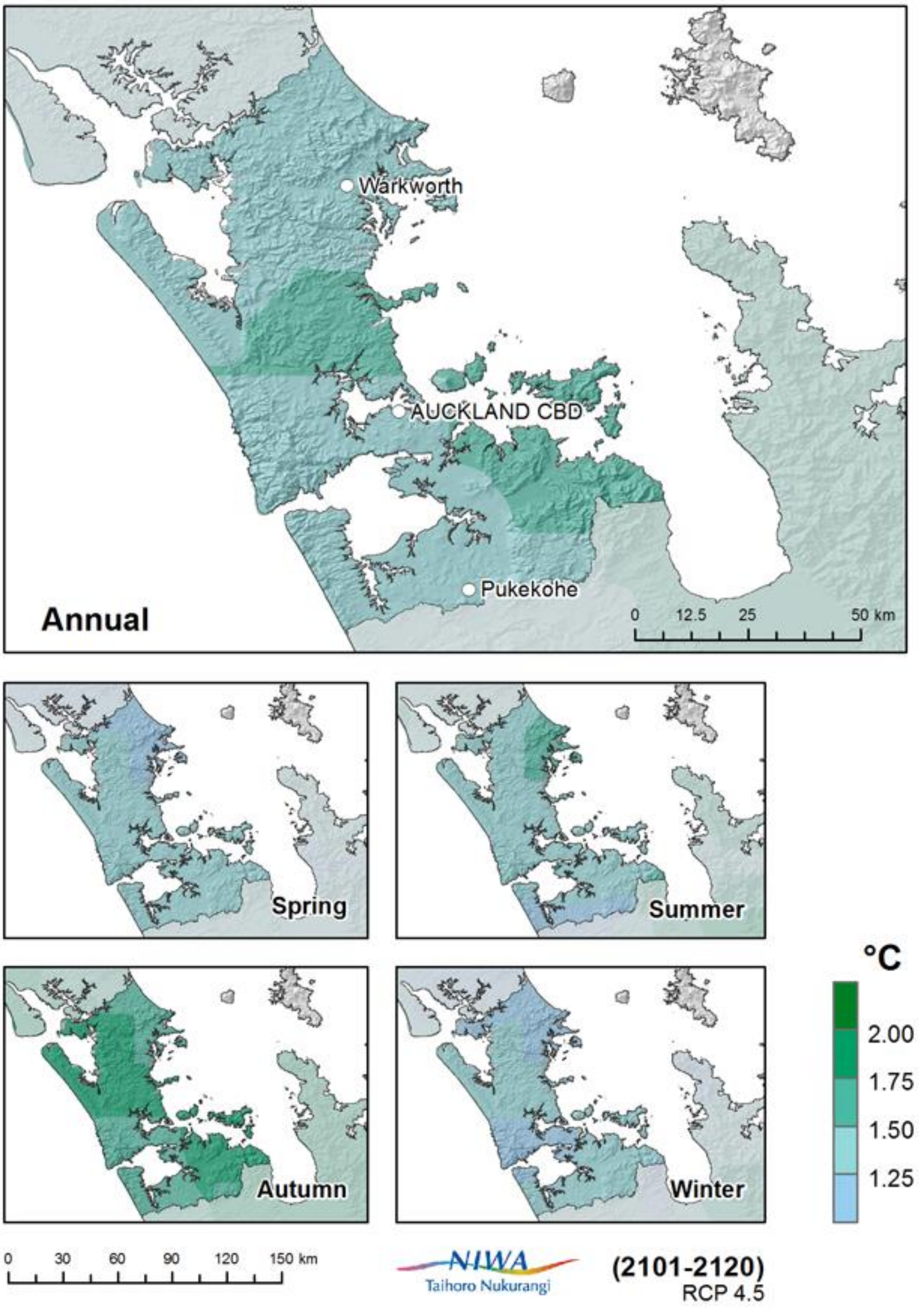

Figure 3-24: Projected annual and seasonal daily mean minimum temperature changes at 2110 (2101-2120 average) for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

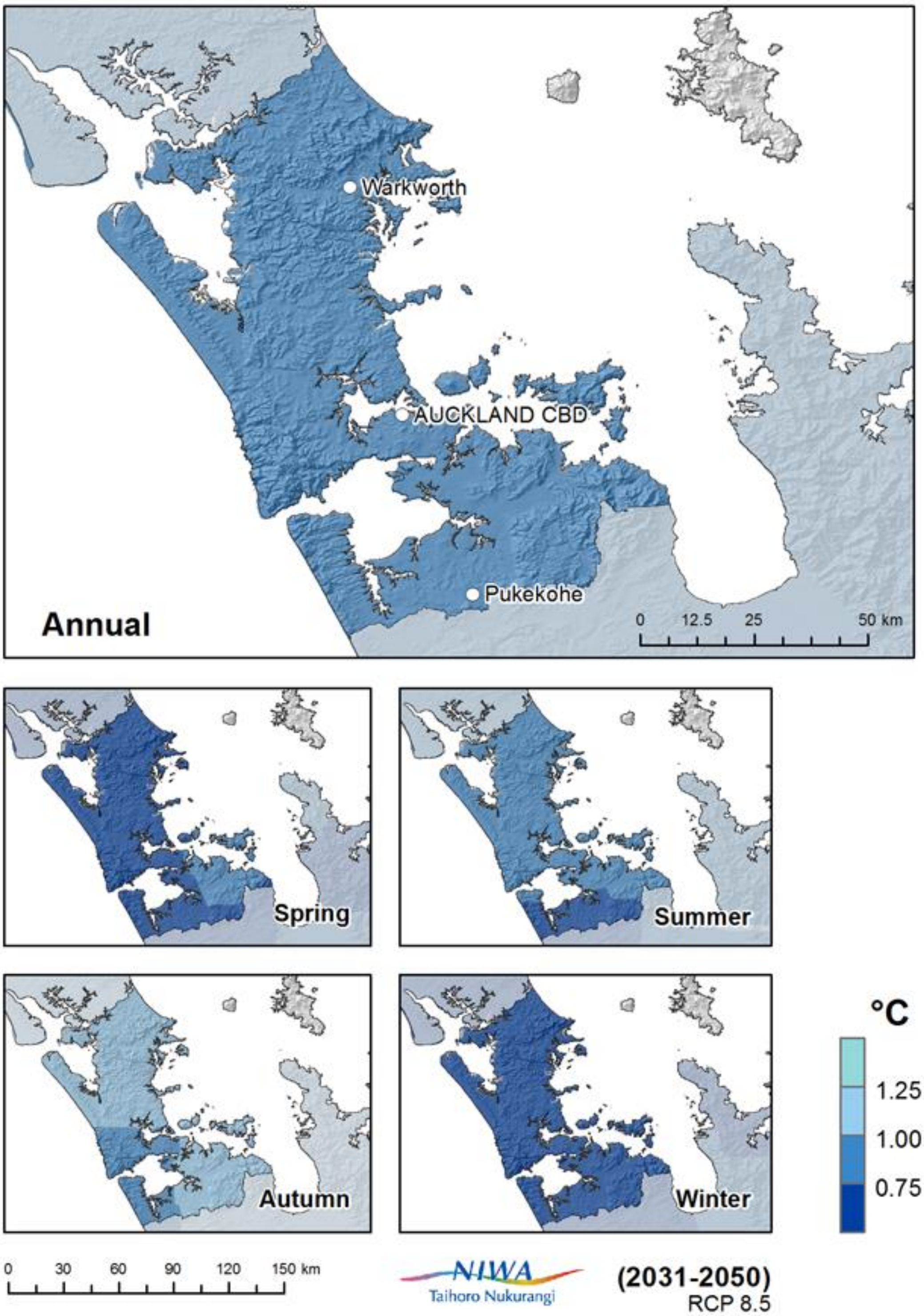

Figure 3-25: Projected annual and seasonal daily mean minimum temperature changes at 2040 (2031-2050 average) for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

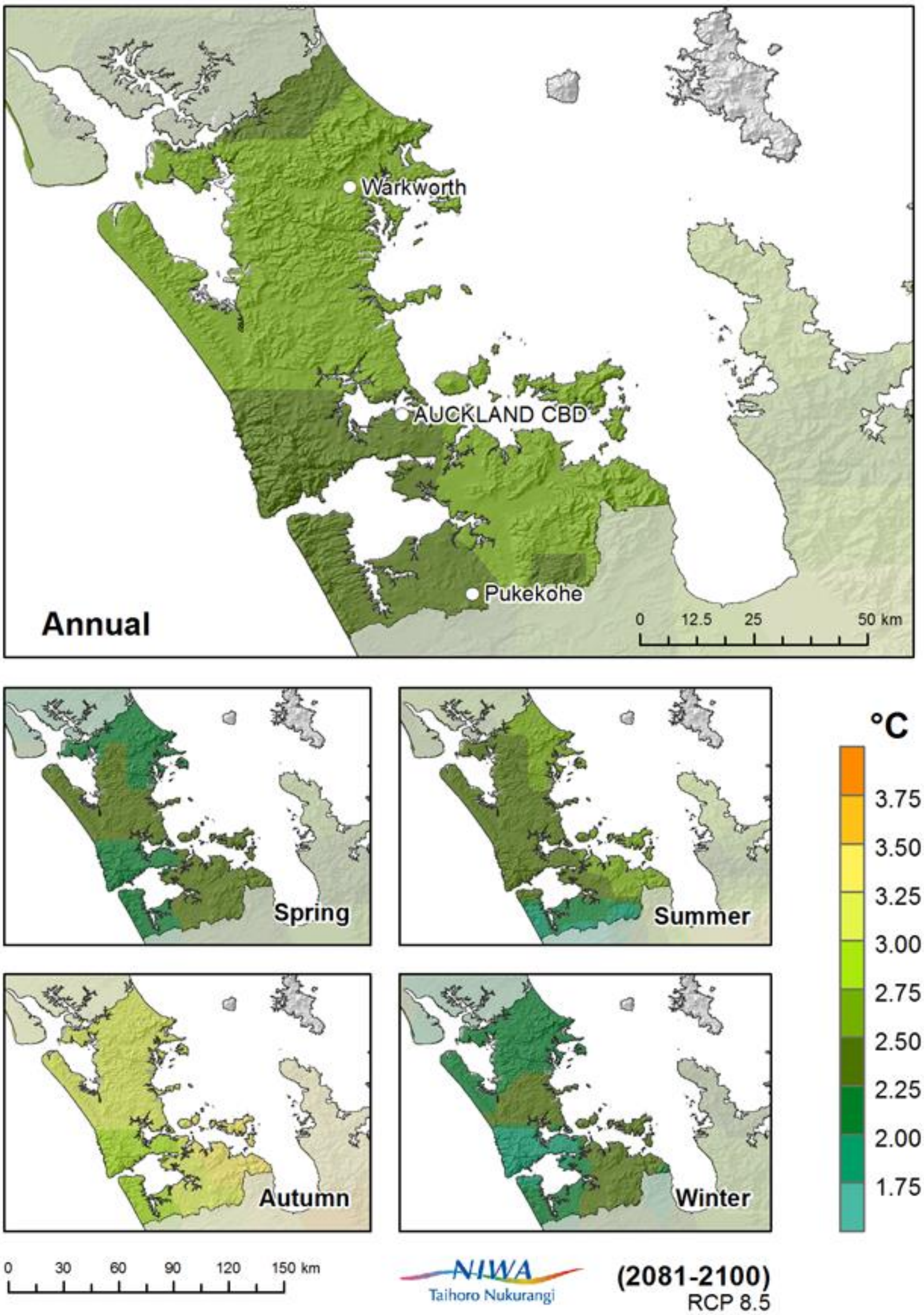

Figure 3-26: Projected annual and seasonal daily mean minimum temperature changes at 2090 (2081-2100 average) for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

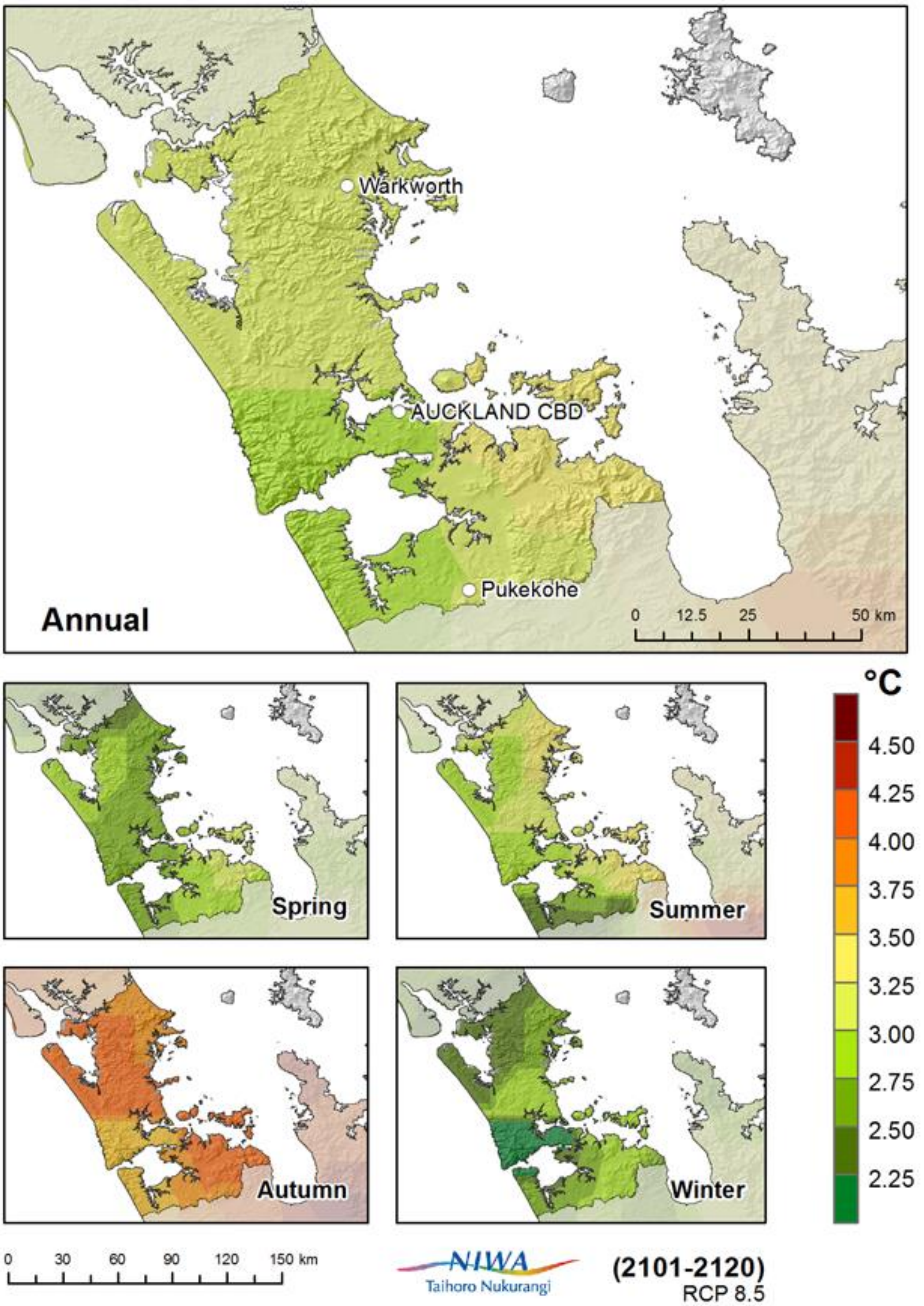

Figure 3-27: Projected annual and seasonal daily mean minimum temperature changes at 2110 (2101-2120 average) for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

3.3 Diurnal temperature range

Key messages

- Diurnal temperature range (the difference between daily maximum and daily minimum temperatures) has been decreasing over time in Auckland.
- Annual average diurnal range is projected to increase by 2040, 2090 and 2110 under both RCP4.5 and RCP8.5.
- Small decreases in diurnal range are projected for north Auckland in autumn under RCP4.5 and RCP8.5 at all time slices.

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

3.3.1 Present

The annual average diurnal range at Auckland Airport has varied between 6.4°C and 8.5°C since 1910 (Figure 3-28). There has been a decline in diurnal temperature range over this time, and this trend is statistically significant above the 95% confidence level.

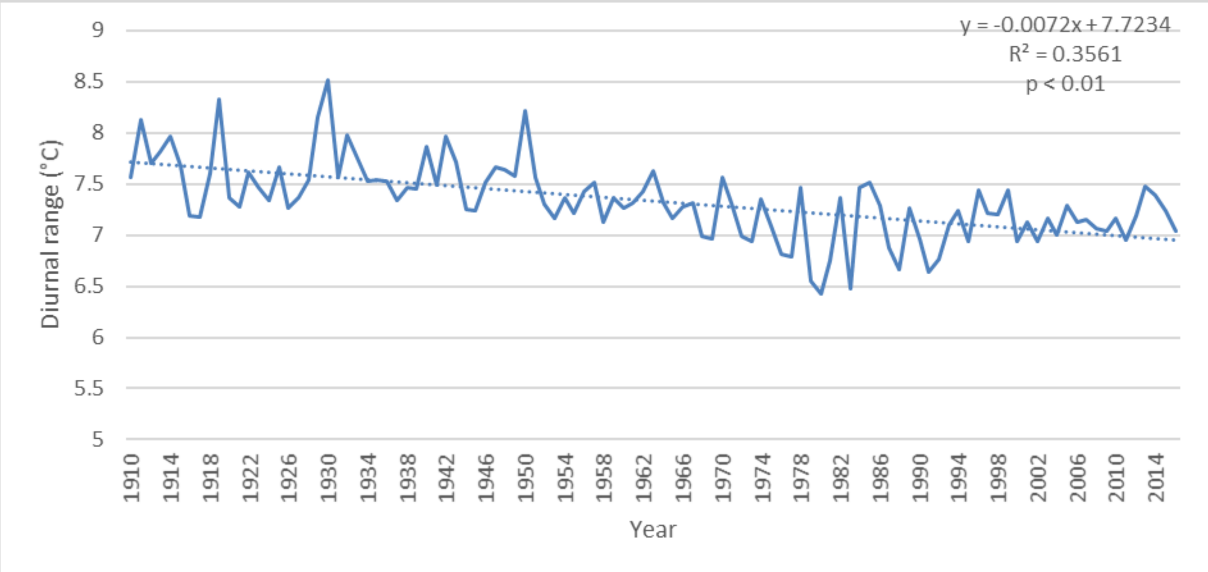

Figure 3-28: Diurnal temperature range (T_{max}-T_{min}) at Auckland, 1910-2016. This data is part of New Zealand's Seven Station Temperature Series and has been homogenised. The trend indicates a decrease of 0.7°C per century.

3.3.2 Future

Future projections for diurnal temperature range (T_{range}) in the Auckland Region are presented for RCP4.5 and RCP8.5 for three time slices, 2040, 2090 and 2110, in Figure 3-29 to Figure 3-34. The ensemble-average of six dynamically downscaled climate models is presented.

For RCP4.5 at all three time slices, the projections indicate most of the region will experience small increases in annual T_{range} of 0-0.25°C, with an increase of 0.25-0.50°C projected for the Waitakere Ranges and parts of the south of the Auckland Region by 2110 (Figure 3-29 to Figure 3-31). At the seasonal timescale, the north of the region projects small decreases in T_{range} for autumn at all time slices (0 to -0.25°C) and much of the region projects increases of 0.25-0.50°C in spring and summer at all time slices.

For RCP8.5, at 2040 there is a small increase in annual T_{range} across the region of 0-0.25°C (Figure 3-32). At 2090, most of the region projects an increase in annual T_{range} of 0.25-0.50°C (Figure 3-33), and at 2110 most of the region projects an increase in annual T_{range} of 0.25-0.75°C, with the largest changes projected for the Waitakere Ranges and the south of the region (Figure 3-34). For seasonal T_{range} projections, increases are projected for most of the region in spring, summer and winter at all time periods and decreases are projected for the north of the region in autumn at all time periods. The largest changes are projected for 2110.

Model agreement is good for T_{range} projections for summer, winter and spring under most time slices and RCPs, as most models project an increase in T_{range}.

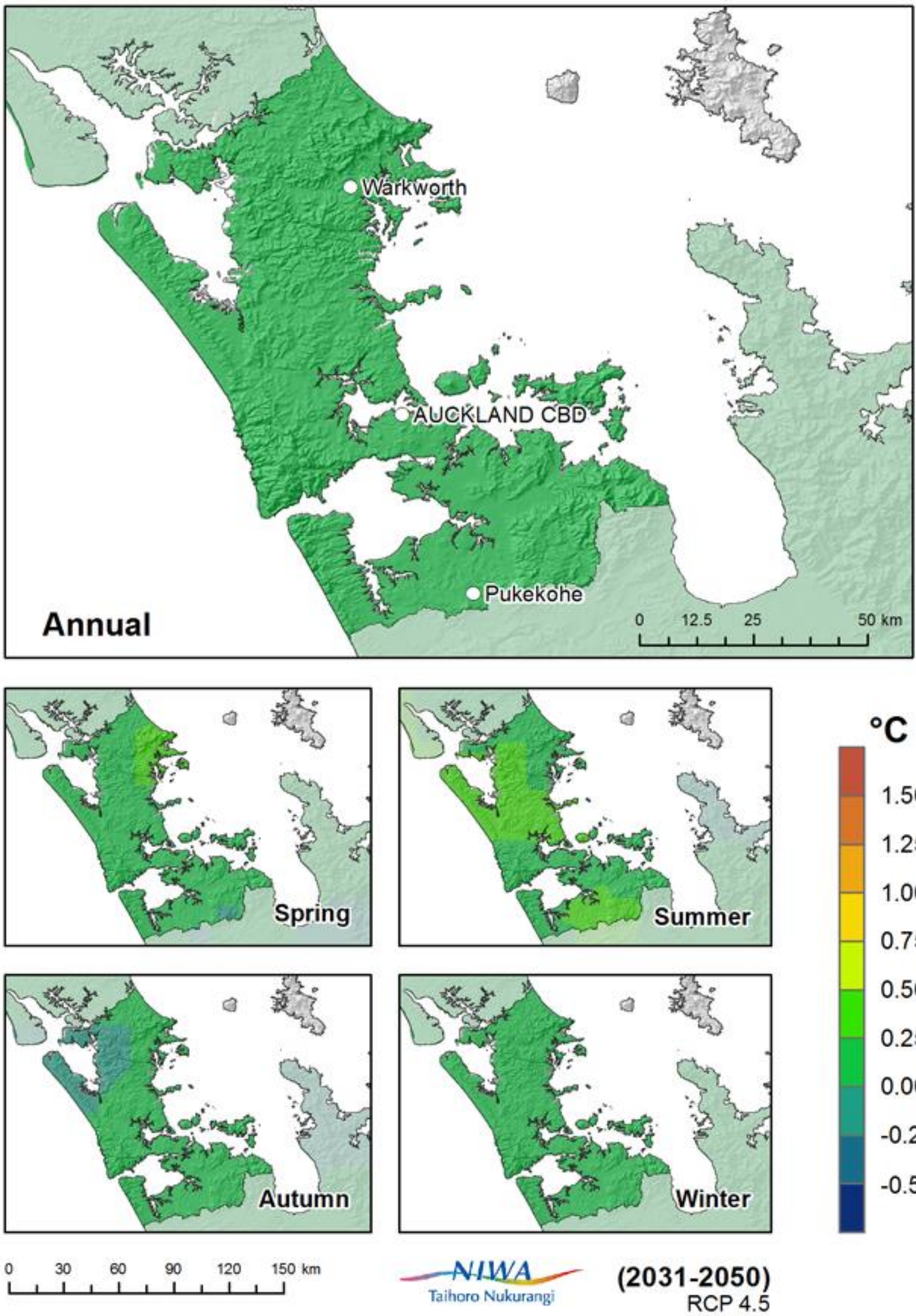

Figure 3-29: Projected annual and seasonal diurnal temperature range (Tmax minus Tmin) changes at 2040 (2031-2050 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

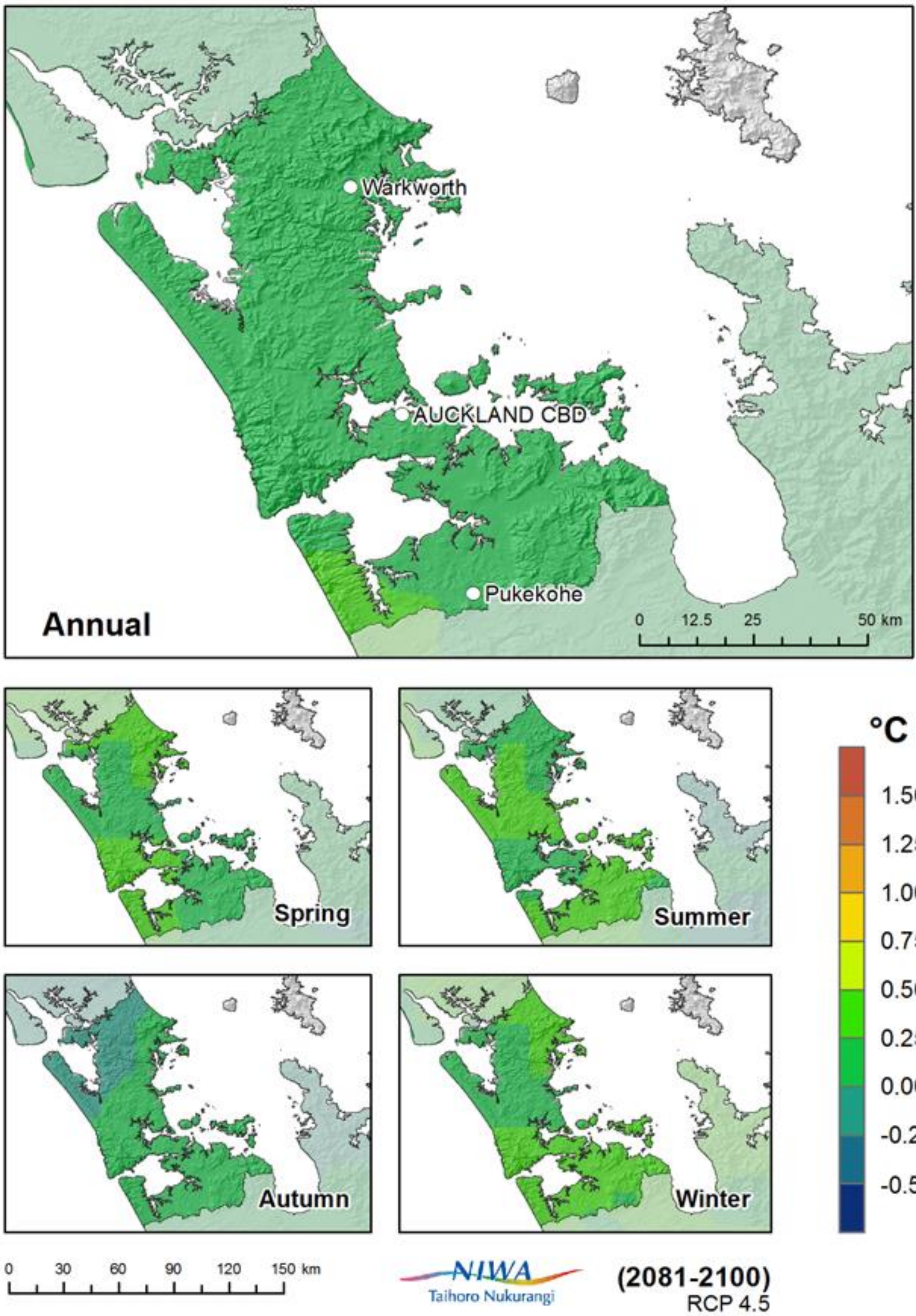

Figure 3-30: Projected annual and seasonal diurnal temperature range (Tmax minus Tmin) changes at 2090 (2081-2100 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

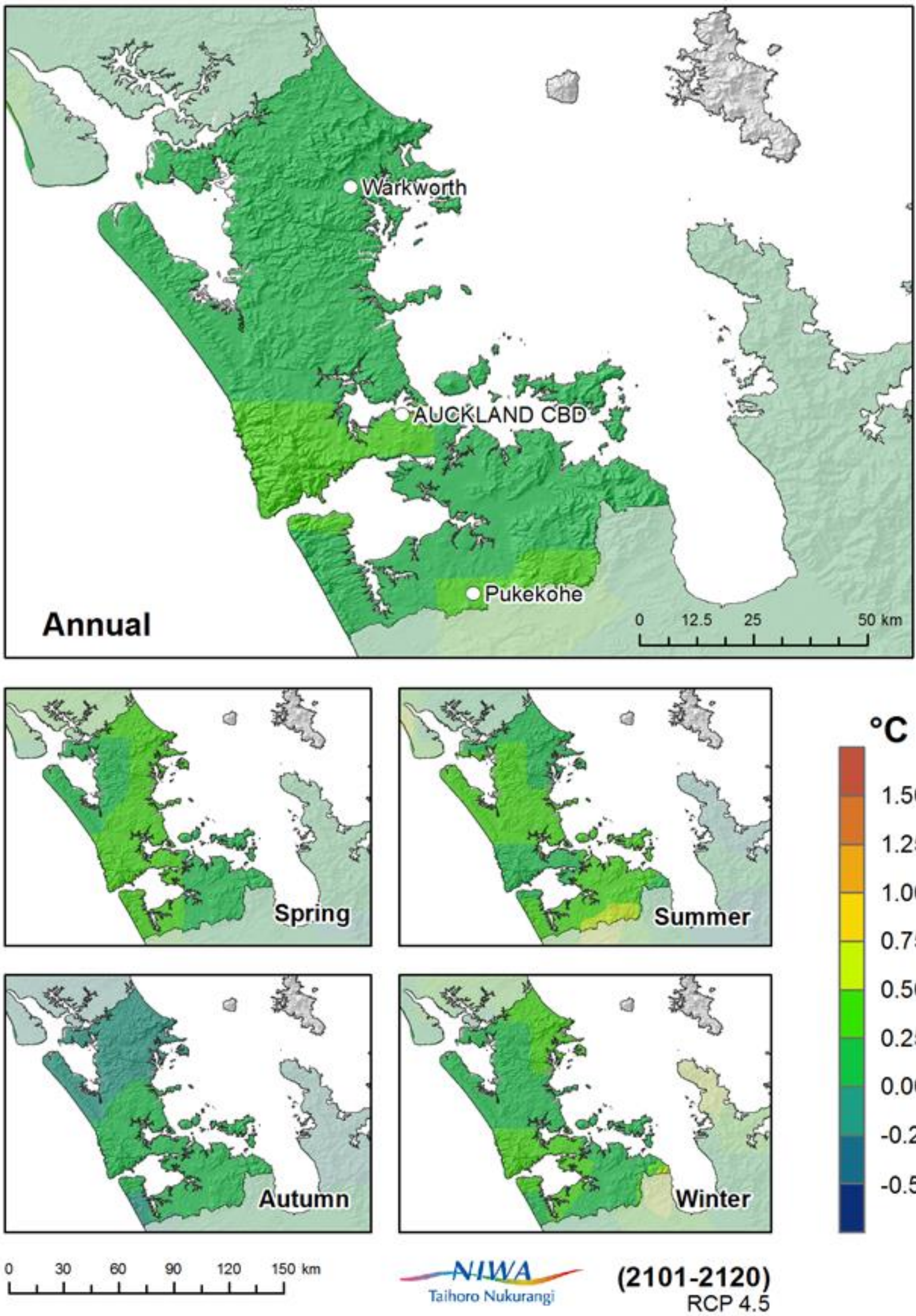

Figure 3-31: Projected annual and seasonal diurnal temperature range (Tmax minus Tmin) changes at 2110 (2101-2120 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

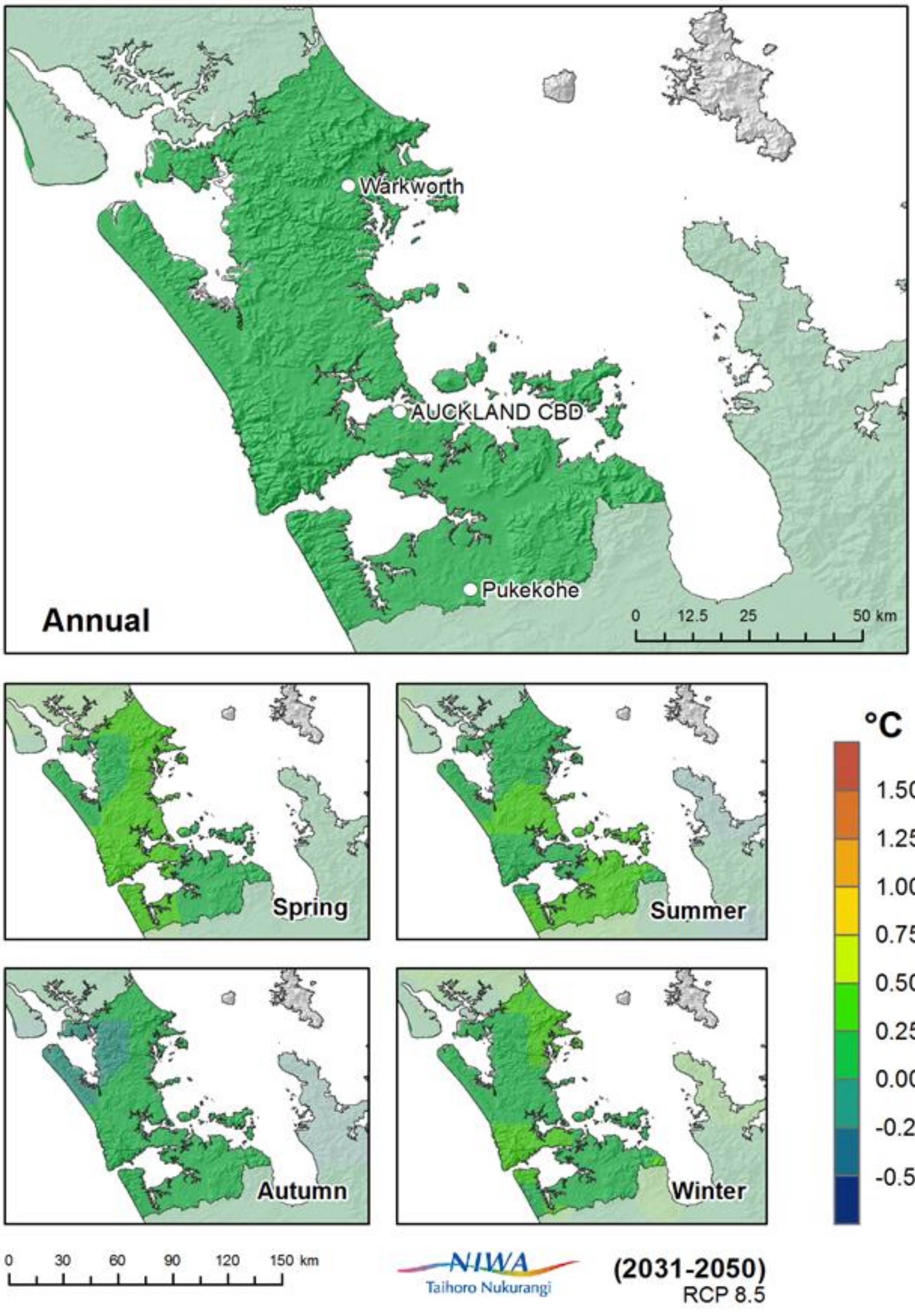

Figure 3-32: Projected annual and seasonal diurnal temperature range (Tmax minus Tmin) changes at 2040 (2031-2050 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

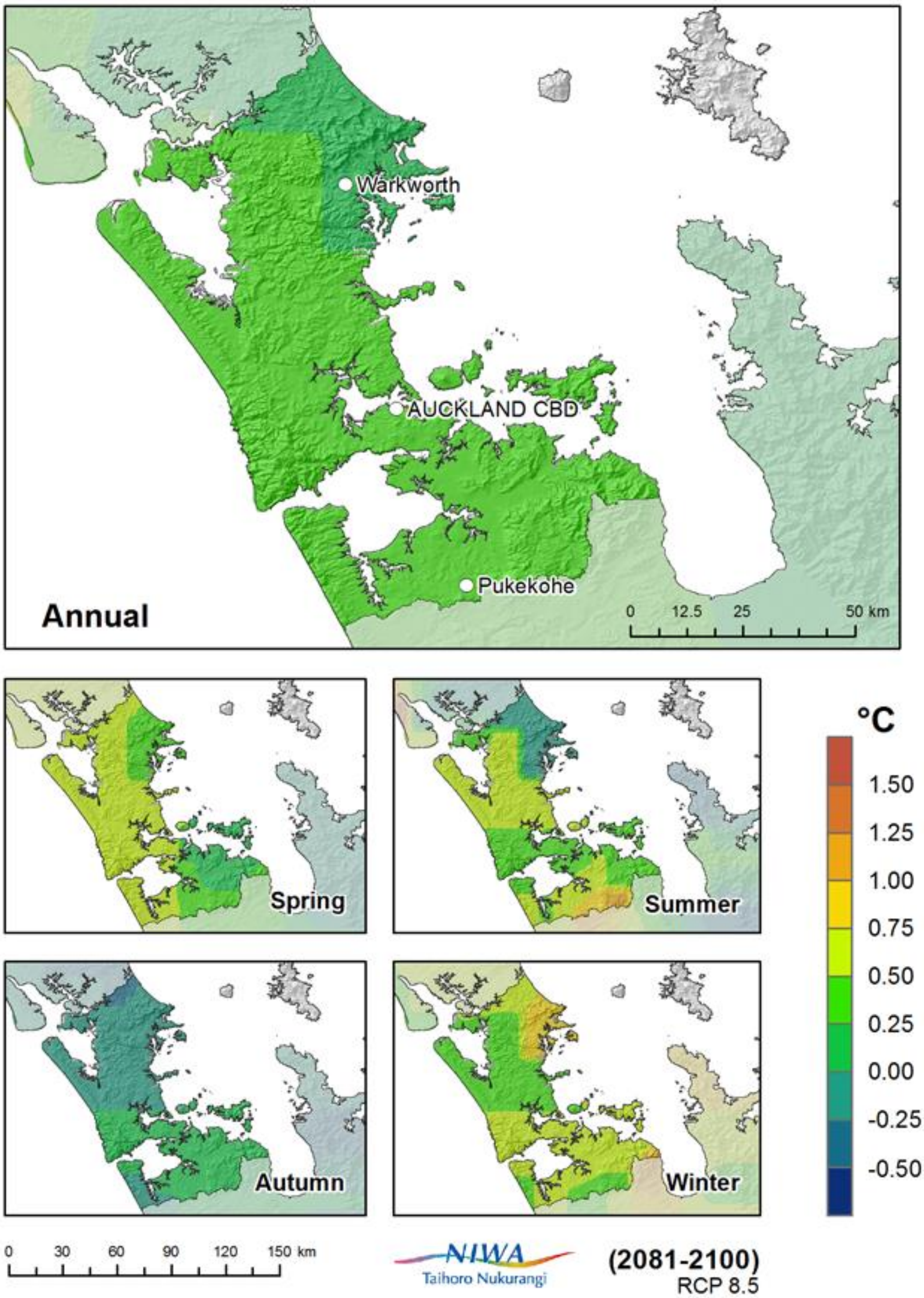

Figure 3-33: Projected annual and seasonal diurnal temperature range (Tmax minus Tmin) changes at 2090 (2081-2100 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

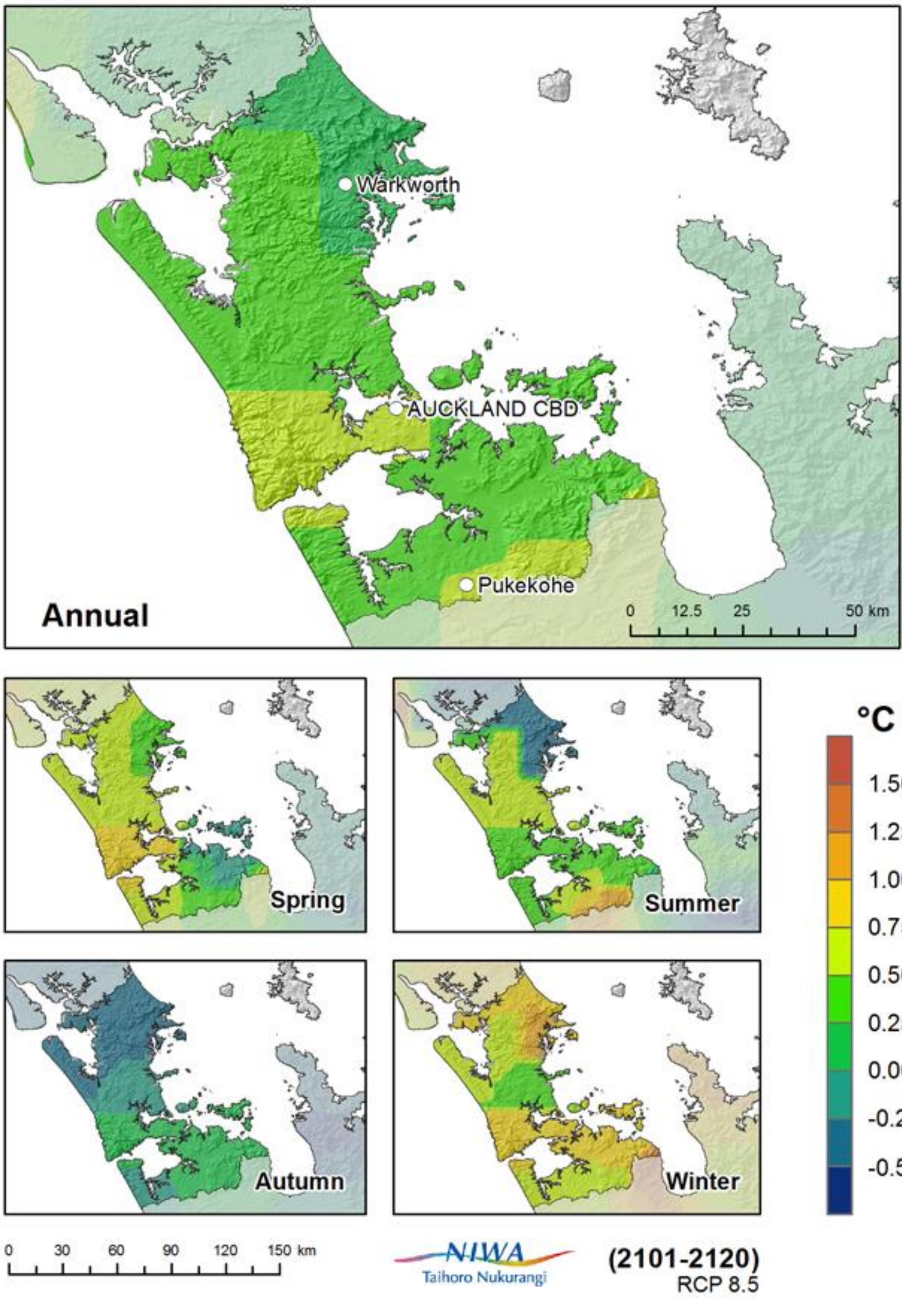

Figure 3-34: Projected annual and seasonal diurnal temperature range (Tmax minus Tmin) changes at 2110 (2101-2120 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

3.4 Temperature extremes

Key messages

- Hot days (maximum temperature > 25°C) have been increasing over time and are projected to continue increasing everywhere in the Auckland Region. Currently most of the region experiences 15-24 hot days per year.
- At 2110, an increase of 30-40 hot days is projected for most of the Auckland Region under RCP4.5 and an increase of more than 70 hot days is projected for most of the region under RCP8.5.
- Cold nights (minimum temperature < 0°C; frosts) have been decreasing over time and are projected to continue decreasing throughout the region. Currently most of the Auckland Region experiences fewer than 2 cold nights per year, with more nights occurring at higher elevations.
- The eastern and isthmus areas of the Auckland Region are projected to be frost-free under all climate change scenarios at all time periods. A small number of frosts are projected to still occur in the highest elevations of the Waitakere Ranges and Hunua Ranges, and also in the northwest of the region, at 2110 under RCP8.5.

Temperature extremes are presented as 'hot days', where the daily maximum temperature exceeds 25°C, and 'cold nights', where the daily minimum temperature is less than 0°C. Cold nights are also classified as frosts, as a screen frost occurs when air temperature is below 0°C at 1.2 m above the ground. Hot days are defined as 25°C or more because temperatures above this threshold are considered 'hot' given New Zealand's temperate maritime climate. Also, cattle begin to exhibit heat stress symptoms over 25°C.

3.4.1 Present

The current annual average number of hot days varies throughout the region, with the most observed in the southeast and isolated patches in the northwest (27-30 hot days per year) (Figure 3-35). The fewest hot days are observed in the northeast (three to six hot days per year) and the Waitakere Ranges (nine-12 hot days per year). Most of the region, including the Auckland Isthmus, currently experiences 15-24 hot days per year.

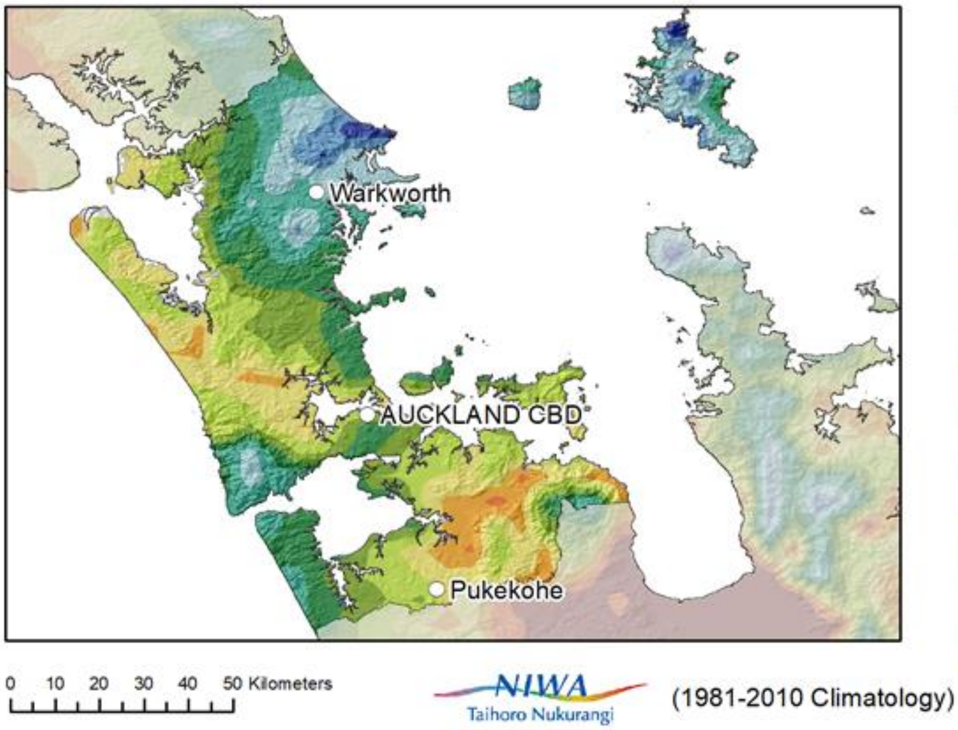

Figure 3-35: Average annual number of hot days in the Auckland Region (Tmax >25°C), 1981-2010. Based on data from NIWA's Virtual Climate Station Network.

In terms of cold nights or frosts, most are currently observed in the Hunua Ranges in the southeast of the region (over eight cold nights per year on average) and the northwest of the region (four to five cold nights per year on average) (Figure 3-36). Most of the rest of the region experiences fewer than two cold nights per year on average, particularly in the east and the isthmus which observe less than one cold night or frost per year on average.

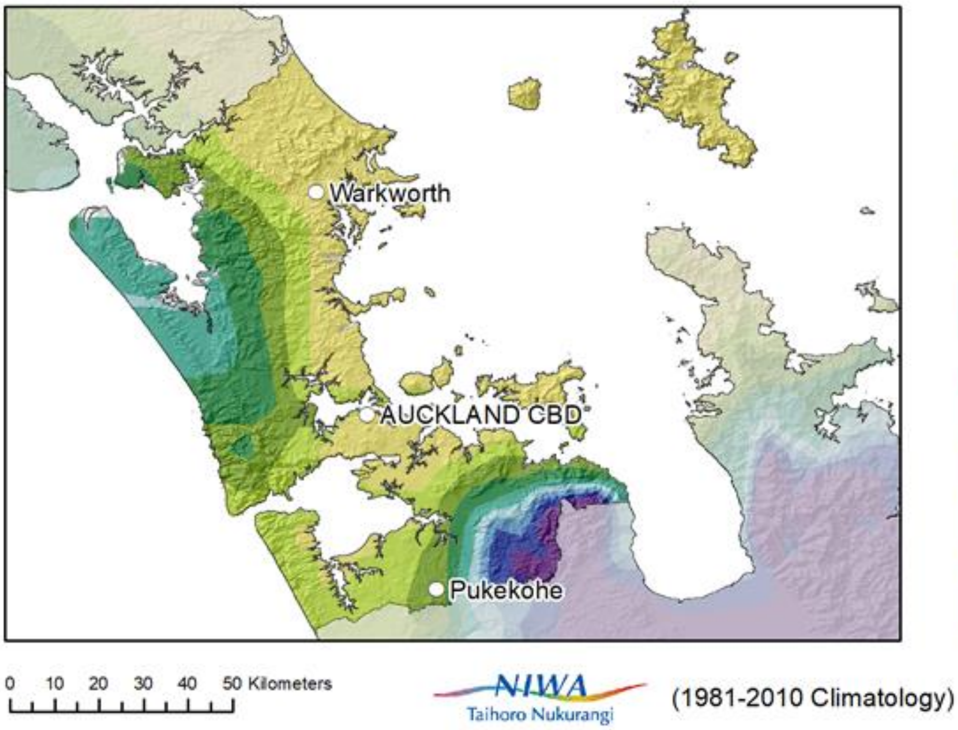

Figure 3-36: Average annual number of cold nights (frosts) in the Auckland Region (Tmin <0°C), 1981-2010. Based on data from NIWA's Virtual Climate Station Network.

There is a trend of increasing annual mean temperature in Auckland (Section 3.1.1), and consequently changes in extreme temperatures. Figure 3-37 shows the number of hot days per year since 1966 at Auckland Airport and Figure 3-38 shows the number of ground frosts (when the grass minimum temperature is <0°C) per year since 1966 at Auckland Airport. Auckland has observed an increasing number of hot days and a decreasing number of ground frosts since the mid-20^{th} century. Both trends are statistically significant above the 95% confidence level. Ground frosts are shown here rather than screen frosts because there are many years when no screen frosts are recorded at Auckland Airport, and ground frosts show a statistically significant trend.

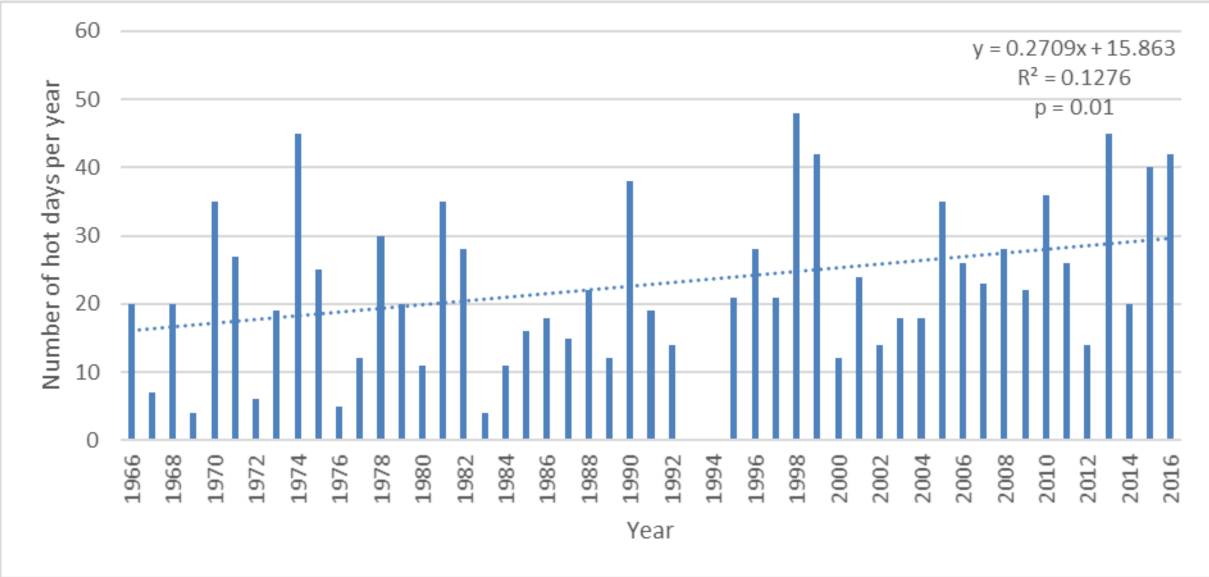

Figure 3-37: Number of hot days (Tmax >25°C) per year at Auckland Airport, 1966-2016. Trend indicates an increase of about three hot days per decade. There was a gap in observations at Auckland Airport during 1993 and 1994.

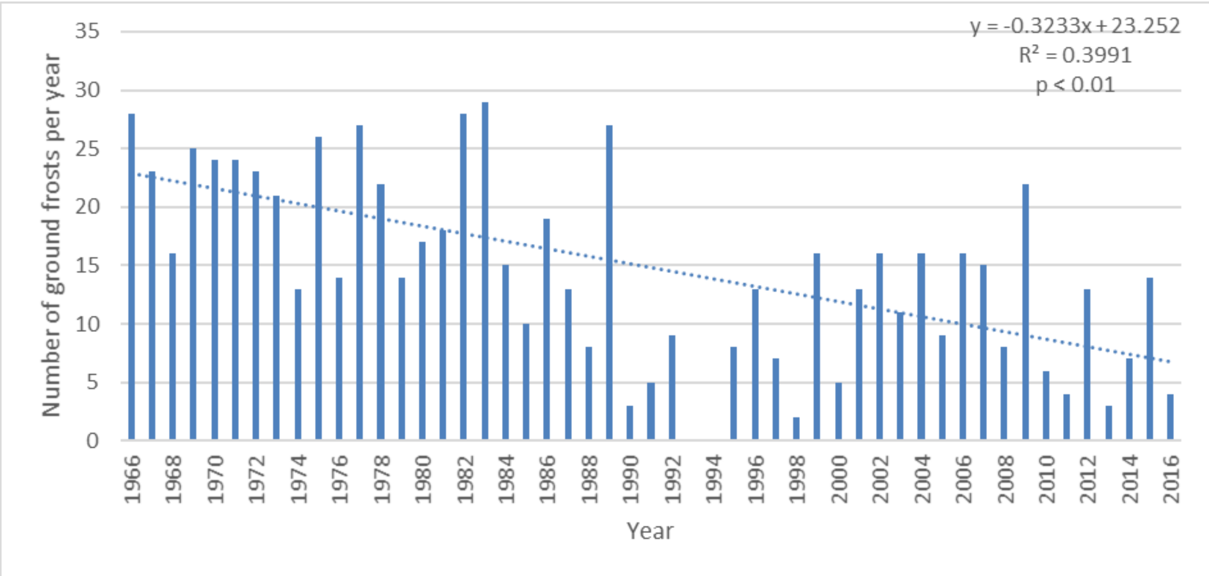

Figure 3-38: Number of ground frosts (grass minimum temperature <0°C) per year at Auckland Airport, 1966-2016. Trend shows a decrease of approximately three ground frosts per decade. There was a gap in observations at Auckland Airport during 1993 and 1994.

3.4.2 Future

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.

Projections for hot days and cold nights 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 slice over the modelled interval. Finally, the climate change signal was computed by averaging the change (with respect to the reference period) over the number of models (six).

The projected increase in the number of hot days per year at 2040, 2090 and 2110 relative to 1995, for RCP4.5 and RCP8.5 is shown in Figure 3-39.

At 2040, the Auckland isthmus is projected to experience increases in hot days of 10-20 days per year for RCP4.5 and 15-20 days per year for RCP8.5. Northeast Auckland is projected to experience 10-20 more hot days per year under both RCPs at 2040. An increase of 15-20 hot days per year is projected for most of the rest of the region under RCP4.5, and 10-15 more hot days per year are projected for the Waitakere Ranges and Hunua Ranges. Under RCP8.5 at 2040, some central and southeast parts of Auckland as well as the Hauraki Gulf islands are projected to experience 20-25 more hot days per year, and 10-15 more hot days per year are projected for the Waitakere Ranges and the Hunua Ranges.

At 2090 under RCP4.5, most of the region is projected to experience 25-30 more hot days per year. The Waitakere Ranges and the southwest of the region are projected to experience 15-20 more hot days per year. Under RCP8.5 at 2090, an increase of at 50-60 hot days is projected for most of the region, with the 40-50 more hot days projected for the Waitakere Ranges and some parts of northeast and southwest Auckland. Some north-central and southeast areas of the region are projected to experience 60-70 more hot days per year.

At 2110, an increase of 30-40 hot days is projected for most of the Auckland Region under RCP4.5, with less warming for the southwest and northeast areas of Auckland. Under RCP8.5, an increase of more than 70 hot days are projected almost everywhere, with more than 90 extra hot days projected for some north-central and southern areas, as well as the Hauraki Gulf islands.

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

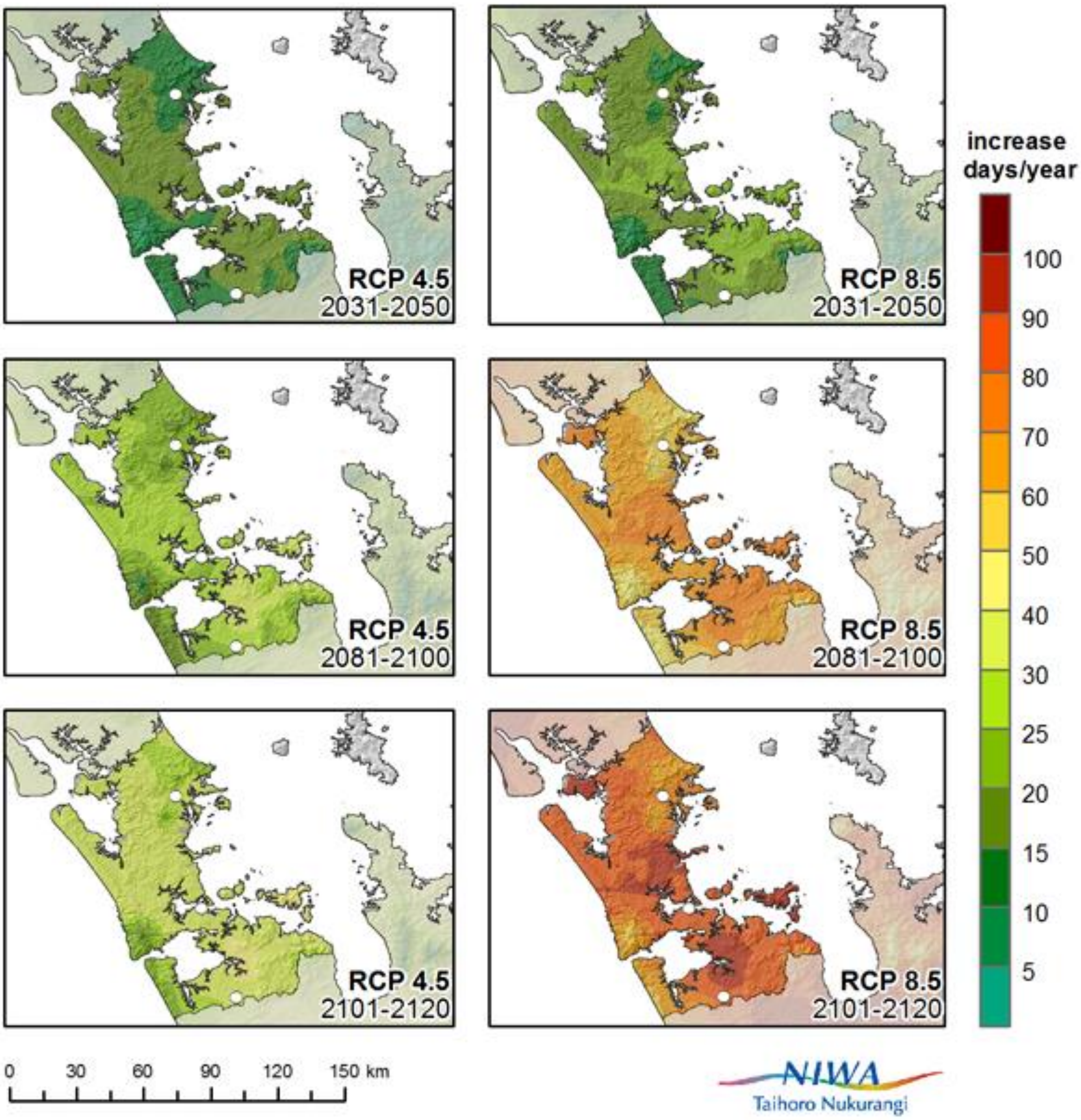

Figure 3-39: Projected increase in number of hot days per year (T_{max} >25°C) at 2040 (2031-2050), 2090 (2081-2100) and 2110 (2101-2120) for RCP4.5 (left panels) and RCP8.5 (right panels), for the Auckland Region. Projected change in hot days is relative to 1986-2005. The numbers on the scale refer to the *increase* in the number of hot days, e.g. the area around Auckland CBD is projected to experience 80-90 more hot days per year by 2110 under RCP8.5 (red shades, lower right panel). Results are based on dynamically downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km. White dots correspond to (north-south) Warkworth, Auckland CBD, Pukekohe.

The projected decrease in the number of cold nights (i.e. frosts) per year at 2040, 2090 and 2110 relative to 1995, for RCP4.5 and RCP8.5 is shown in Figure 3-40. Similar patterns are shown for changes in cold nights at 2040 under both RCP4.5 and RCP8.5. Most parts of the region outside of the high elevation Hunua Ranges are projected to experience a decrease of one cold night per year. Cold nights in the Hunua Ranges are projected to decrease by up to three nights per year at 2040.

By 2090, one fewer cold night is projected for most of the region under RCP4.5, and up to two fewer cold nights are projected for parts of northwest Auckland and the Waitakere Ranges. Up to three fewer cold nights are projected for the Hunua Ranges. Under RCP4.5 at 2110, a larger area of western Auckland is projected to experience up to two fewer cold nights than at 2090. For RCP8.5 at 2090, most of the western Auckland Region is projected to experience one to three fewer cold nights per year, and up to eight fewer cold nights for the high elevations in the Hunua Ranges. This pattern is largely the same for RCP8.5 at 2110.

Therefore, under all future climate change scenarios and time periods the eastern and isthmus parts of the region are projected to experience no frosts. By 2110 under RCP8.5 most of the region including the Waitakere and Hunua Ranges, except for the highest elevations, are also projected to experience no frosts. Northwest parts of the Auckland Region are projected to experience one to two frosts per year under RCP8.5 at 2110. The climate change projections are at a 5 km resolution so more local-scale frosts may still be observed where cold air may settle, for example on valley floors.

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

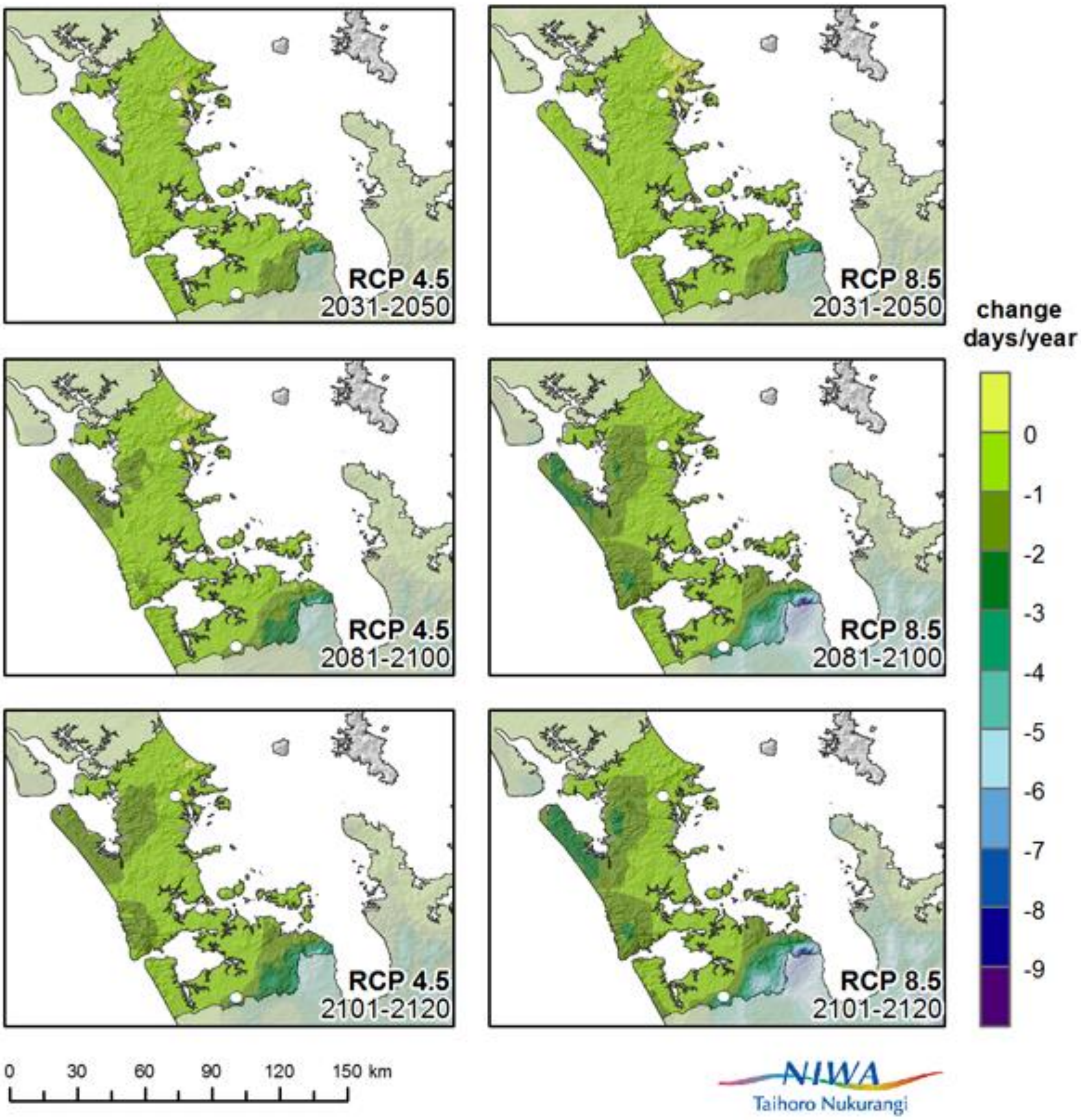

Figure 3-40: Projected decrease in number of cold nights (frosts) per year (Tmin <0°C) at 2040 (2031-2050), 2090 (2081-2100) and 2110 (2101-2120) for RCP 4.5 (left panels) and RCP8.5 (right panels), for the Auckland Region. Projected change in cold nights is relative to 1986-2005. The numbers on the scale refer to the *decrease* in the number of cold nights, e.g. parts of the Hunua Ranges are projected to experience eight fewer cold nights per year under RCP8.5 at 2110 (blue shades, lower right panel). Results are based on dynamically downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km. White dots correspond to (north-south) Warkworth, Auckland CBD, Pukekohe.

3.5 Growing degree-days

Key messages

- There has been an upward trend in the annual number of growing degree-days in Auckland since the mid-20th century.
- The number of growing degree-days is projected to increase in the future, which will likely influence the growing rate of plants, harvest times, and the types of plants able to be grown in the Auckland Region.

Growing degree-days (GDD) express the sum of daily temperatures above a selected base temperature (e.g. 10˚C) that represent a threshold for plant growth. The average amount of growing degree-days in a location may influence the choice of crops to grow, as different species have different temperature thresholds for survival. The daily GDD total is the amount the daily average temperature exceeds the threshold value (e.g. 10°C) per day. For example, a daily average temperature of 18°C would have a GDD base 10°C value of 8 and a GDD base 5°C value of 13. The daily GDD values are accumulated over the period 1 July to 30 June to calculate an annual GDD value.

3.5.1 Present

The number of current growing degree-days follows the same spatial pattern as mean temperature, with the highest number along the east coast and on the Auckland Isthmus, and the lowest number in the Hunua Ranges in the southeast of the region. Most of the region experiences about 3400-3700 GDD per year with base 5°C and 1700-2000 GDD per year with base 10°C. The present number of growing degree-days in Auckland is shown for base 5°C and base 10°C in Figure 3-41.

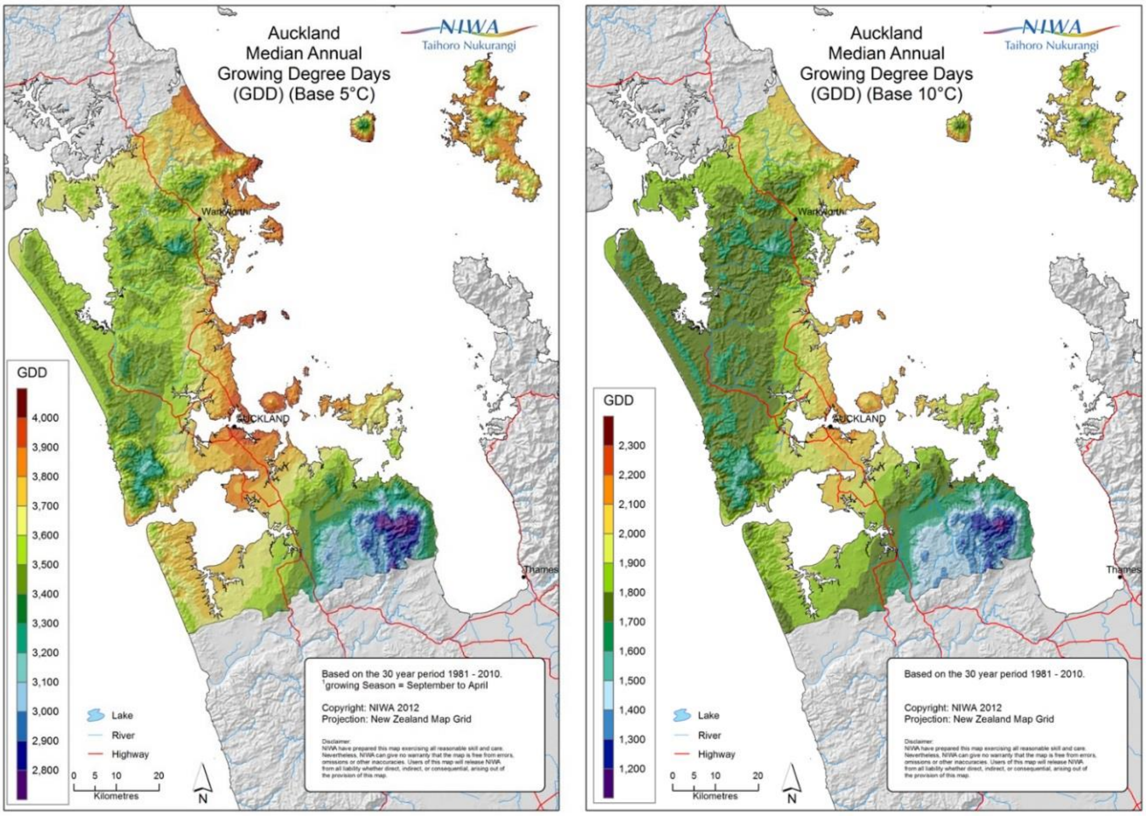

Figure 3-41: Median annual Growing Degree-Days (GDD) (base 5°C (left) and base 10°C (right)) for Auckland (1981-2010). Note the change in scale between maps. Based on data from NIWA's Virtual Climate Station Network.

Air temperatures in the Auckland Region have increased over the past century (Section 3.1.1). 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 3-42). This trend is not statistically significant at or above the 95% confidence level.

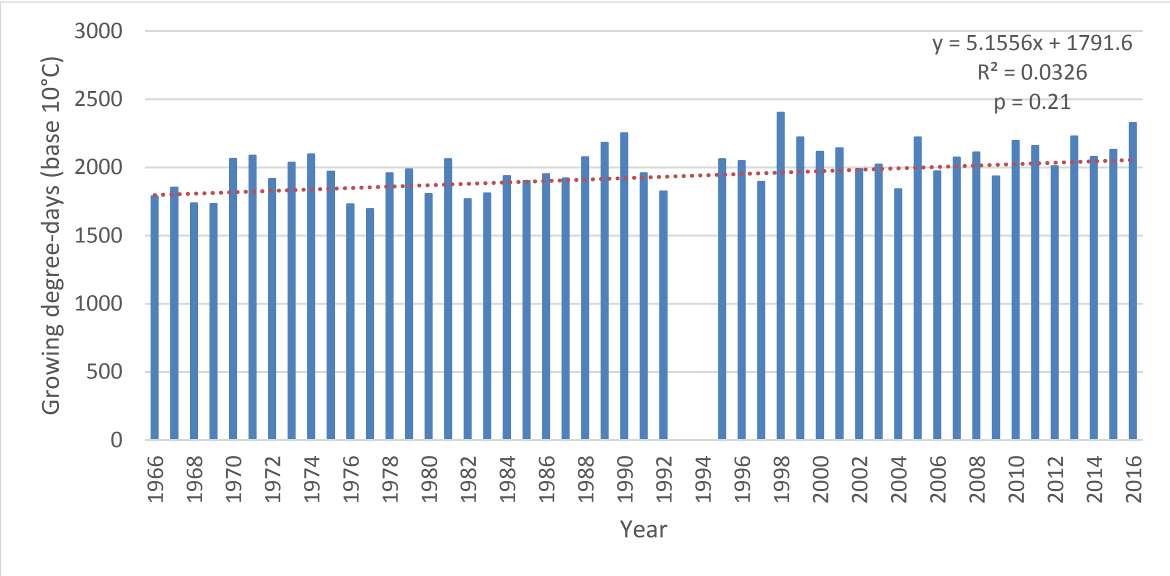

Figure 3-42: Annual growing degree-days (base 10°C) at Auckland Airport, 1966-2016. This trend indicates an increase of approximately 5 GDD per year. There was a gap in observations at Auckland Airport in 1993 and 1994.

3.5.2 Future

Projections for growing degree days using base 5°C and base 10°C are presented in Figure 3-43 and Figure 3-44, respectively. The base temperature is different for different organisms and is based on the minimum temperature threshold for growth of that organism. 5°C is the optimal base temperature for wheat and 10°C the optimal base temperature for maize (corn). The future number of growing degree days has been calculated from dynamically downscaled daily temperature using NIWA's Regional Climate Model, and the ensemble-average of the six dynamically downscaled models is presented.

By 2040, growing degree days (base 5°C) under RCP4.5 are projected to increase by 200-300 GDD for the entire Auckland Region (Figure 3-43). Under RCP8.5, GDD base 5°C is expected to increase by 300-400 GDD the entire region. At 2090, further increases in GDD are shown, with an increase of 400-500 GDD projected for the region under RCP4.5, and an increase of 900-1100 GDD for RCP8.5 (the higher amounts of GDD are projected in the southeast and central-north). At 2110, an increase of 500-600 GDD is projected for the region for RCP4.5 and an increase of 1100-1300 GDD is projected for RCP8.5 (the higher amounts of GDD are projected in a swathe from northwest to southeast across the region) (Figure 3-43).

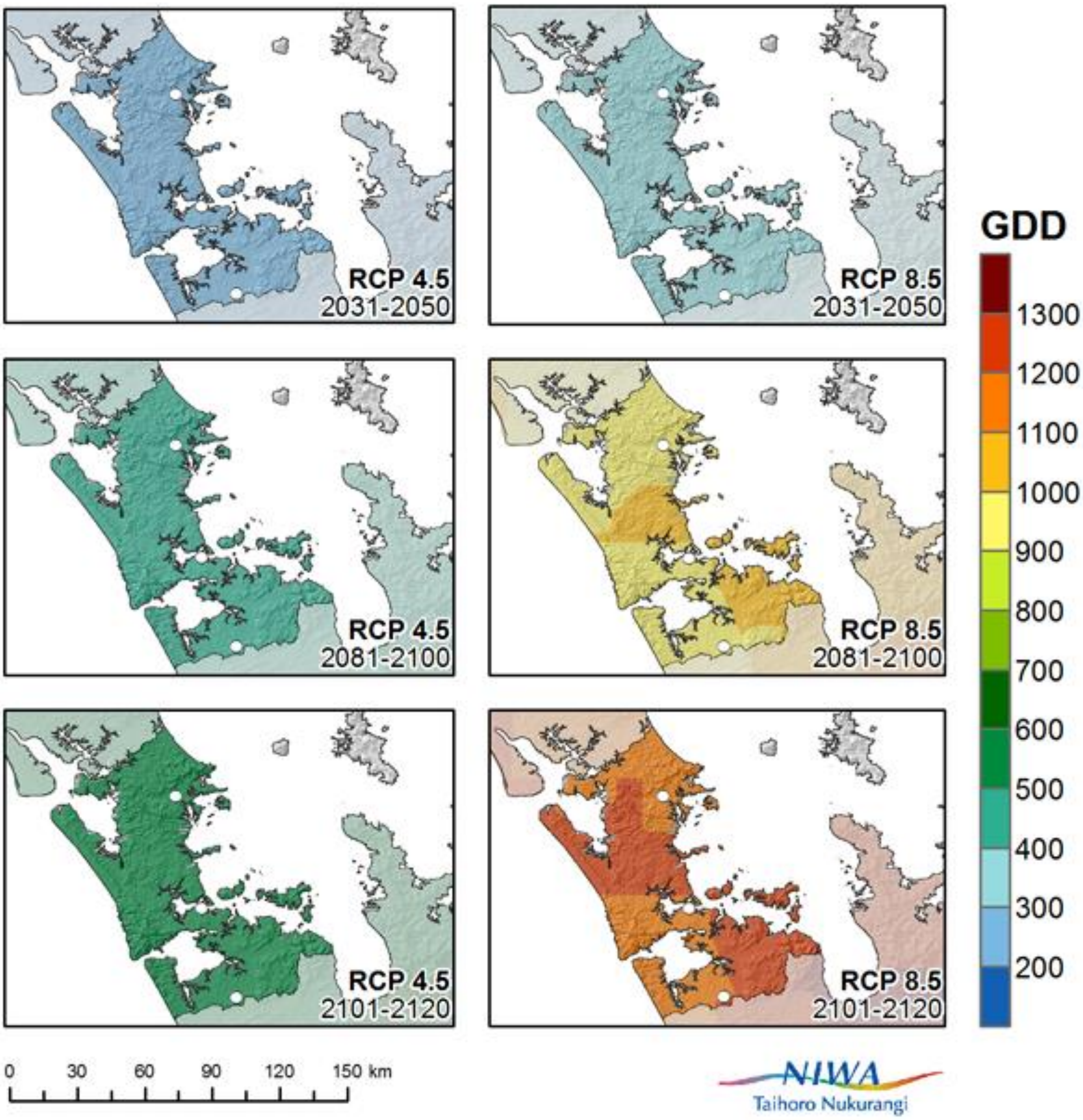

Figure 3-43: Projected increase in number of growing degree days per year (base 5°C) at 2040 (2031-2050), 2090 (2081-2100) and 2110 (2101-2120) for RCP4.5 (left panels) and RCP8.5 (right panels), for the Auckland Region. Projected change in growing degree days is relative to 1986-2005. Results are based on dynamically downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km. White dots on map refer to (north-south) Warkworth, Auckland CBD, Pukekohe.

As with GDD base 5°C, GDD base 10°C increases with time and RCP forcing (Figure 3-44). The projections of GDD base 5°C and GDD base 10°C are very similar, although there are some slightly lower increases in GDD base 10°C for some areas of Auckland (relative to GDD base 5°C). This difference is because most days experience temperatures >10°C in the region; therefore, the projected change does not show much difference between GDD base 5°C and GDD base 10°C.

The increase in GDD will likely influence the types of crops that can be grown at a location, and harvesting times for crops into the future – one would expect to see crops only suitable for warmer northern climates at present move further south as the climate warms, and harvesting times for crops presently grown in the Auckland Region may shift to an earlier time in the season.

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

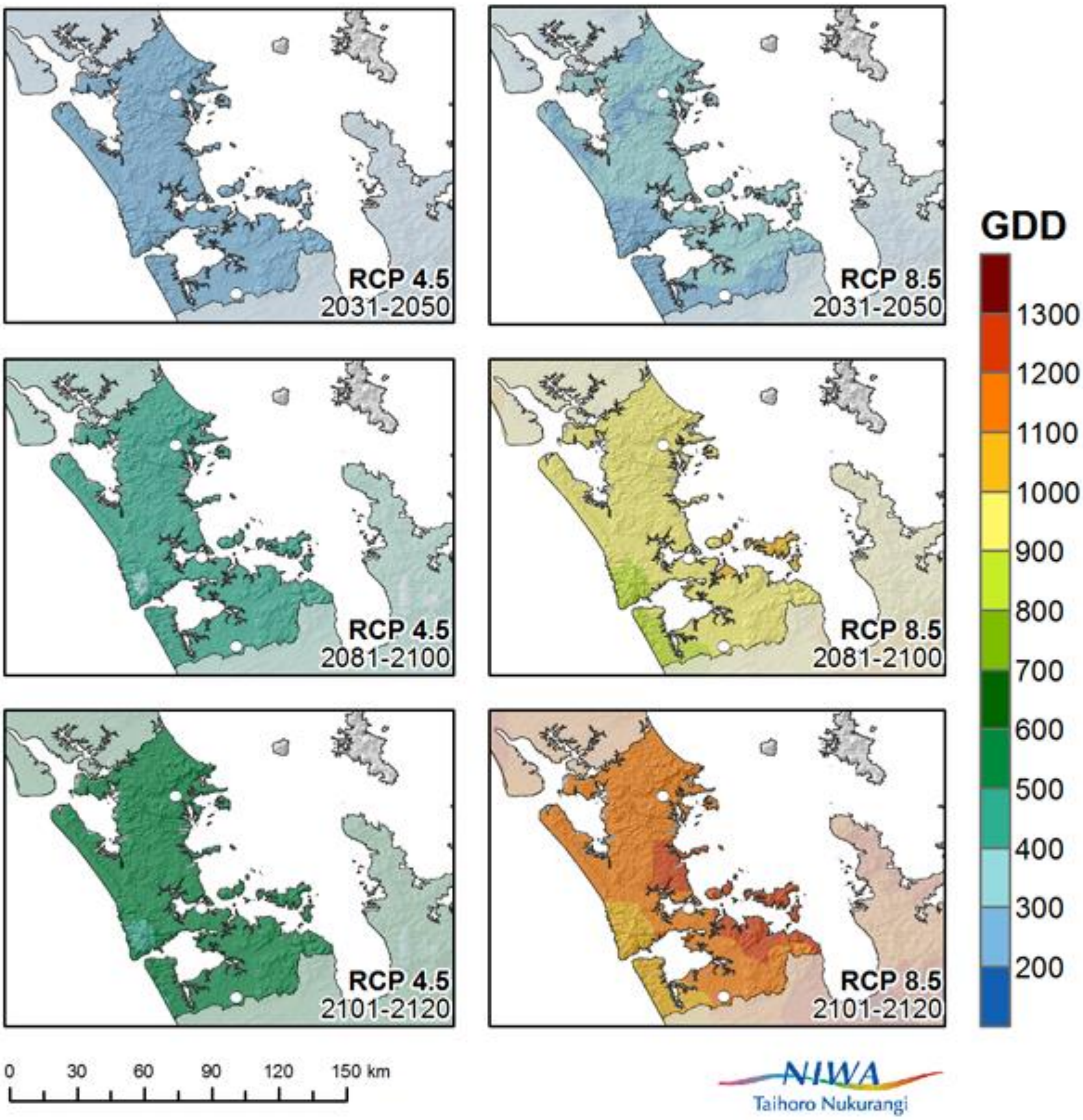

Figure 3-44: Projected increase in number of growing degree days per year (base 10°C) at 2040 (2031-2050), 2090 (2081-2100) and 2110 (2101-2120) for RCP4.5 (left panels) and RCP8.5 (right panels), for the Auckland Region. Projected change is relative to 1986-2005. Results are based on dynamically downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km. White dots on map refer to (north-south) Warkworth, Auckland CBD, Pukekohe.

3.6 Temperature projections within RCPs

Key messages

- All models show future warming for Auckland for all RCPs at 2040, 2090 and 2110.
- Model spread increases with time and RCP forcing (i.e. more spread for RCP8.5 than RCP2.6).
- Summer is the season with the greatest model spread.

The average picture of projected temperature changes in the tables and maps earlier in this section obscures significant variations between the individual models run under each RCP on the projected seasonal changes. Figure 3-45 to Figure 3-47 show seasonal and annual temperature projections from all the models individually averaged over the Auckland Region for 2040, 2090, and 2110, respectively. The coloured vertical bars, and inset stars, show the individual models, so the complete range is displayed (unlike Table 3-1, where the 5th to 95th percentile range has been calculated). Figure 3-45 to Figure 3-47 are a clear way of demonstrating not only 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.

For 2040 (Figure 3-45), all four RCPs project quite similar mean temperature 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 RCP8.5 have the greatest spread, particularly in summer and secondly for winter (the red bars). For 2090 (Figure 3-46), the model spread is much larger, with the models for summer for RCP8.5 spread across about 3.5°C of warming. However, the models all agree on the direction of change (i.e. warming). For 2110 (Figure 3-47), the results for each RCP are also spread out, with a range of about 3.5°C for the models under RCP8.5 in summer. Some models project temperatures very close to 0°C change under RCP2.6 (the blue bar) for summer. It is important to note that the number of models available at 2110 is considerably less than at the other time slices, such that RCP6.0 is no longer represented by enough models to feature on this plot. Caution is advised in comparing projections from 2110 to the other time slices as the number of models is much fewer, and therefore the ensemble-average results at 2110 may be skewed (if, for example, the missing model(s) at 2110 were the highest or lowest at 2090).

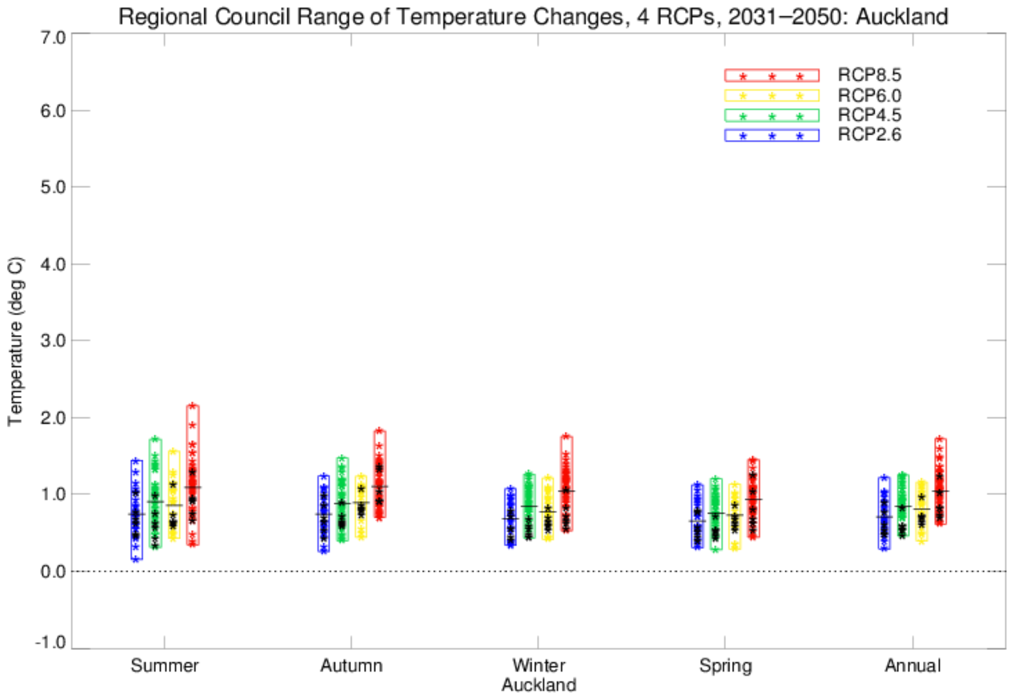

Figure 3-45: Projected seasonal temperature changes by 2040 (2031-2050) averaged over the Auckland Region, for the four RCPs. The vertical coloured bars show the range over all climate models used. The coloured stars show the projected changes for each statistically downscaled model, and the black stars represent the projected changes for each of the six dynamically downscaled models. The short black 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.

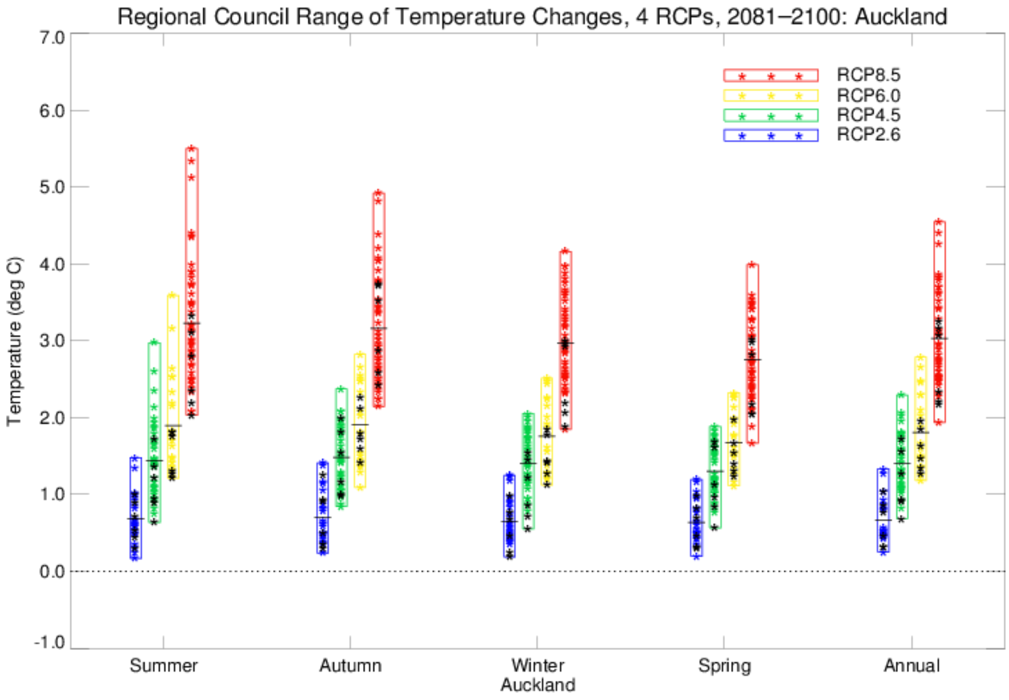

Figure 3-46: Projected seasonal temperature changes by 2090 (2081-2100) averaged over the Auckland Region, for the four RCPs. The vertical coloured bars show the range over all climate models used. The coloured stars show the projected changes for each statistically downscaled model, and the black stars represent the projected changes for each of the six dynamically downscaled models. The short black 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.

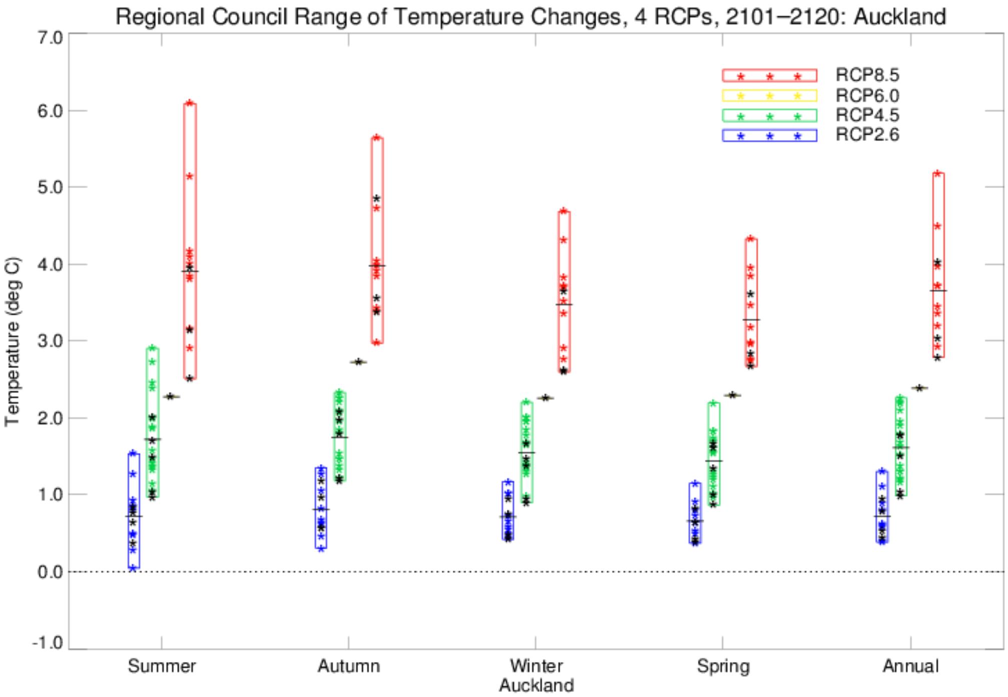

Figure 3-47: Projected seasonal temperature changes by 2110 (2101-2120) averaged over the Auckland Region, for three RCPs. The vertical coloured bars show the range over all climate models used. The coloured stars show the projected changes for each statistically downscaled model, and the black stars represent the projected changes for each of the six dynamically downscaled models. The short black horizontal line is the model-average warming over all statistical and dynamical models. Note that there are limited models available for RCP6.0 hence no bar is displayed here. Blue = RCP2.6, 9 models; green = RCP4.5, 16 models; red = RCP8.5, 9 models. © NIWA.

4 Rainfall

Key messages

- There is high model variability in rainfall projections, therefore averaged projections for annual total rainfall change are close to zero.
- Spring rainfall is projected to decline and autumn rainfall is projected to increase across the Auckland Region.
- The number of rain days (> 1 mm of rain) per year is projected to decline across the region.
- The number of heavy rain days (> 25 mm of rain) per year is projected to increase for most of the region, but decrease in the northeast of the region.
- By the end of the 21st century under RCP8.5 there is an increased frequency of consecutive days with > 40 mm of rainfall across the Auckland Region.
- Extreme, rare rainfall events are likely to increase in intensity in the Auckland Region because a warmer atmosphere can hold more moisture.
- The magnitude of 99th percentile of daily rainfall (the 1-2 wettest rain days of the year) is projected to increase across most of the region, by more than 25% for southeast locations at 2110.
- The number of dry days (< 1 mm of rain) per year is projected to increase for most of the region in the future.
- Potential evapotranspiration deficit (PED) is projected to increase throughout the region in the future. This means Auckland is likely to become more drought-prone. PED represents the gap between water demand and water availability. It affects soil moisture retention and plant growth.
- The number of days of soil moisture deficit is projected to increase with time and RCP forcing across the region.

Rainfall variables presented include total rainfall amount, number of rain days (> 1 mm), number of heavy rain days (> 25 mm), days with consecutive heavy rainfall, 99th percentile of daily rainfall, extreme rainfall, number of dry days (< 1 mm), Potential Evapotranspiration Deficit, and soil moisture deficit. For all variables, present-day conditions are summarised and future projections are presented for RCP4.5 and RCP8.5 at 2040, 2090 and 2110.

4.1 Total rainfall

Key messages

- There is high inter-annual variability in Auckland's historic rainfall but no statistically significant long-term trend.
- Model-average annual rainfall is projected to increase or decrease by less than 5% across the Auckland Region for all three time slices under RCP4.5 and 2040 and 2090 under RCP8.5.
- At 2110 under RCP8.5, some southeast and west Auckland areas are projected to experience up to 10% more annual rainfall.
- In general, spring is the season with the largest decreases in rainfall projected, particularly for the northeast of the region, and autumn is projected to experience the largest increases in rainfall.

4.1.1 Present

The area that receives the most annual rainfall is the Hunua Ranges in the southeast of the Auckland Region, which records over 1800 mm per year (Figure 4-1). The Waitakere Ranges and the northeast of the region, as well as western Great Barrier Island, receive 1500-1800 mm per year. The driest areas are the eastern coasts of the Hauraki Gulf Islands (900-1000 mm per year), the east coast of the mainland, and the Auckland Isthmus (1100-1200 mm per year). Winter is the season with the highest rainfall throughout the region, and summer is the driest season.

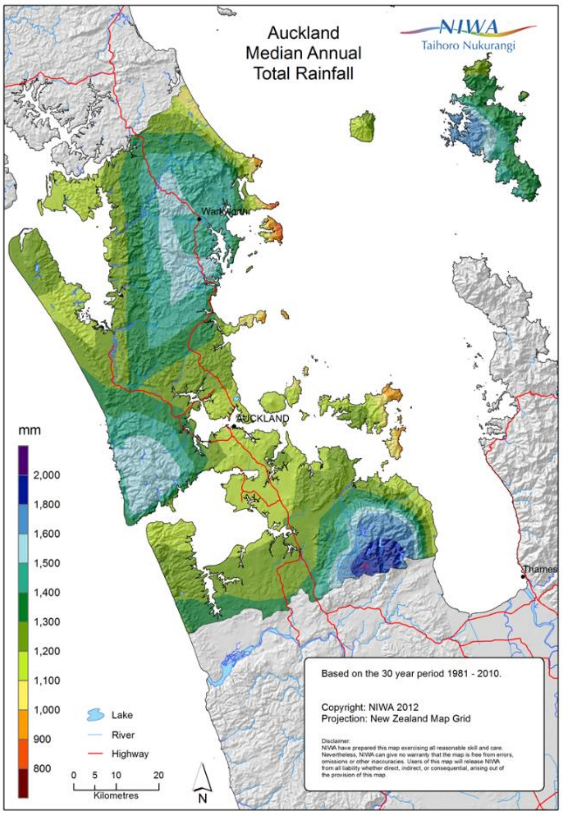

Figure 4-1: Median annual total rainfall for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

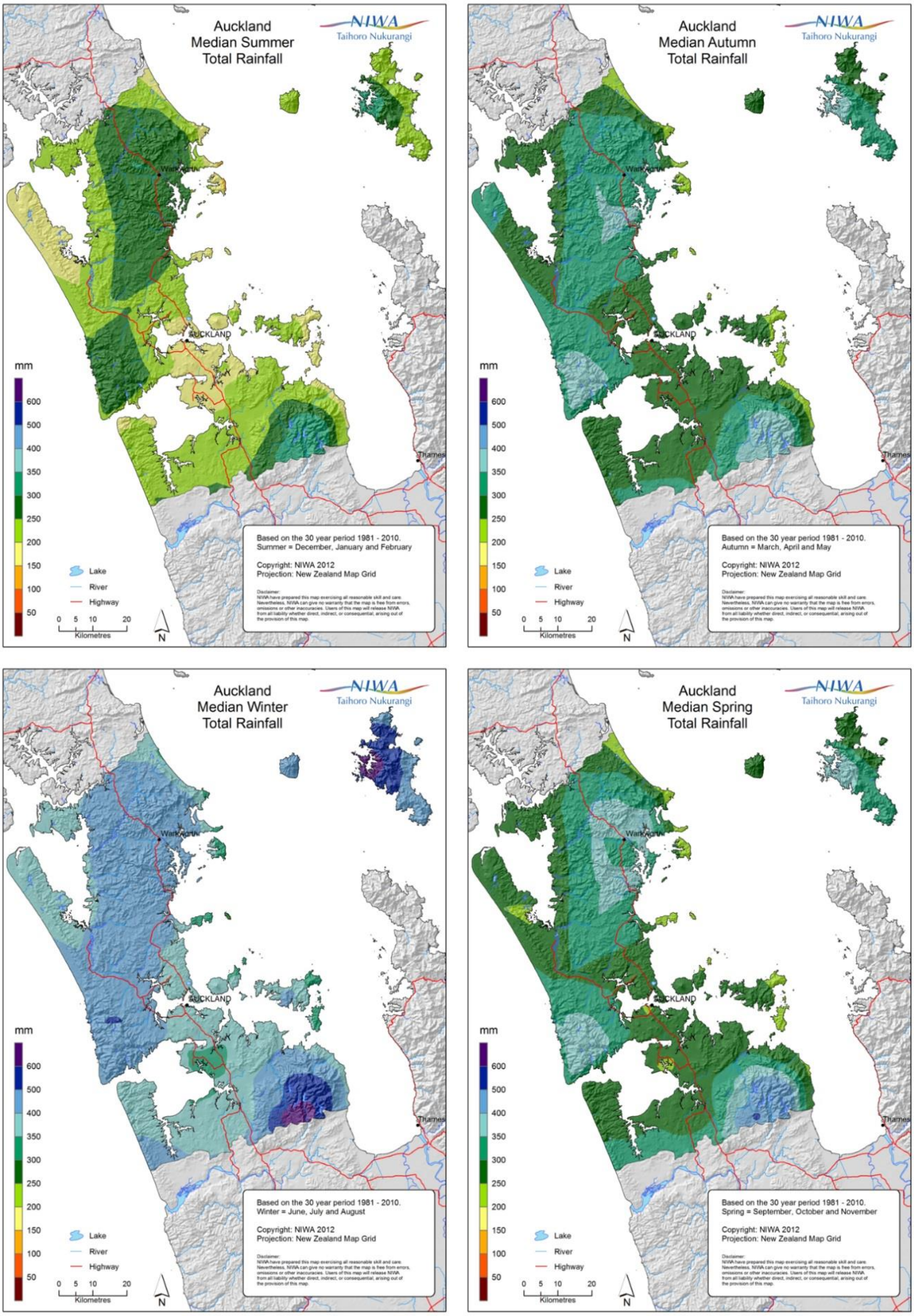

Figure 4-2: Median seasonal total rainfall for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

Total annual rainfall is presented for Auckland Airport in Figure 4-3. There is year-to-year variability in the data, with some years recording almost 600 mm more than other years. There is a minimal negative long-term trend in rainfall at Auckland Airport but this is not statistically significant at or above the 95% confidence level.

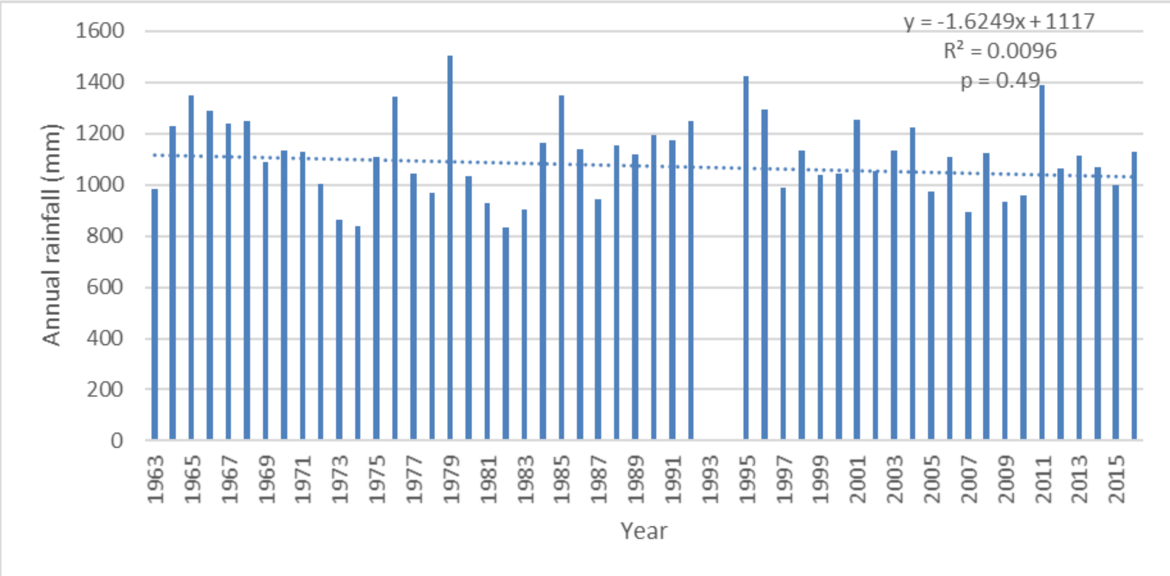

Figure 4-3: Total annual rainfall at Auckland Airport, 1963-2016. Trend indicates a decrease in rainfall of approximately 2 mm per year. There was a gap in observations at Auckland Airport in 1993 and 1994.

4.1.2 Future

The ensemble averages for dynamically downscaled projections of total rainfall, using NIWA's Regional Climate Model, are presented in this section. Figure 4-4 to Figure 4-6 show the projected seasonal and annual patterns of rainfall change over the Auckland Region at 2040, 2090 and 2110 for RCP4.5, and Figure 4-7 to Figure 4-9 show the same for RCP8.5.

In general, at the annual timescale, rainfall is projected to increase or decrease by less than 5% across the Auckland Region, under RCP4.5 at 2040, 2090, and 2110 (Figure 4-4 to Figure 4-6), and under RCP8.5 at 2040 and 2090 (Figure 4-7 and Figure 4-8). Under RCP8.5 at 2110 (Figure 4-9), rainfall is projected to increase by up to 10% for some small southeast and western parts of the region.

Spring is the season with the largest decreases in rainfall for all RCPs and time slices except for RCP4.5 at 2040 (summer has the largest rainfall reductions then). Under RCP4.5 at 2090 and 2110, spring rainfall is projected to decrease by 10-15% in northern Auckland and 5-10% in the rest of the region. Under RCP8.5 at 2090 and 2110, spring rainfall is projected to decrease by more than 15% in northern Auckland and by 10-15% for the rest of the region.

Autumn is projected to experience the largest increases in rainfall for all time slices and RCPs. Under RCP4.5 at 2090 and 2110, autumn rainfall increases of 10-20% are projected for northwest and southeast parts of the region. For RCP8.5 at 2110, over 15% more rainfall is projected in autumn around these same areas.

Summer rainfall is projected to increase under RCP8.5 at 2110, with over 10% more rainfall projected for much of the central, eastern and western parts of the region. Winter rainfall is projected to decrease by up to 10% under RCP8.5 at 2090 and 2110 in northern Auckland, and by up to 5% under RCP4.5 at all time slices.

Model agreement is good for spring at 2090 and 2110 under RCP4.5 and 2040 and 2090 under RCP8.5 as most models project a decrease in rainfall. Model agreement is good for autumn at 2040 and 2110 under RCP4.5 as most models project an increase in rainfall.

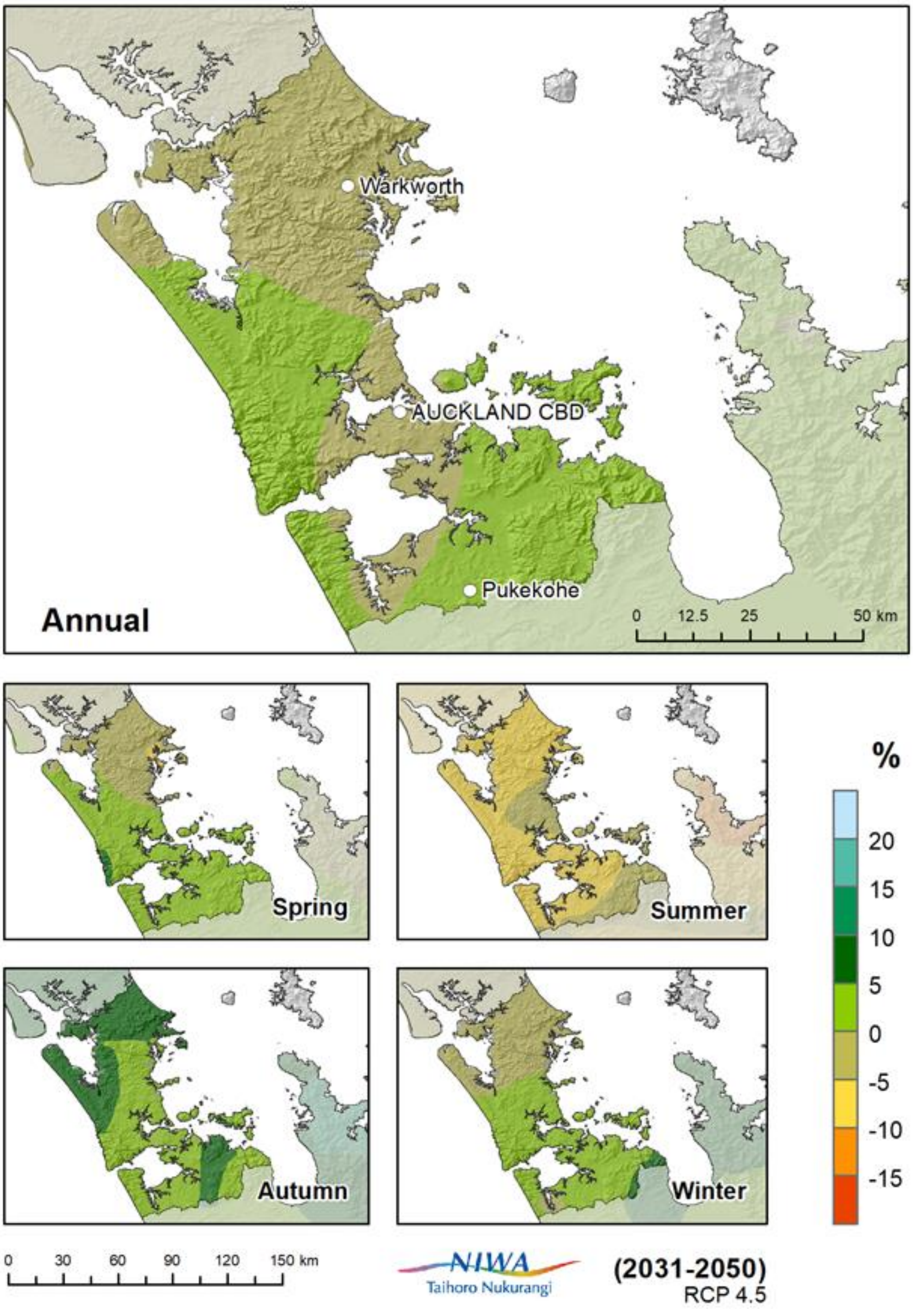

Figure 4-4: Projected annual and seasonal rainfall changes (in %) at 2040 (2031-2050 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

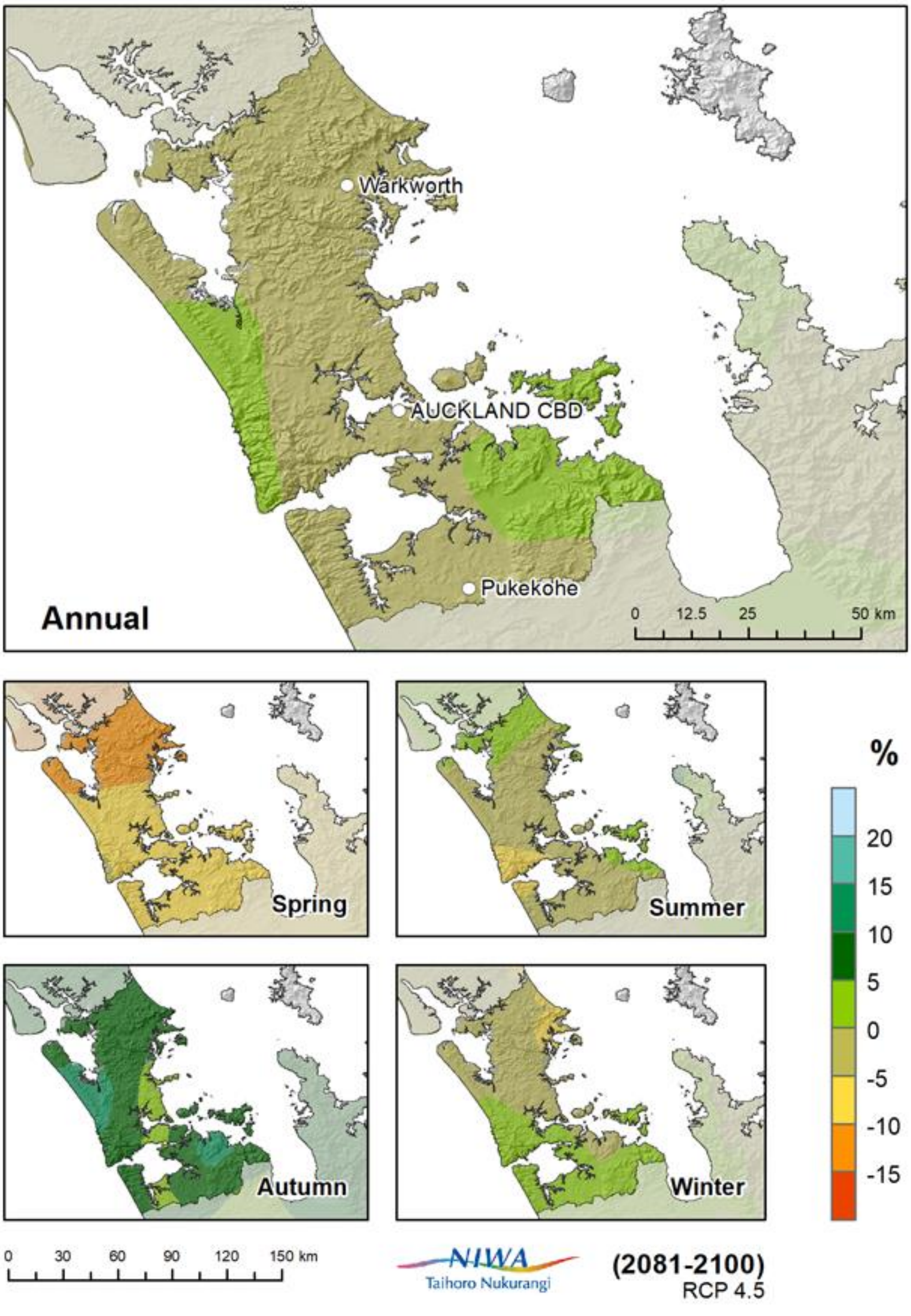

Figure 4-5: Projected annual and seasonal rainfall changes (in %) at 2090 (2081-2100 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

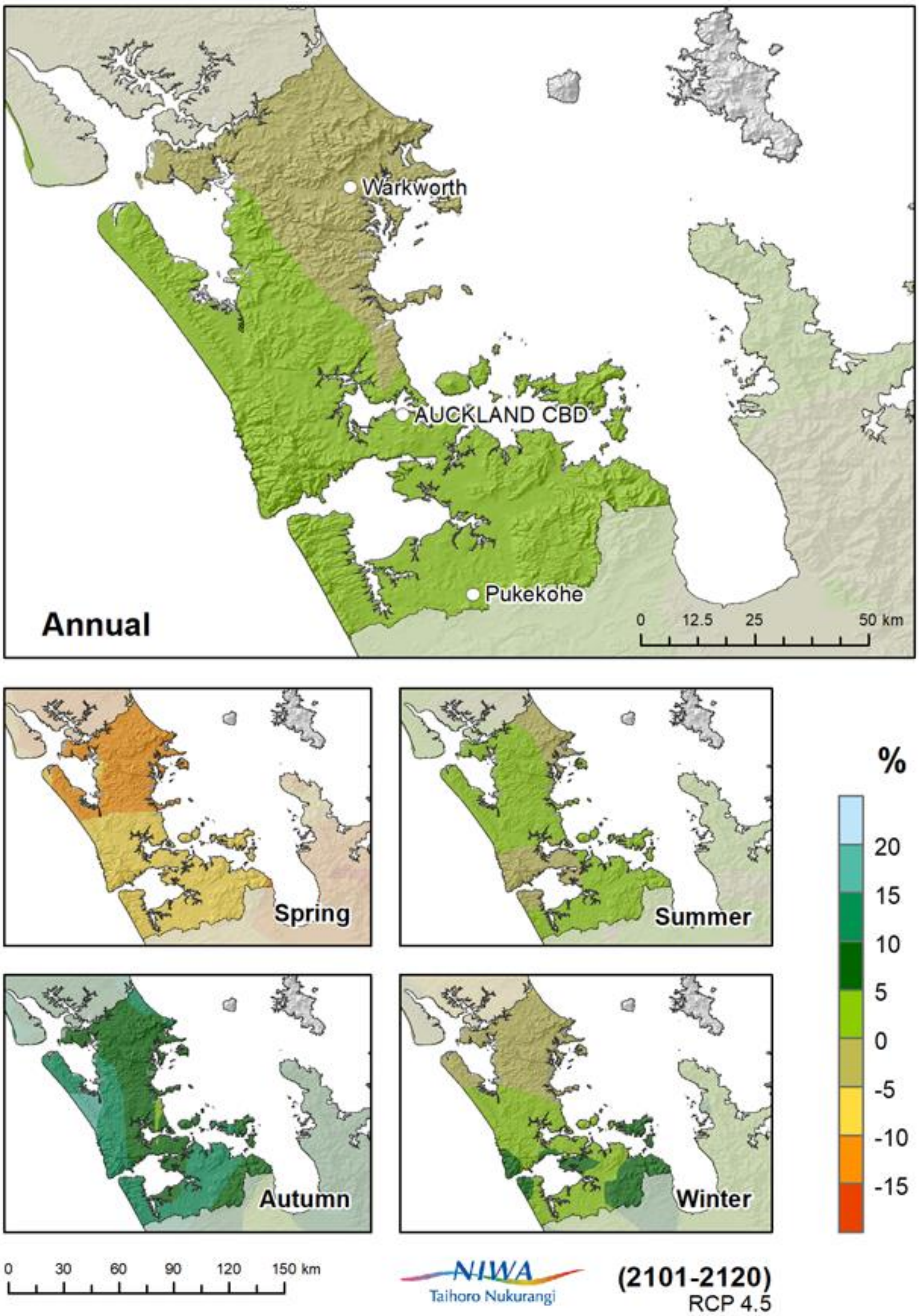

Figure 4-6: Projected annual and seasonal rainfall changes (in %) at 2110 (2101-2120 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

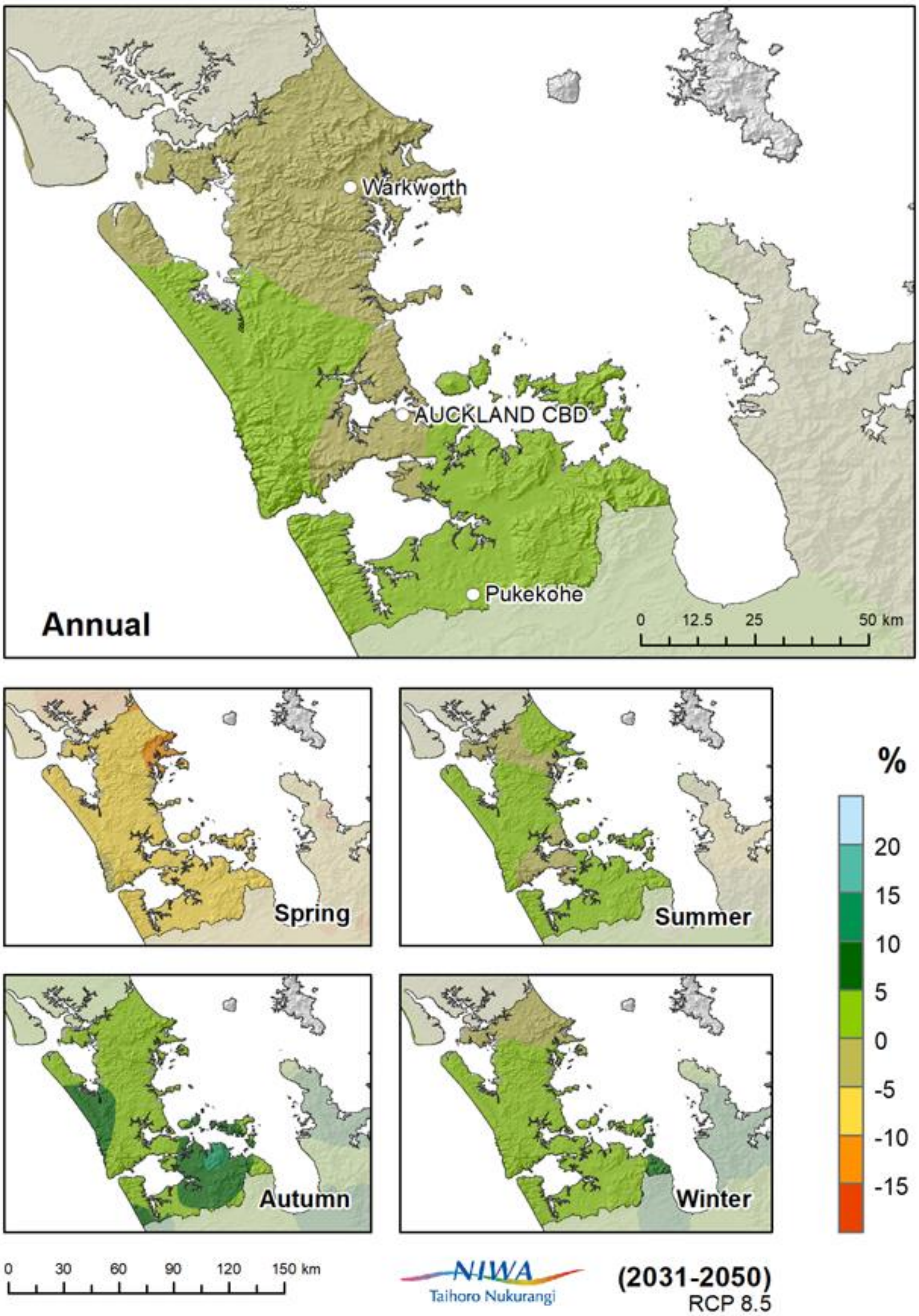

Figure 4-7: Projected annual and seasonal rainfall changes (in %) at 2040 (2031-2050 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

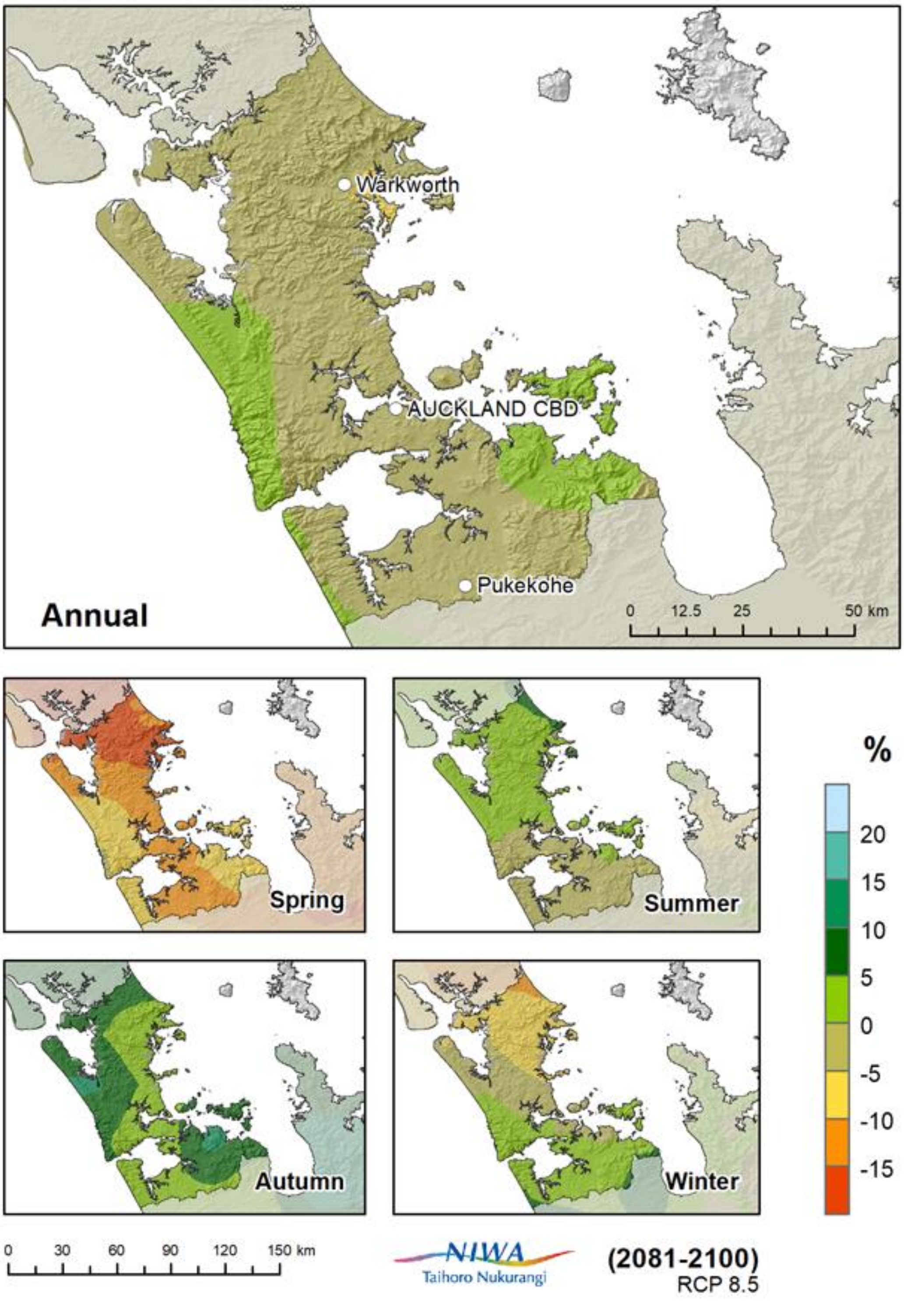

Figure 4-8: Projected annual and seasonal rainfall changes (in %) at 2090 (2081-2100 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

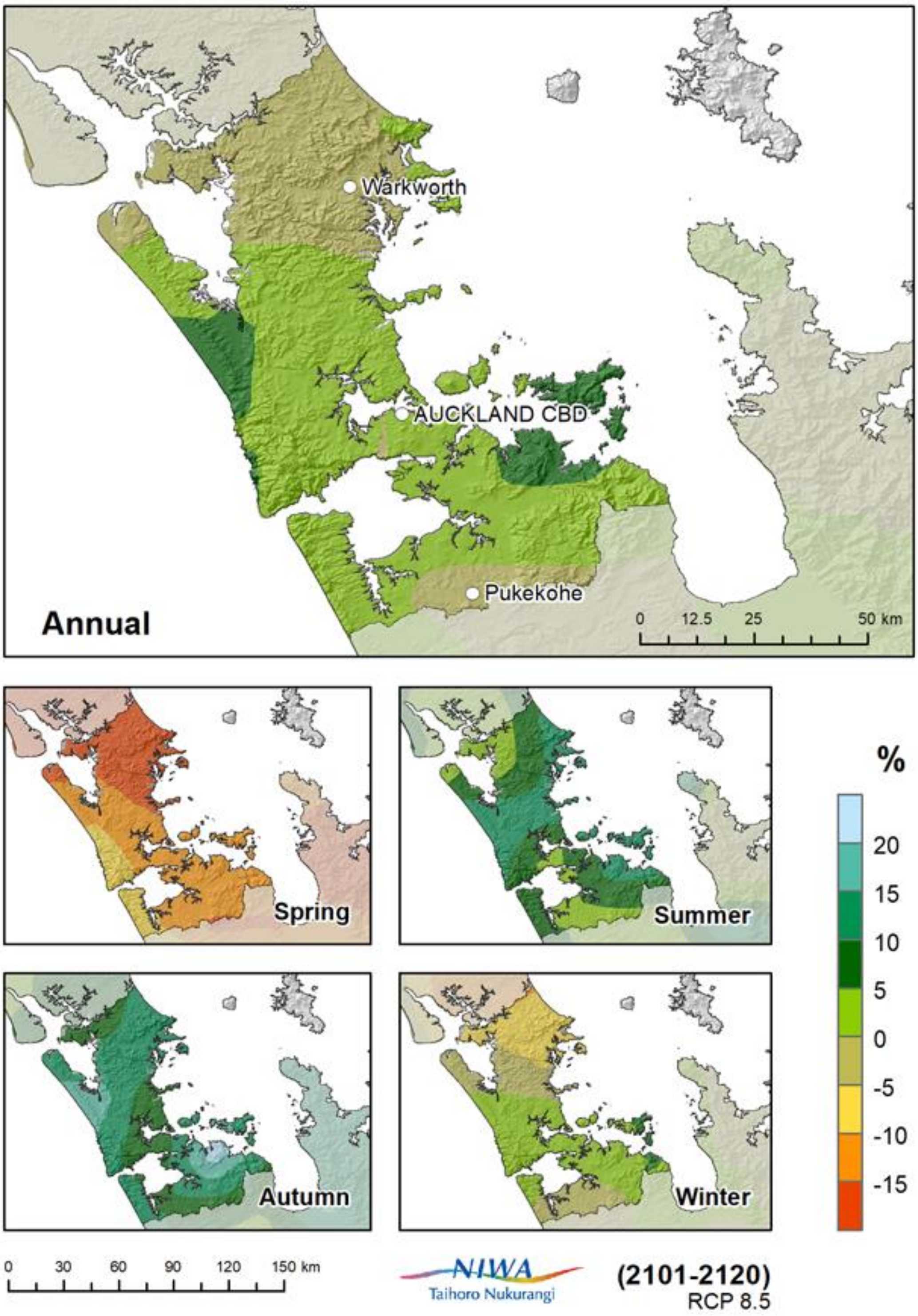

Figure 4-9: Projected annual and seasonal rainfall changes (in %) at 2110 (2101-2120 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

The full range of model-projected rainfall change (in %) is given for the Mangere grid point below, using statistical downscaling and dynamical downscaling methods (the maps in this report are generated from dynamically downscaled projections). Model-projected changes are given for statistically downscaled projections 2040, 2090, and 2110 in Table 4-1, and dynamically downscaled projections are given for 2040, 2090 and 2110 in Table 4-2. The rainfall changes are relative to the baseline period 1986-2005 (1995). The seasonal and annual ensemble average projection (the number outside the brackets) in Table 4-1 is the rainfall change (in %) for Mangere for 2040, 2090 and 2110, 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 (for 2040 and 2090, there are fewer models for 2110). 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.

For Mangere, limited rainfall change is projected for 2040, with small increases seen in winter and small decreases in spring for all RCPs (Table 4-1). At 2090, however, larger changes are projected, with up to 10% less rain in spring under RCP8.5 and 5% more rainfall in summer and winter under RCP6.0. At 2110, 13% less rainfall is projected in spring under RCP8.5. However, for most seasons and RCPs, the ensemble average change in rainfall is less than ±5%, with the model range (the 5th and 95th percentile values) varying between quite large (>10%) increases and decreases. Overall, there are small changes to the annual rainfall total at all time slices and RCPs (<5% change).

Table 4-1: Projected changes in seasonal and annual rainfall (in %) between 1986-2005 and 2031-2050 (2040), 2081-2100 (2090), and 2101-2120 (2100) for the Auckland Mangere grid point, 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 historic average rainfall for 1986-2005 at Mangere is given in the '1995' row (rainfall in mm). The values in each RCP 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. No results are shown for RCP6.0 at 2110 because only two models in the NIWA CMIP5 archive have data available beyond 2100 for this RCP. From Mullan et al. (2016).

Period	RCP	Summer	Autumn	Winter	Spring	Annual
1995		225 mm	285 mm	389 mm	281 mm	1181 mm
2040	RCP2.6	1 (-6, 13)	0 (-6, 7)	2 (-3, 9)	-1 (-8, 7)	1 (-3, 5)
	RCP4.5	0 (-11, 12)	1 (-10, 9)	2 (-9, 12)	-1 (-8, 8)	1 (-4, 5)
	RCP6.0	0 (-14, 17)	1 (-6, 10)	3 (-7, 9)	-2 (-10, 9)	1 (-3, 5)
	RCP8.5	1 (-8, 12)	0 (-7, 9)	2 (-7, 9)	-4 (-9, 6)	0 (-5, 4)
2090	RCP2.6	3 (-8, 13)	2 (-7, 9)	3 (-4, 11)	0 (-6, 6)	2 (-2, 8)
	RCP4.5	2 (-13, 15)	1 (-8, 12)	2 (-10, 11)	-3 (-11, 7)	1 (-6, 6)
	RCP6.0	5 (-16, 26)	3 (-8, 27)	5 (-11, 21)	-4 (-12, 4)	2 (-8, 16)
	RCP8.5	4 (-14, 24)	-2 (-12, 8)	1 (-11, 12)	-10 (-22, 0)	-2 (-10, 6)
2110	RCP2.6	4 (-9, 14)	1 (-3, 5)	3 (-2, 9)	-1 (-3, 1)	2 (-1, 5)
	RCP4.5	2 (-11, 16)	-1 (-7, 6)	4 (-7, 12)	-3 (-11, 9)	1 (-5, 9)
	RCP6.0					
	RCP8.5	-1 (-27, 35)	-3 (-12, 9)	1 (-11, 17)	-13 (-26, 5)	-4 (-14, 7)

The dynamical downscaled rainfall projections for Mangere in Table 4-2 show differences to the statistical downscaled projections in Table 4-1. For 2040 (Table 4-2), a 9% decrease in rainfall is projected for summer under RCP4.5 and an 8% decrease in rainfall is projected for spring under RCP8.5. For 2090, both summer and spring project decreases in rainfall, with most RCPs projecting more than a 5% decrease in rainfall and the resulting annual change is slightly negative. For 2110, 11% less rainfall is projected for RCP8.5 in spring, and increases in rainfall are projected for autumn and winter (up to 9% increase for RCP8.5 in autumn).

For the range of downscaled model results presented in Table 4-1 and Table 4-2, the model spread is generally large and often crosses zero, therefore the direction and magnitude of change for rainfall (increase or decrease) is uncertain. This is because of the uncertainty in the climate models themselves with relation to New Zealand's future climate. Note that this uncertainty is captured in the maps in this section, where the mapped ensemble average for annual rainfall is often close to zero.

Table 4-2: Projected changes in seasonal and annual rainfall (in %) between 1986-2005 and 2031-2050 (2040), 2081-2100 (2090), and 2101-2120 (2110) for the Auckland Mangere grid point, as derived from dynamical downscaling. The historic average rainfall for 1986-2005 at Mangere is given in the '1995' row (rainfall in mm). 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 RCP column represent the ensemble average, and in brackets the range (minimum and maximum) over all models within that ensemble. No results are shown for RCP6.0 at 2110 because only one model has data available beyond 2100 for this RCP. From Mullan et al. (2016)

Period	RCP	Summer	Autumn	Winter	Spring	Annual
1995		225 mm	285 mm	389 mm	281 mm	1181 mm
2040	RCP2.6	2 (-11, 14)	4 (-7, 28)	1 (-7, 7)	1 (-16, 20)	2 (-6, 11)
	RCP4.5	-9 (-21, 3)	1 (-18, 19)	2 (-8, 13)	0 (-15, 24)	-1 (-8, 10)
	RCP6.0	1 (-19, 30)	5 (-18, 35)	-1 (-8, 4)	0 (-15, 17)	0 (-8, 12)
	RCP8.5	-2 (-11, 11)	4 (-11, 19)	3 (1, 6)	-8 (-19, -1)	-1 (-8, 3)
2090	RCP2.6	-7 (-21, 4)	7 (0, 24)	2 (-6, 8)	-1 (-15, 8)	0 (-2, 2)
	RCP4.5	-6 (-16, 2)	5 (-15, 22)	1 (-6, 9)	-7 (-25, 3)	-2 (-6, 2)
	RCP6.0	-4 (-11, 8)	1 (-15, 11)	1 (-6, 12)	-10 (-25, -3)	-3 (-6, 3)
	RCP8.5	-6 (-14, 5)	2 (-16, 27)	2 (-16, 9)	-11 (-18, 2)	-3 (-12, 4)
2110	RCP2.6	-2 (-6, 5)	8 (-13, 31)	8 (4, 14)	1 (-3, 8)	4 (0, 9)
	RCP4.5	-5 (-14, 3)	7 (-13, 27)	6 (-2, 15)	-7 (-13, 9)	0 (-5, 5)
	RCP6.0					
	RCP8.5	3 (-8, 12)	9 (-11, 30)	2 (-9, 12)	-11 (-23, 3)	0 (-10, 9)

4.2 Rain days (>1 mm)

Key messages

- Most parts of the Auckland Region currently experience around 130-150 rain days (days with > 1 mm of rainfall) per year. Most rain days occur in winter and the least occur in summer.
- The annual number of rain days is projected to decline across the Auckland Region under both RCP4.5 and RCP8.5 at 2040, 2090 and 2110.
- Under RCP4.5 at all time slices, annual rain days are projected to decline by up to 10 days for most of the region. Under RCP8.5 at 2090 and 2110, 10-20 fewer annual rain days are projected across the region, with the largest decreases in the north of the region.
- Under RCP8.5, spring is the season projected to experience the largest decrease in number of rain days.

In this report, 'rain days' are days where greater than 1 mm of rainfall is recorded.

4.2.1 Present

The highest amount of rain days per year is recorded in the south of the Auckland Region, where over 150 rain days per year are experienced on average (Figure 4-10). The west and northeast of the region also experience high numbers of rain days per year (140-150 rain days per year). The least rain days occur in summer (mostly less than 25 days per summer) and the most in winter (around 30-35 days per winter), but the spatial pattern of rain days generally remains the same as the annual timescale (Figure 4-11). There are no statistically significant trends at or above the 95% confidence level in the number of rain days per year experienced at Auckland Airport (Figure 4-12).

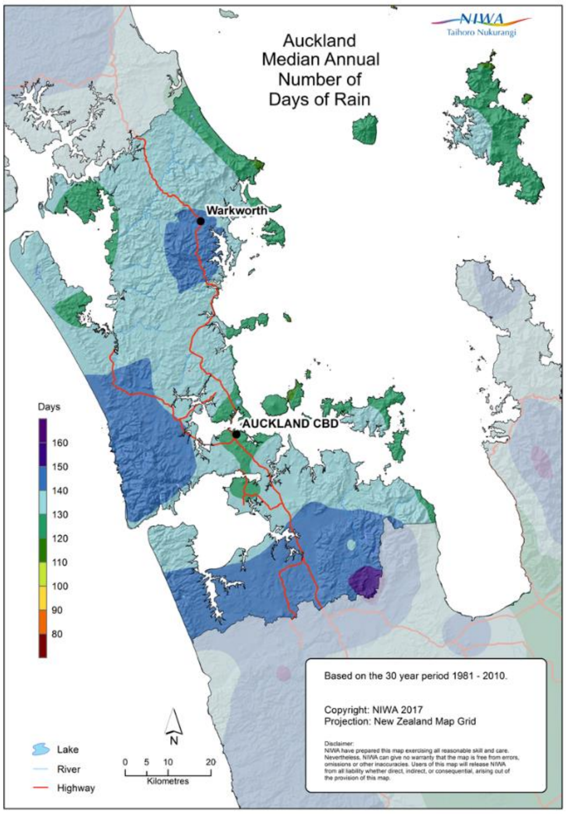

Figure 4-10: Median annual number of rain days for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

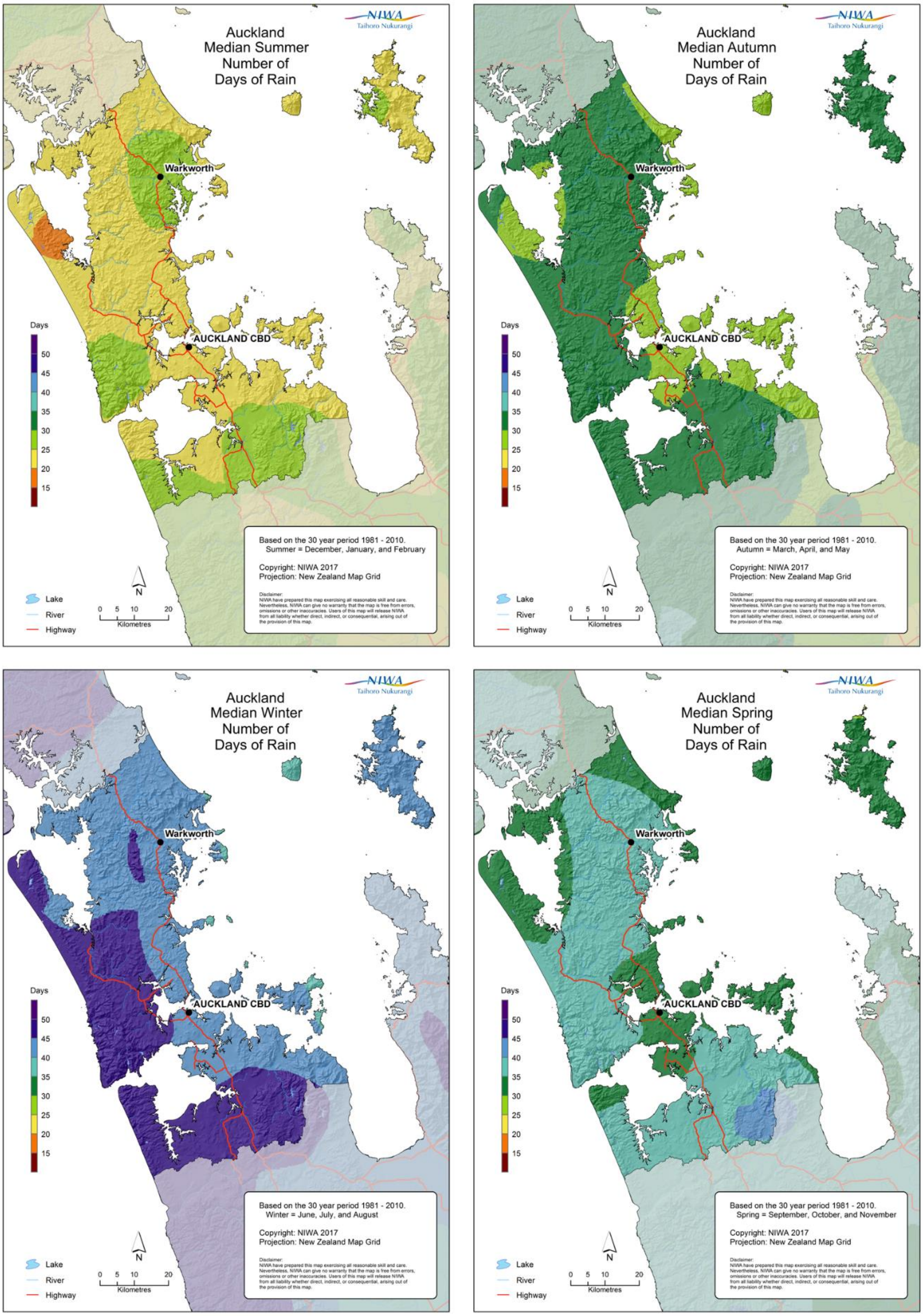

Figure 4-11: Median seasonal number of rain days for the Auckland Region (median for 1981-2010). Based on data from NIWA's Virtual Climate Station Network.

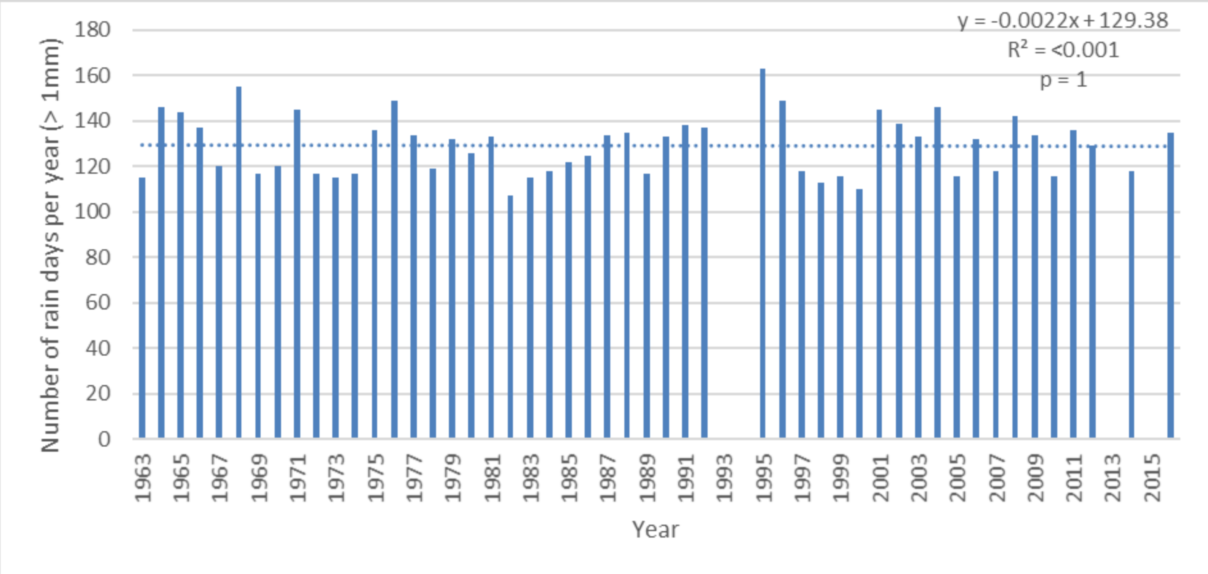

Figure 4-12: Number of rain days per year (>1mm) at Auckland Airport, 1963-2016. There was a gap in observations at Auckland Airport in 1993 and 1994.

4.2.2 Future

Projections of changes to rain days (where daily rain >1 mm) are presented for 2040, 2090 and 2110, compared to 1995 under RCP4.5 and RCP8.5 in Figure 4-13 to Figure 4-18, based on the ensemble average of six dynamically downscaled models.

The annual number of rain days is expected to decline across the Auckland Region under both RCP4.5 and RCP8.5 at 2040, 2090 and 2110. Under RCP4.5 at all three time slices, annual rain days are projected to decline by up to 10 days across most of the region, with the area projected to experience 5-10 fewer rain days more extensive at 2090 and 2110 than at 2040 (Figure 4-13 to Figure 4-15). Seasonal rain days are projected to decrease by 0-5 days per season at all three time slices, with some small isolated areas of increasing rain days of 0-5 days per season.

Under RCP8.5 at 2040, small decreases in rain days are projected (0-5 days per year) (Figure 4-16). Some increases in the number of autumn and winter rain days (0-5 days) are projected in parts of the region, mostly in the west and south. However, for 2090 (Figure 4-17) and 2110 (Figure 4-18) under RCP8.5, a reduction of 10-20 rain days per year is projected for the region, with the largest decreases projected for the northern part of the region. Most decreases in rain days are projected for spring, with 5-10 fewer rain days for most of the region at both 2090 and 2110.

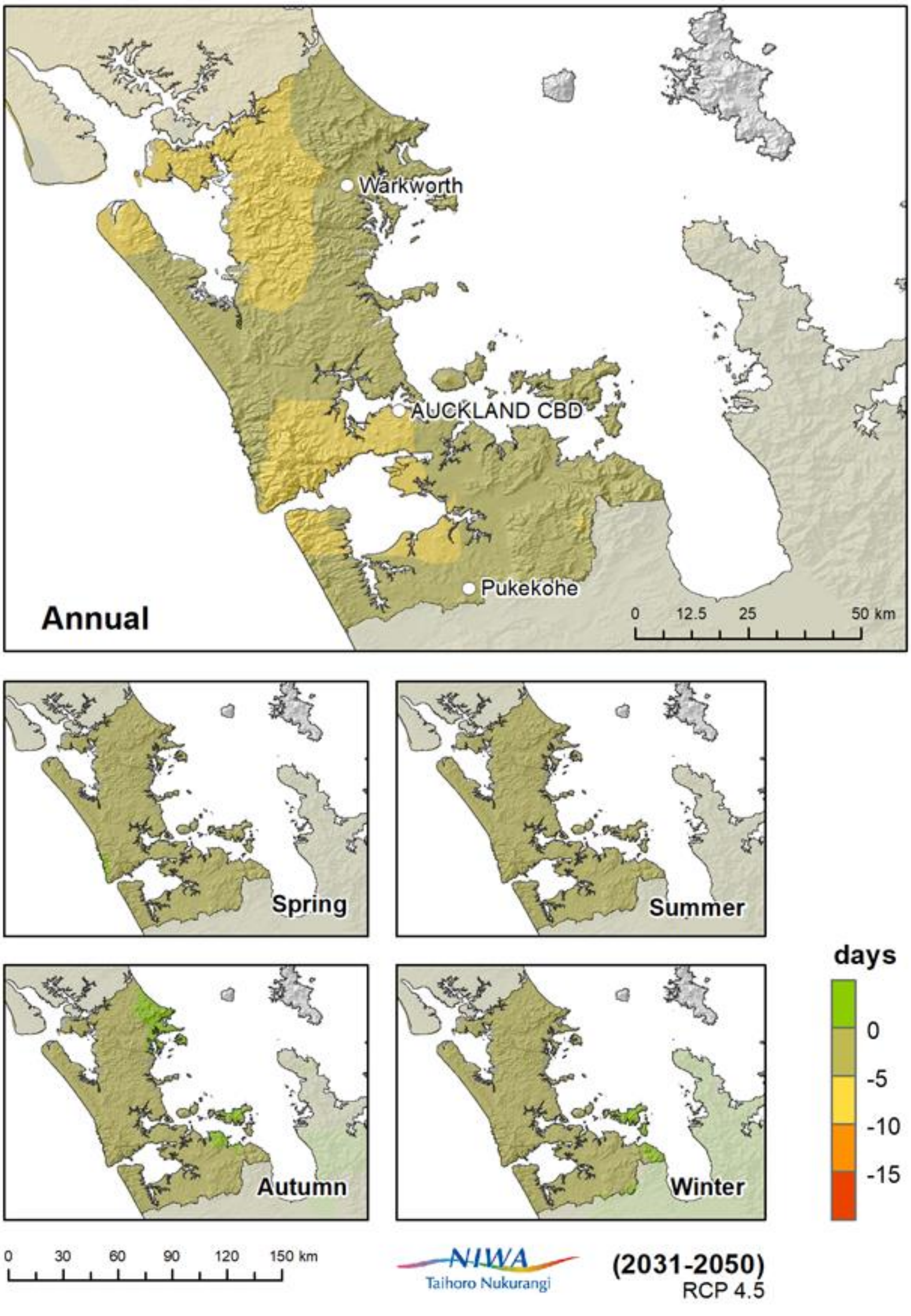

Figure 4-13: Projected annual and seasonal rain day changes (days where rain > 1 mm; in number of days) at 2040 (2031-2050 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

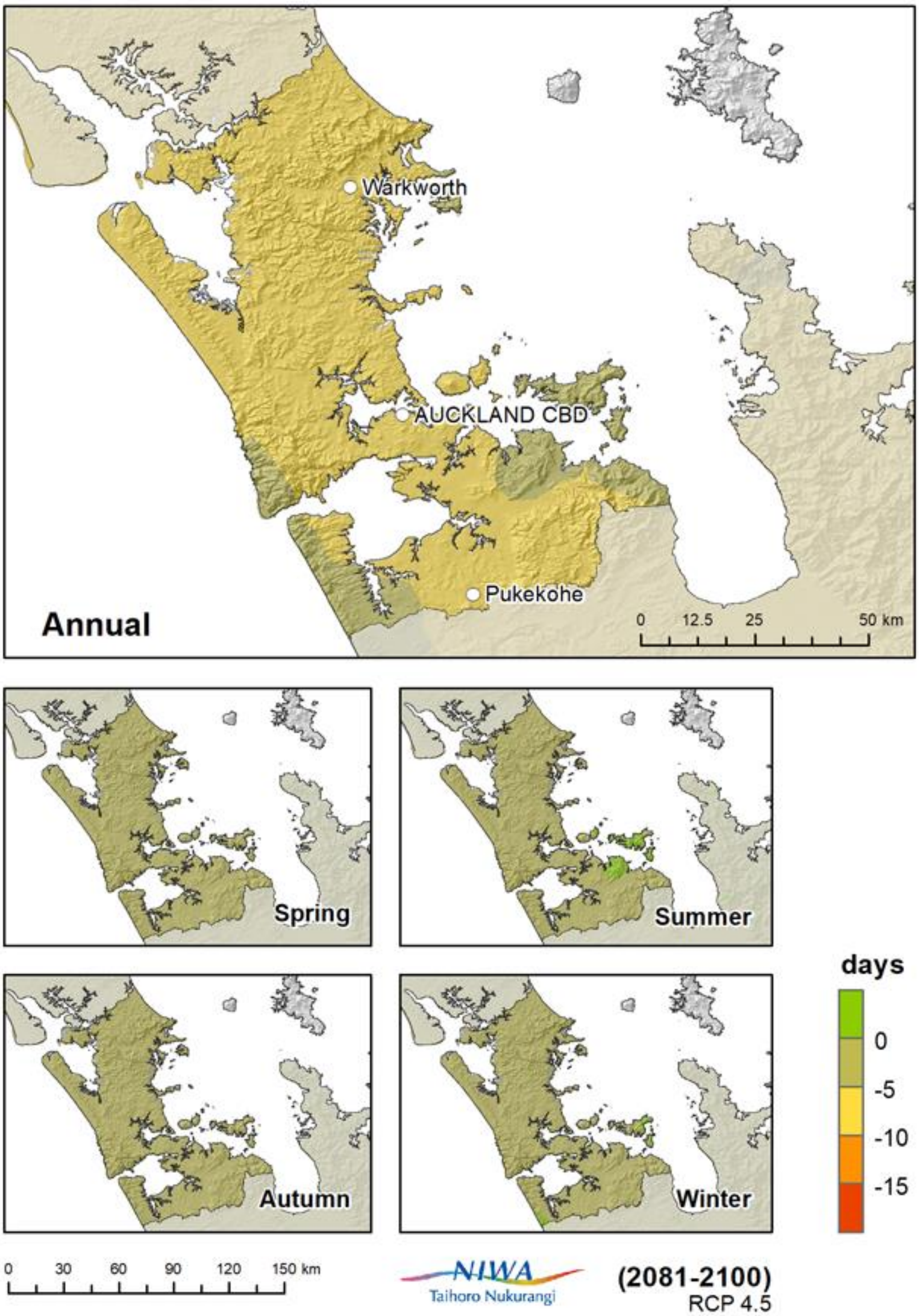

Figure 4-14: Projected annual and seasonal rain day changes (days where rain > 1 mm; in number of days) at 2090 (2081-2100 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

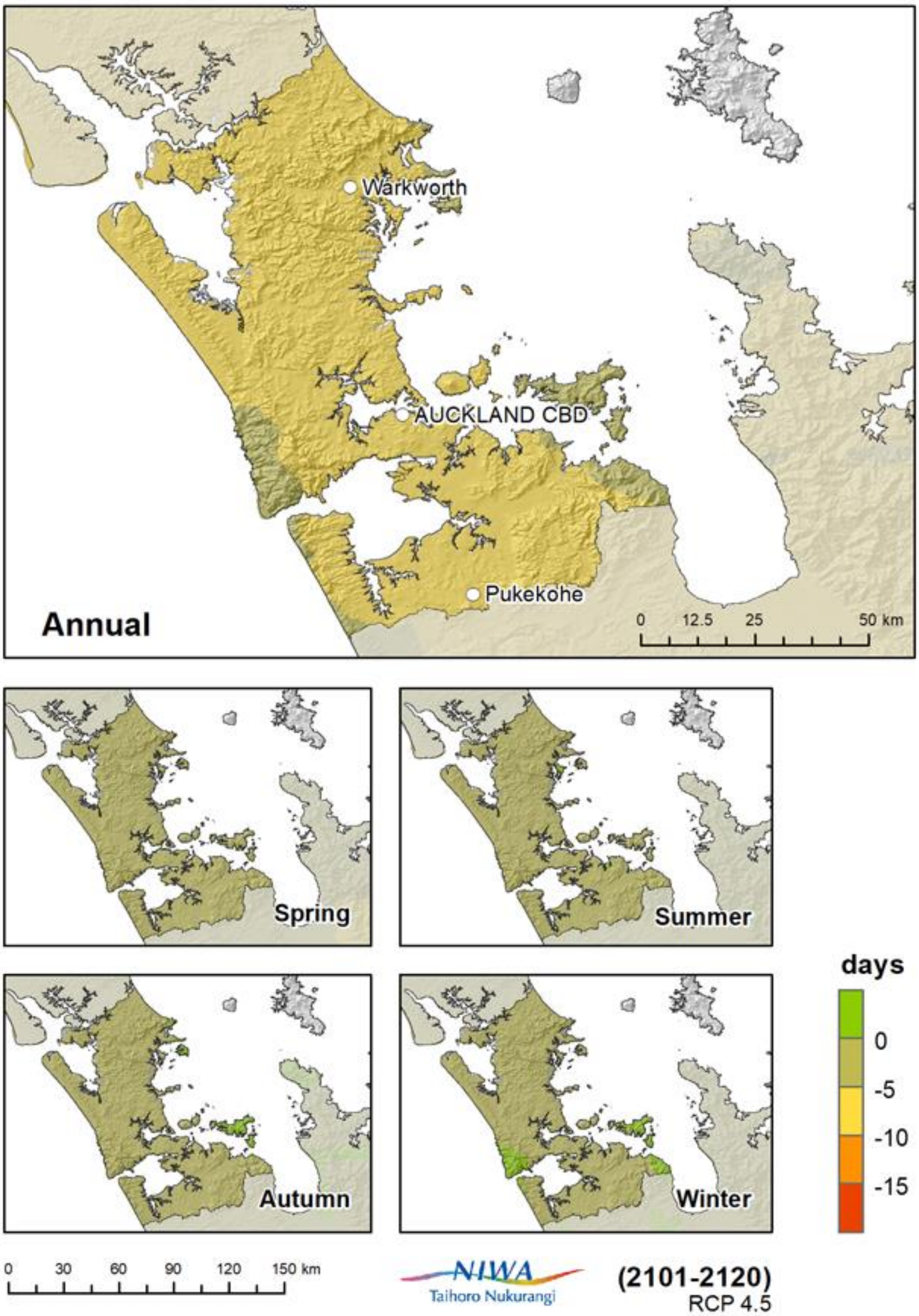

Figure 4-15: Projected annual and seasonal rain day changes (days where rain > 1 mm; in number of days) at 2110 (2101-2120 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

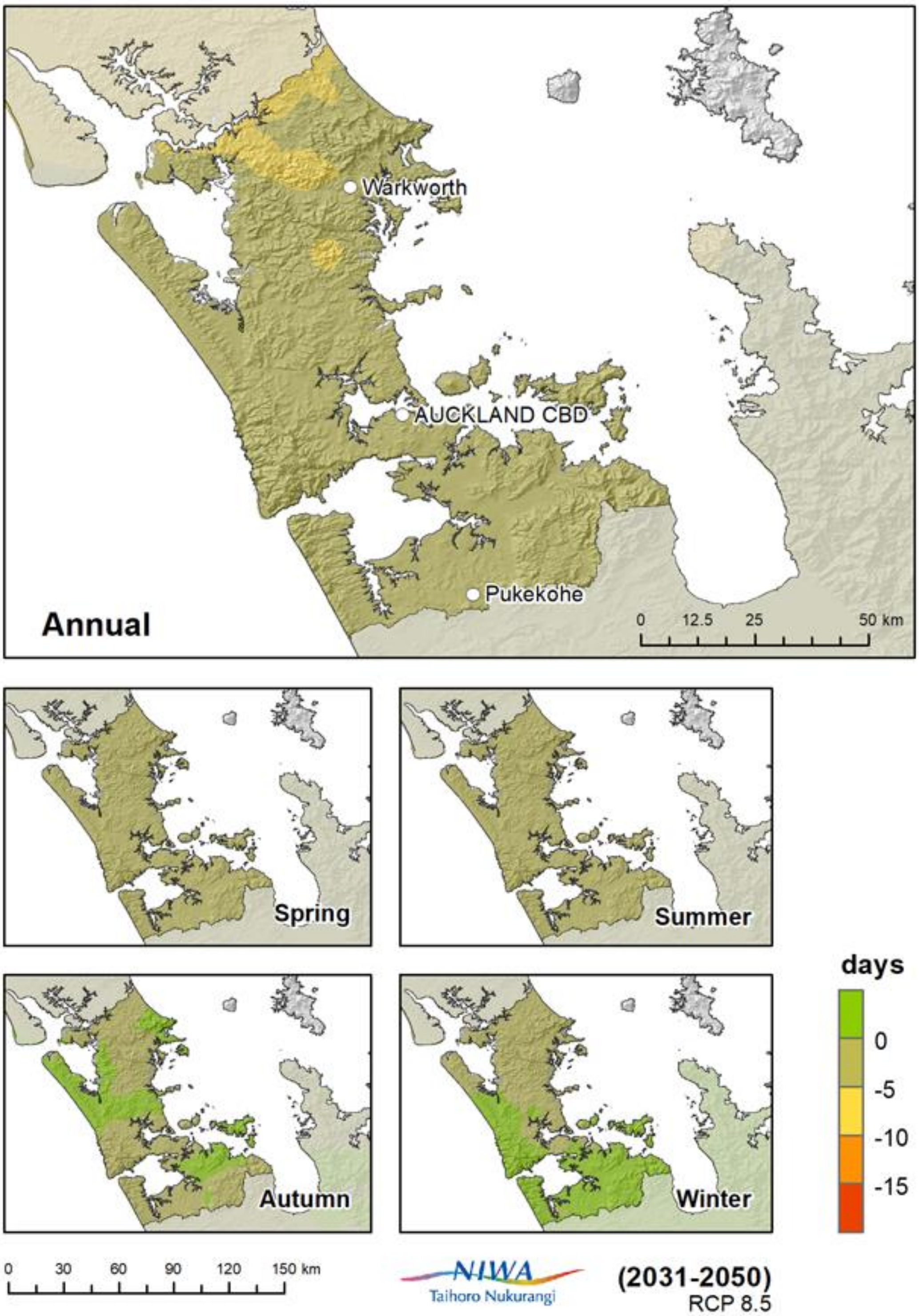

Figure 4-16: Projected annual and seasonal rain day changes (days where rain > 1 mm; in number of days) at 2040 (2031-2050 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

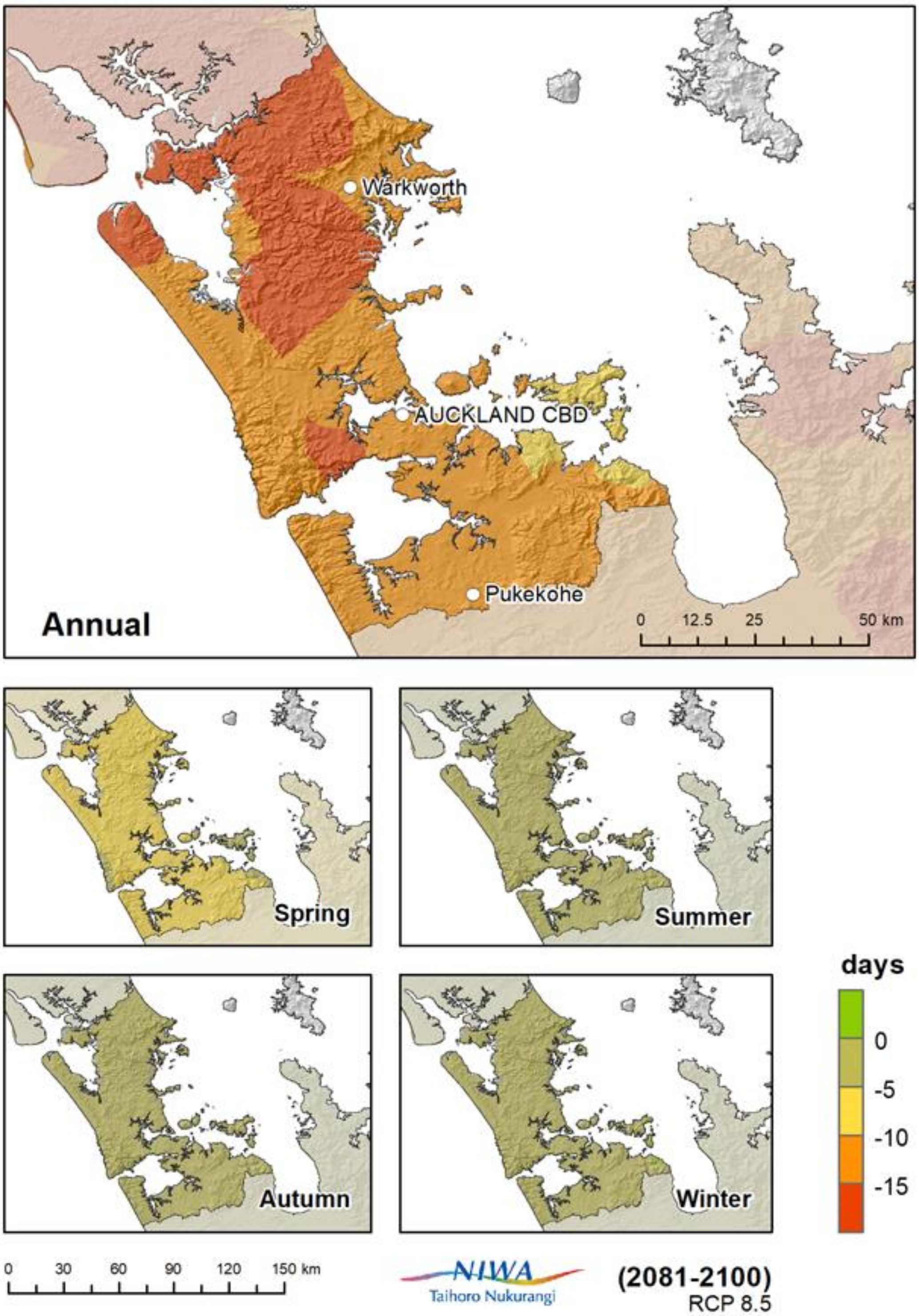

Figure 4-17: Projected annual and seasonal rain day changes (days where rain > 1 mm; in number of days) at 2090 (2081-2100 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

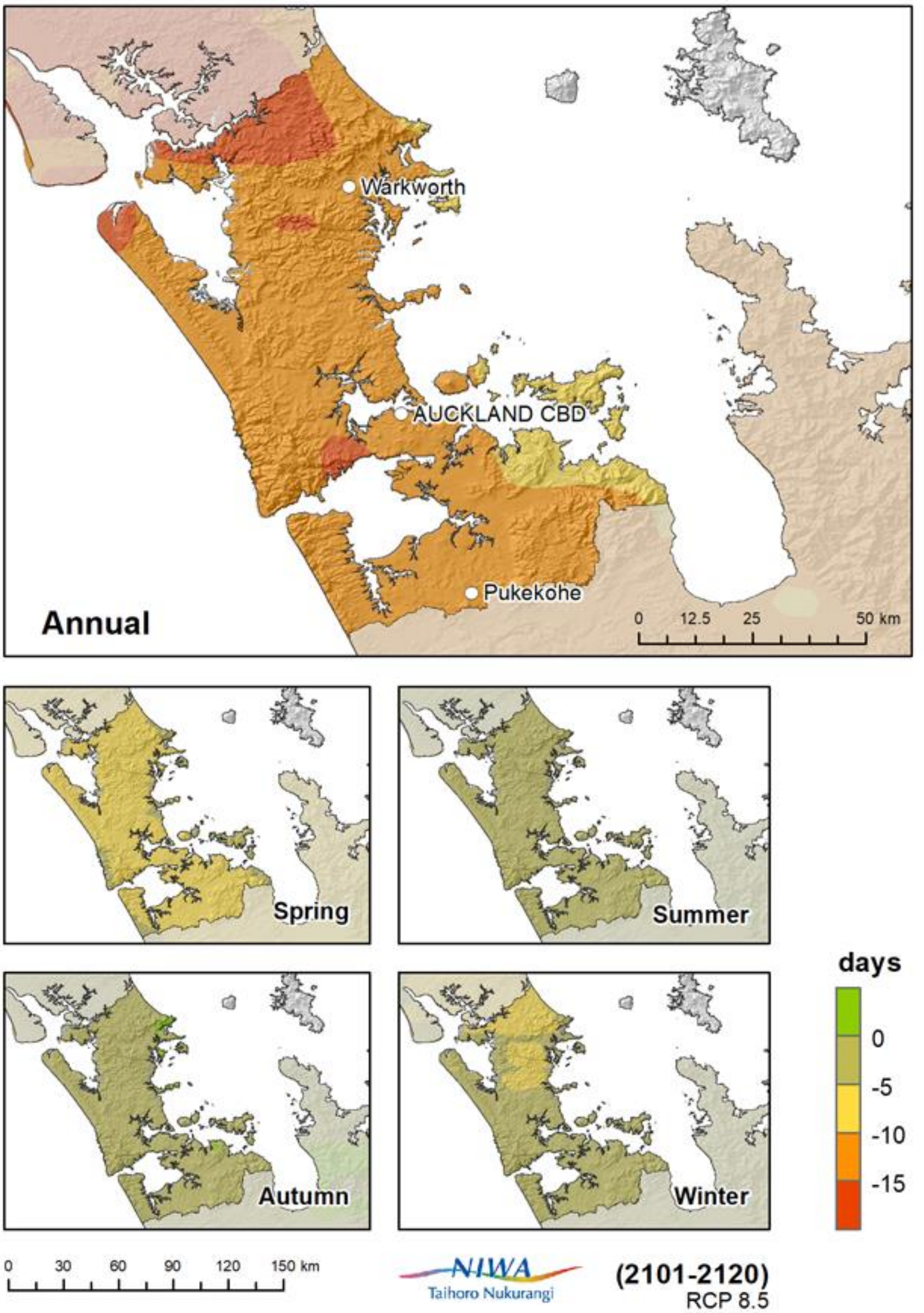

Figure 4-18: Projected annual and seasonal rain day changes (days where rain > 1 mm; in number of days) at 2110 (2101-2120 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

4.3 Heavy rain days (> 25 mm)

Key messages

- Auckland Airport currently experiences an average of 7.5 heavy rain days (days with > 25 mm of rainfall) per year.
- The number of future annual heavy rain days is projected to increase by 0-5 days for both RCP4.5 and RCP8.5 at 2040, 2090 and 2110 for most of the Auckland Region.
- The northeast of the Auckland Region is projected to experience 0-5 fewer annual heavy rain days under both RCPs at all time slices.
- In general, spring and summer project decreases in the number of heavy rain days and autumn and winter project an increase in the number of heavy rain days.

Numerous measures can be used to describe heavy rainfall. The threshold used in this section is 25 mm of rain per day, an amount which approximately represents the top 5% of rain days at Mangere. Following sections use different measures of heavy and extreme rainfall to consider different ways rainfall changes over time in Auckland.

4.3.1 Present

Heavy rain day statistics are presented for 1963-2016 for Auckland Airport in Figure 4-19. There is a small negative long-term trend in the number of days per year with rainfall over 25 mm at Auckland Airport, which has an average of around 8 days per year, but year-to-year variability is high. This trend is not statistically significant at or above the 95% confidence level. The average number of heavy rain days is 7.5 days per year at Auckland Airport (1981-2010 average). Note that this number is likely to be larger in higher elevation areas of the Auckland Region, and for locations that record higher annual rainfall (Figure 4-1).

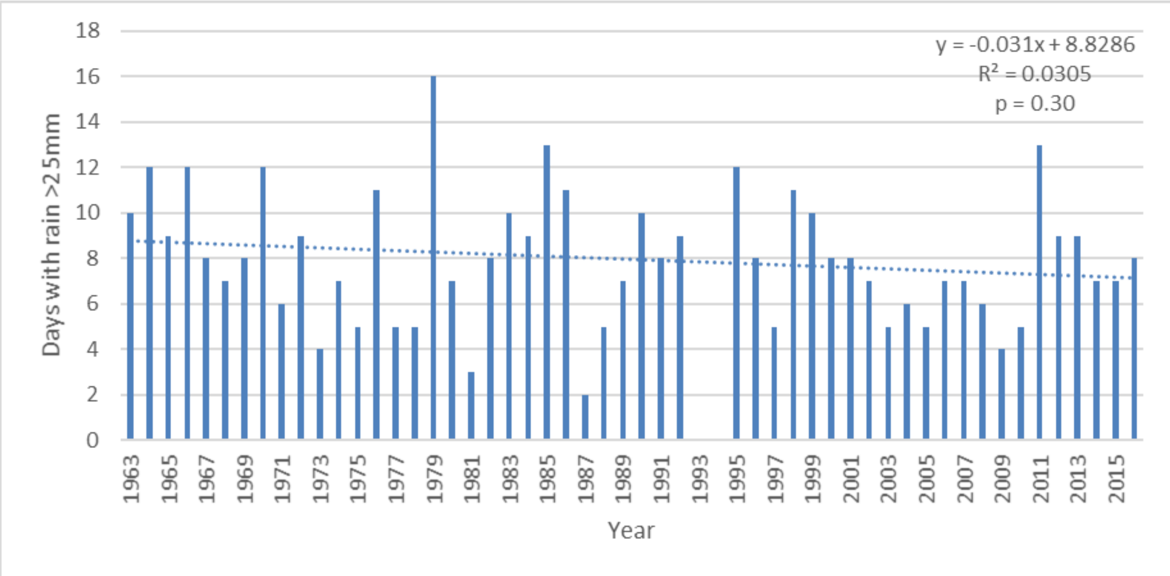

Figure 4-19: Number of days per year with >25 mm rainfall for Auckland Airport, 1963-2016 (R25mm). Trend indicates a decrease of heavy rain days of approximately 3 days per century. There was a gap in observations at Auckland Airport in 1993 and 1994.

4.3.2 Future

Projections of heavy rain days (where daily rainfall >25 mm) are presented for 2040, 2090 and 2110 under RCP4.5 and RCP8.5 in Figure 4-20 to Figure 4-25, derived from the ensemble average of six dynamically downscaled models.

The number of future heavy rain days is projected to increase by 0-5 days per year for the west, centre, and south of the Auckland Region for both RCP4.5 and RCP8.5 at 2040, 2090 and 2110. The northeast of the region is projected to experience a decrease in the number of heavy rain days per year by 0-5 days per year for both RCPs at all time slices.

For seasonal projections, generally spring and summer project decreases in the number of heavy rain days and autumn and winter project an increase in the number of heavy rain days across the region.

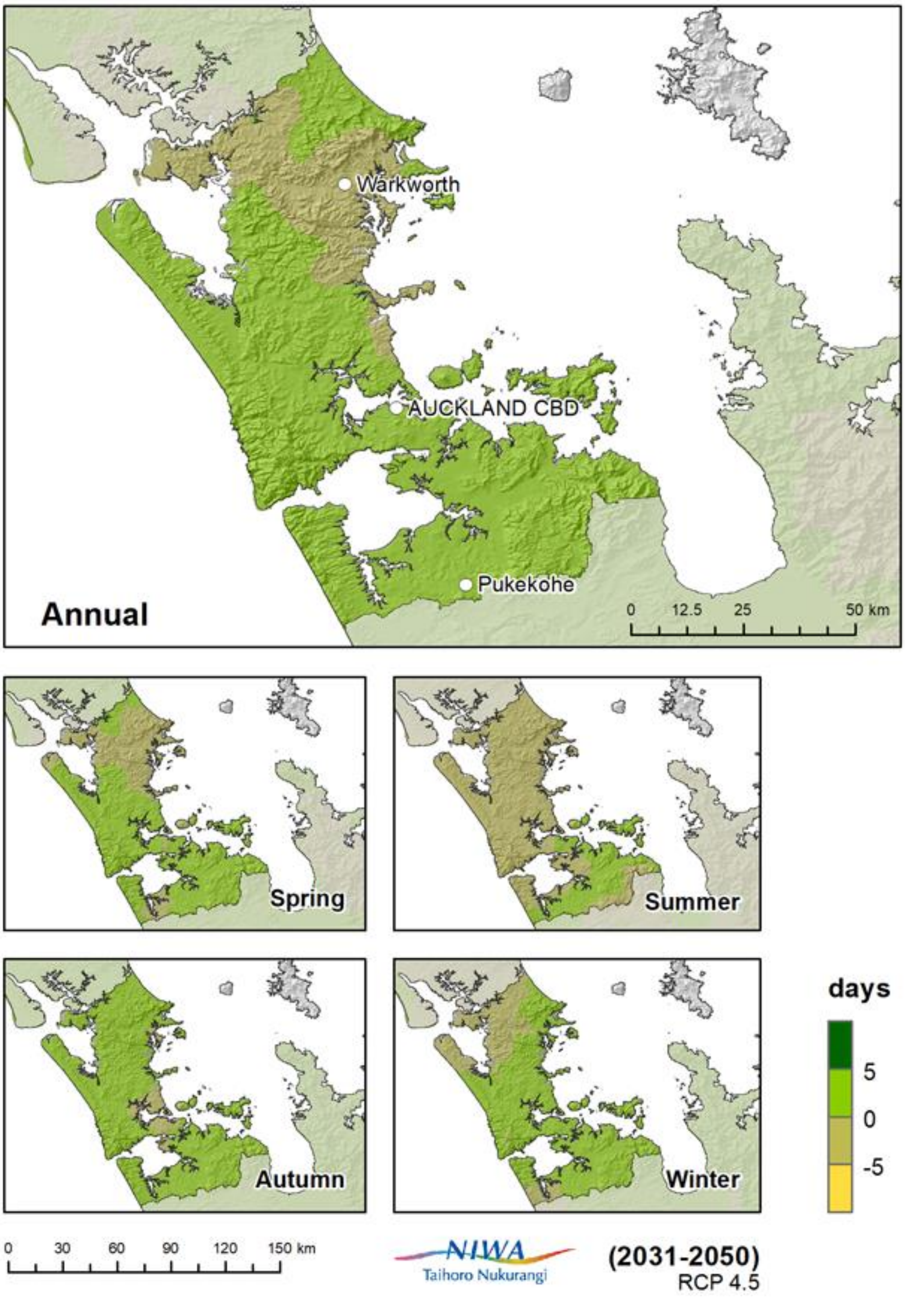

Figure 4-20: Projected annual and seasonal heavy rain day changes (days where rain > 25 mm; in number of days) at 2040 (2031-2050 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

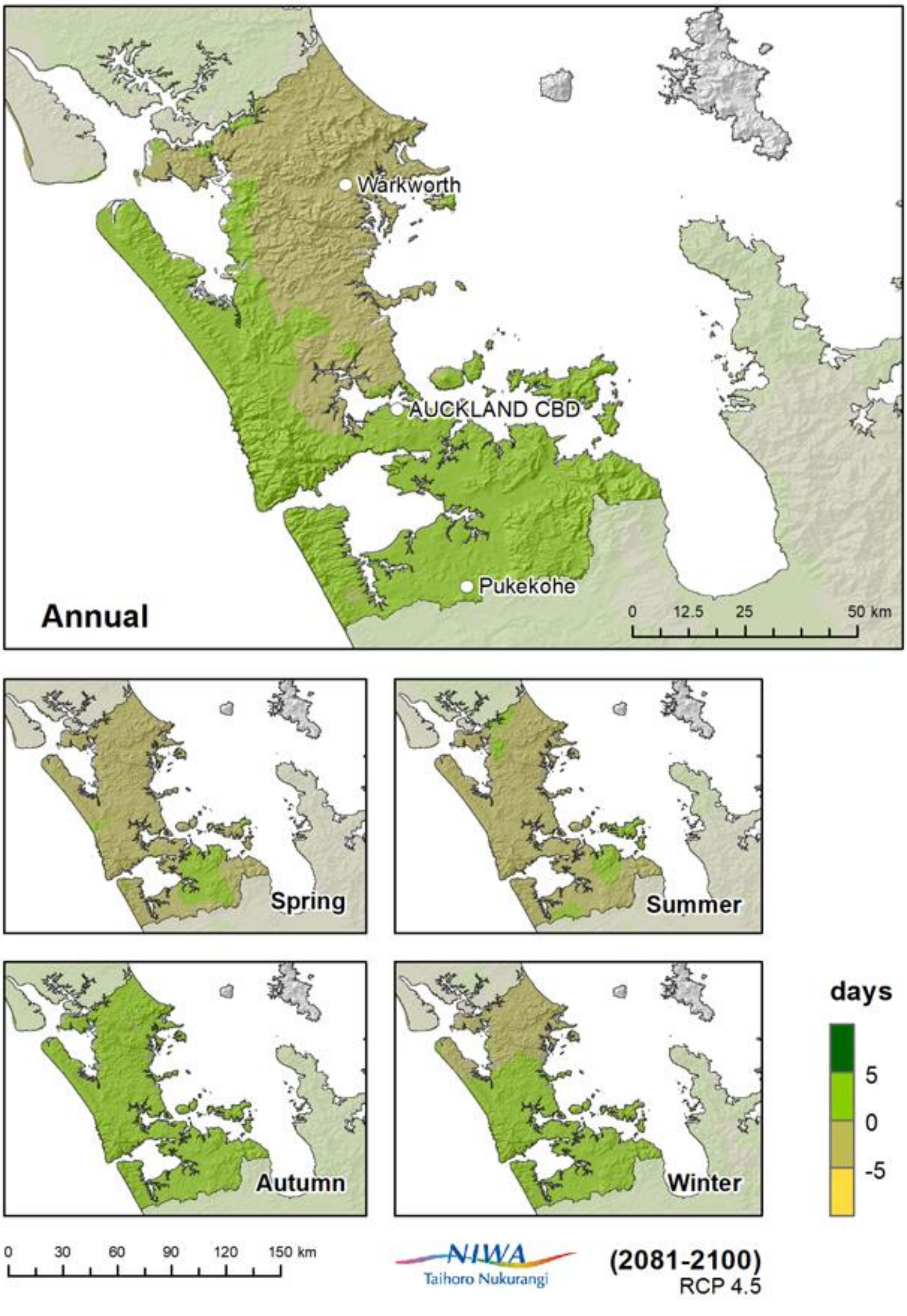

Figure 4-21: Projected annual and seasonal heavy rain day changes (days where rain > 25 mm; in number of days) at 2090 (2081-2100 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

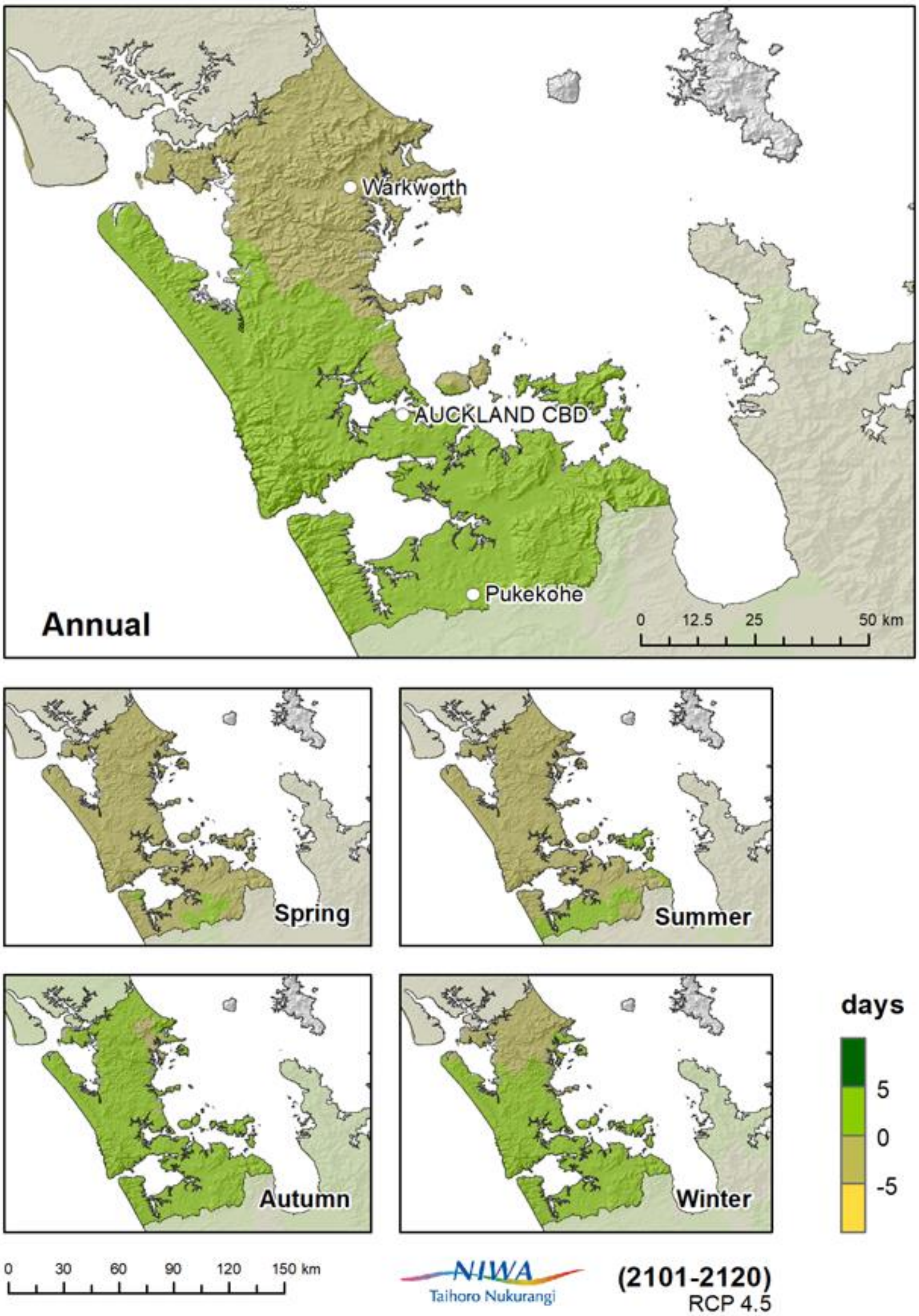

Figure 4-22: Projected annual and seasonal heavy rain day changes (days where rain > 25 mm; in number of days) at 2110 (2101-2120 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

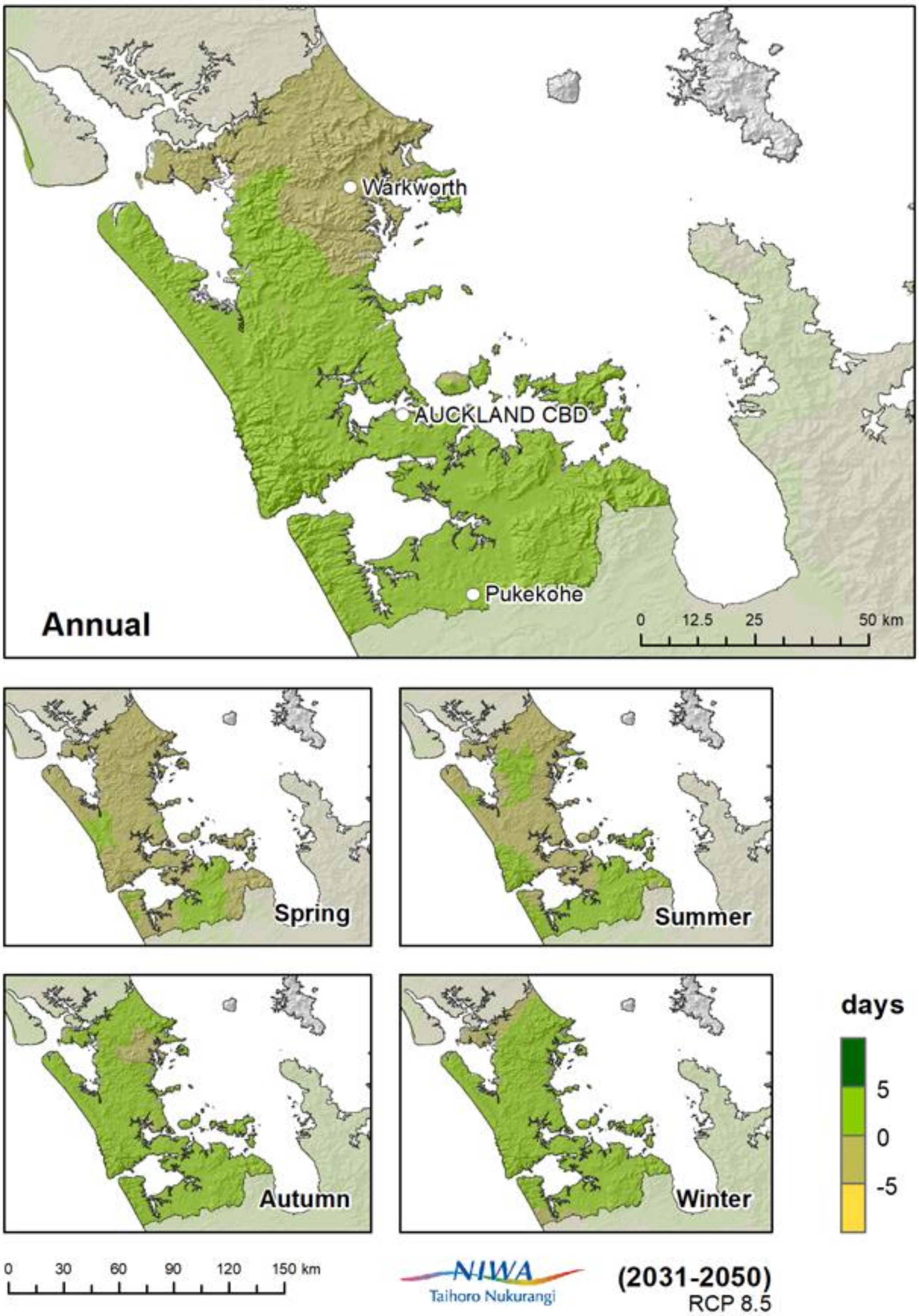

Figure 4-23: Projected annual and seasonal heavy rain day changes (days where rain > 25 mm; in number of days) at 2040 (2031-2050 average) for Auckland for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

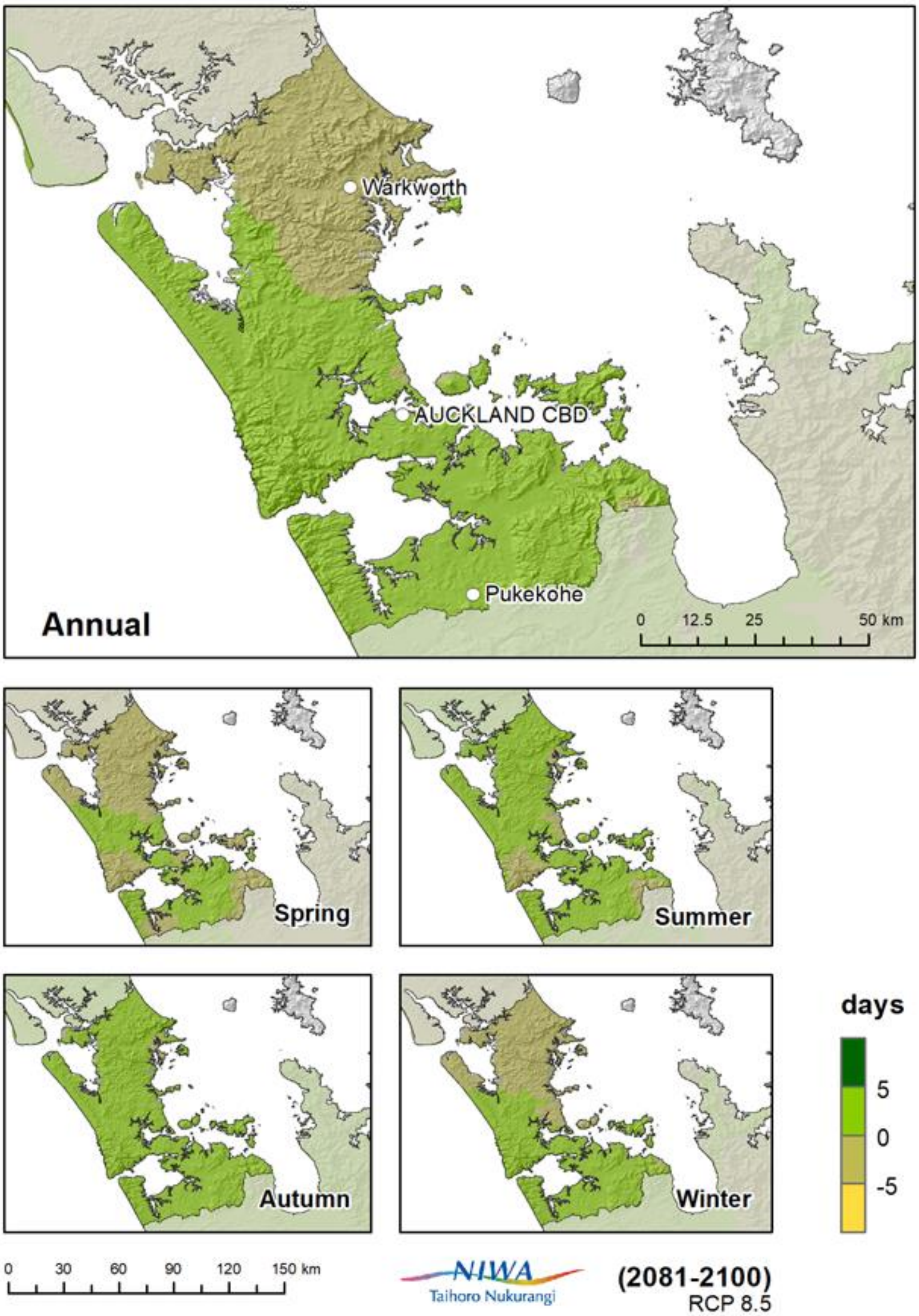

Figure 4-24: Projected annual and seasonal heavy rain day changes (days where rain > 25 mm; in number of days) at 2090 (2081-2100 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

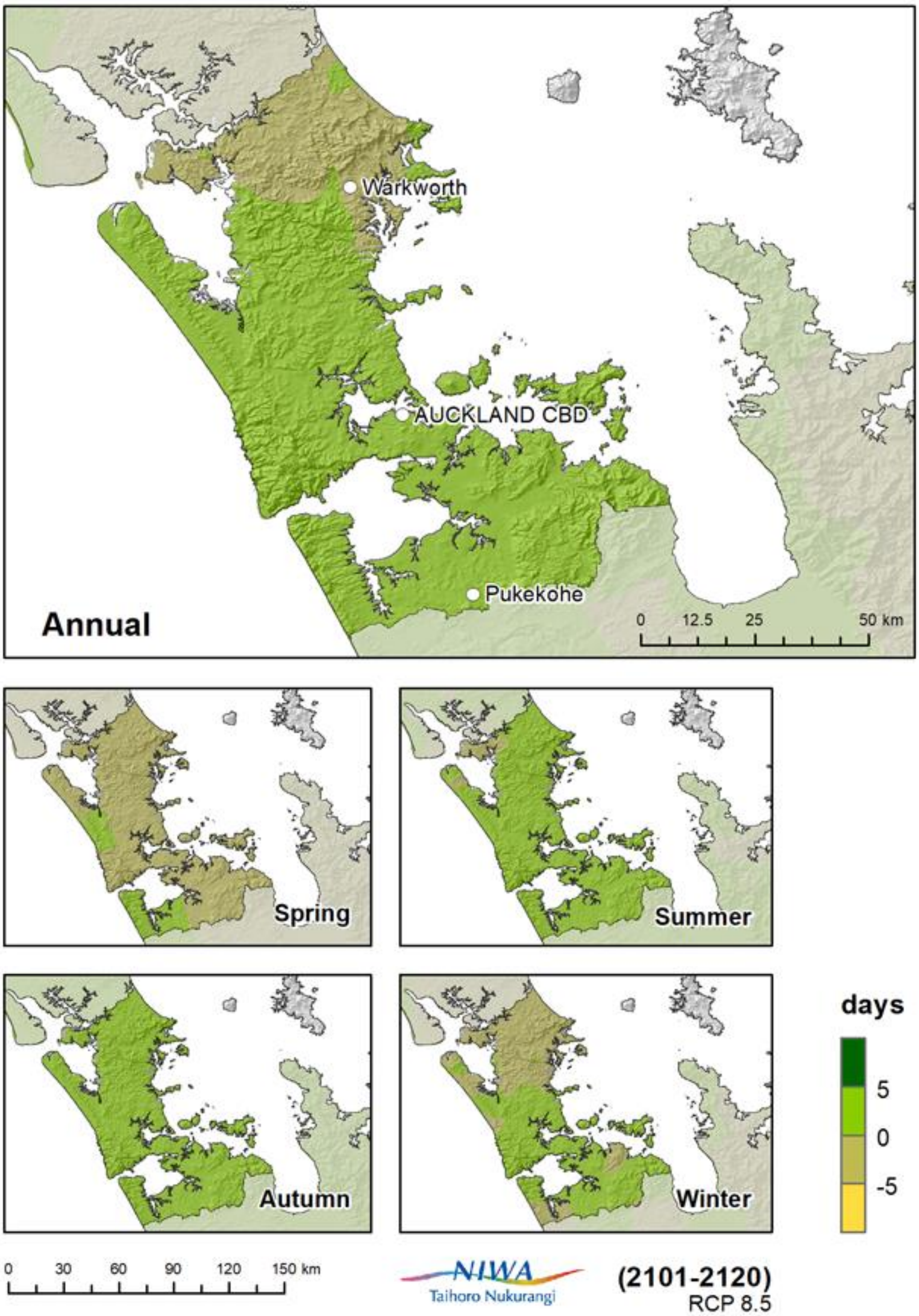

Figure 4-25: Projected annual and seasonal heavy rain day changes (days where rain > 25 mm; in number of days) at 2110 (2101-2120 average) for Auckland for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections. Resolution of projection is 5km x 5km.

4.4 Days with consecutive heavy rainfall

Key messages

- Heavy rainfall in this section was defined as days with > 40 mm of rainfall.
- At present, the highest amount of > 40 mm rain days is observed in the Waitakere Ranges, Hunua Ranges, and in the northeast of the Auckland Region (about six to eight days per year).
- By the late 21st century, increases in the number of > 40 mm days are projected for the Waitakere and Hunua Ranges, and decreases are projected for the northeast of the region.
- Under RCP8.5 in the late 21st century there is an increased frequency of consecutive days with > 40 mm of rainfall across the Auckland Region.

Heavy rainfall can lead to landslips and damage to infrastructure. The biggest problem with landslips arises when there are wet periods of at least several days duration, with high rainfall accumulations on one or more days within the period. Thus, this exploratory analysis assesses how climate change might influence 'consecutive days' of heavy rainfall, rather than single extreme events.

This analysis was initiated due to the impact of rainfall events in March 2017, where heavy rain fell in Auckland on consecutive or near-consecutive days, causing significant damage to urban stormwater infrastructure and disrupting Auckland's water supply network[5]. It was determined, in consultation with Auckland Council, that 40 mm per day was an appropriate threshold for heavy rainfall to be analogous to the March 2017 events. Note that Section 4.3 uses a threshold of 25 mm to define a 'heavy rain' day.

In the Auckland Region, the annual average rainfall is projected to slightly reduce over much of the region (e.g., Figure 4-8 for the RCP8.5 change at 2090), whereas days of 'heavy' (> 25 mm) rainfall are projected to increase in general (e.g., Figure 4-24 for the RCP8.5 change at 2090), except in the northeast of the region.

This analysis uses data from the six dynamical model simulations, and presents projections for RCP4.5 and RCP8.5. Consecutive days of heavy rainfall are calculated for the historical period (taking the 30 years 1976-2005), and compared with a 30-year period 2070-2099 at the end of the 21st century. The present occurrence and future projections of the number of days with > 40 mm of rain are considered first, and analysis of consecutive days of > 40 mm of rain is considered second.

Figure 4-26 and Figure 4-27 show the average number of days per year above the 40 mm threshold of a heavy rainfall day. The historical climate (1976-2005) is common to both figures; the frequency of heavy rainfall days is also shown for the future climates (2070-2099) under RCP4.5 (Figure 4-26) and RCP8.5 (Figure 4-27), as well as the change maps. Note that days of heavy rainfall, as defined in this section, is most apparent in the Waitakere Ranges in the west of the region, followed by the Hunua Ranges in the southeast, with a third higher occurrence in the northeast of the region.

As far as changes are concerned, RCP8.5 clearly shows an increase in frequency of heavy rainfall days in the Waitakere Ranges and a smaller increase in the Hunua Ranges. The number of days involved is small, but then the present occurrence of rainfall above 40 mm is limited to about six to eight days

[5] https://www.niwa.co.nz/climate/summaries/monthly/climate-summary-for-march-2017

per year. For RCP4.5, the northeast of the region shows a decrease in the number of heavy rainfall days, consistent with the decrease in days of rainfall above 25 mm (e.g. Figure 4-21) and decrease in overall annual rainfall (e.g. Figure 4-5).

It should be noted that the maps illustrate the six-model average (the ensemble-mean, as for all projection maps in this report). There are of course differences between the six models in their future projections. For heavy rainfall in the Auckland region, four of the six models become wetter, one drier, and the other shows little change from the historical climate.

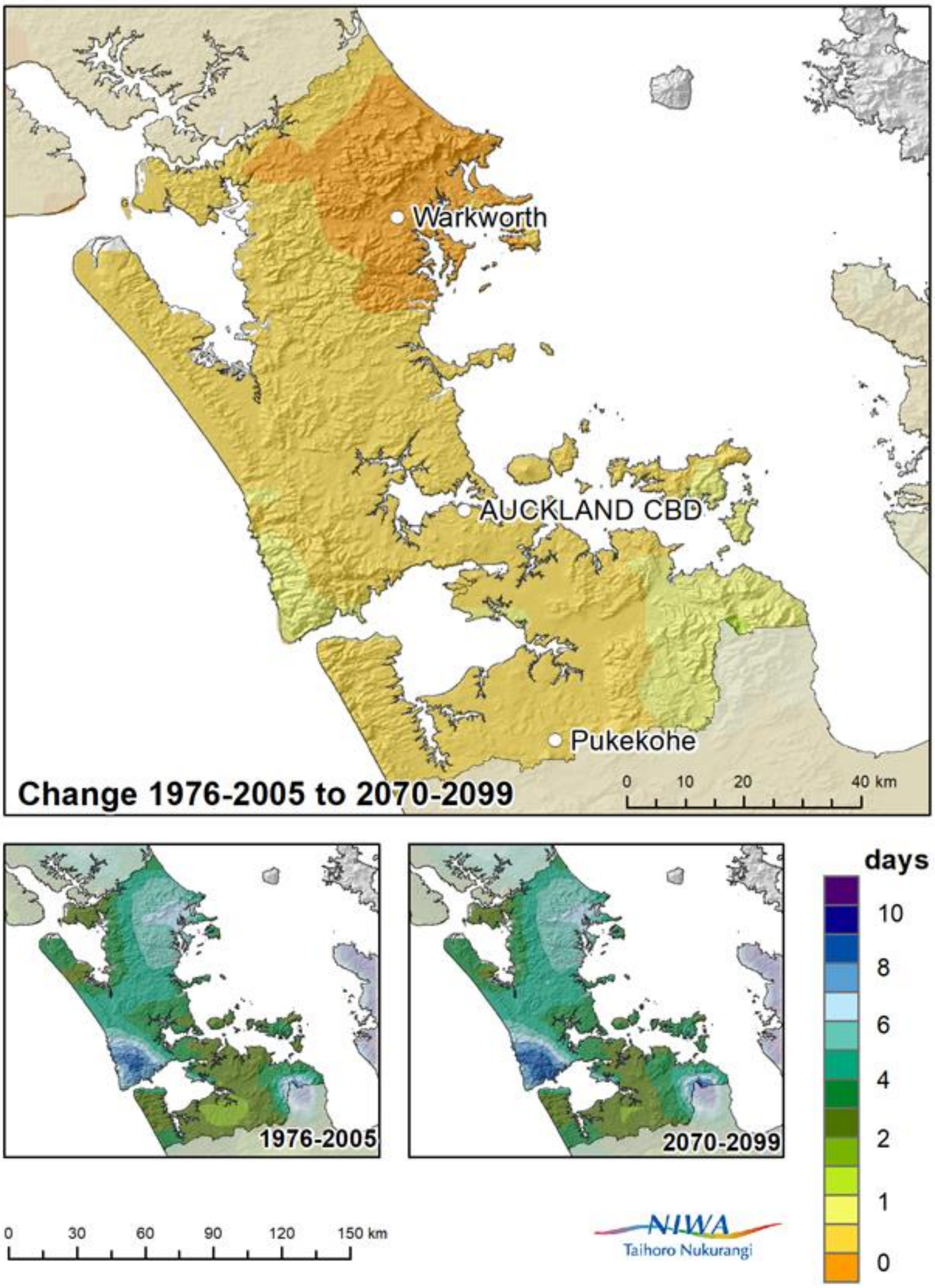

Figure 4-26: Average number of days per year with rainfall accumulation above 40mm in the historical period (1976-2005, bottom left) and at the end of the century under RCP4.5 (2070-2099, bottom right), and the change between the two periods (top panel) for Auckland.

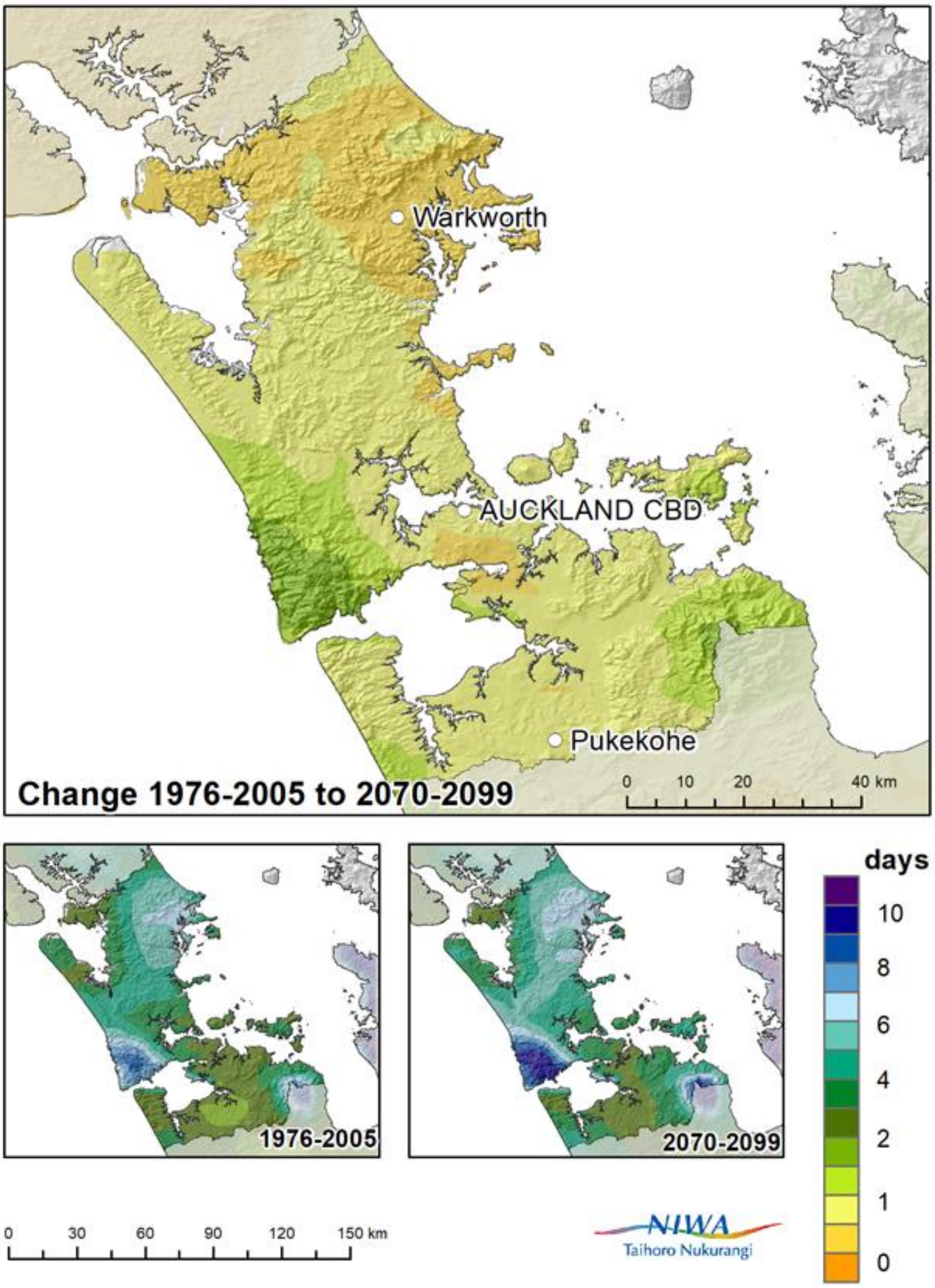

Figure 4-27: Average number of days per year with rainfall accumulation above 40mm in the historical period (1976-2005, bottom left) and at the end of the century under RCP8.5 (2070-2099, bottom right), and the change between the two periods (top panel) for Auckland.

There are many permutations of rainfall thresholds and periods that could be considered when analysing future projections for consecutive days of heavy rainfall. The exploratory analysis presented here takes a threshold of > 40 mm in daily accumulation at a grid-point. Days with rainfall above the threshold are identified, and then recurrences of heavy rainfall within three days above the same threshold are recorded. This is a 40:40:03 permutation (where 40 mm of rain must fall twice within three days). A simple example here illustrates the method of calculation. Here is a 12-day sequence of daily rainfall accumulations: 0, 0, 10, 50, 20, 10, 60, 10, 70, 10, 0, 0 (in millimetres per day). There are three days (4^{th}, 7^{th} and 9^{th}) above the threshold of 40 mm. Starting with the first occurrence of heavy rainfall (50 mm on the 4^{th} day), one would look for another occurrence within three days above the same threshold. An occurrence of 60 mm can be found on the 7^{th} day. If the analysis was restarted on the 7^{th} day, another heavy rainfall occurrence can be seen on the 9^{th} day (70 mm). Such a sequence would therefore be considered as two distinct occurrences of 40:40:03 events.

The definition of 'consecutive days' is deliberately loose, since another heavy rainfall event within a few days of the first might be just as damaging as back-to-back days of heavy rainfall. Note that if the permutation was 40:40:02 events (i.e. two 40 mm rainfall events occurring twice within two days), then there would be only the one occurrence within the example 12-day sequence (the 7^{th} and 9^{th}).

Figure 4-28 and Figure 4-29 show the results when 'consecutive' days of heavy rainfall are considered. There are, of course, fewer occurrences of consecutive days with accumulations above 40 mm than there are single days above 40 mm – the highest number is about two occurrences per year over the Waitakere Ranges and the Hunua Ranges, and most of the region currently experiences less than one occurrence of consecutive days with > 40 mm of rain per year. The changes are more marked for RCP8.5 than RCP4.5. There is a small decrease in the occurrence of consecutive days of heavy rainfall in the north of the region under RCP4.5 (a decrease of about one occurrence every two years (0.5 occurrences per year)), and small increases are projected for much of the centre, west and south of the region, of about one occurrence of consecutive days with > 40 mm of rain every two years (0.5 occurrences per year) (Figure 4-28). Under RCP8.5, there is an increased frequency of consecutive days of heavy rainfall across the Auckland Region of about one occurrence every two years (0.5 occurrences per year) (Figure 4-29).

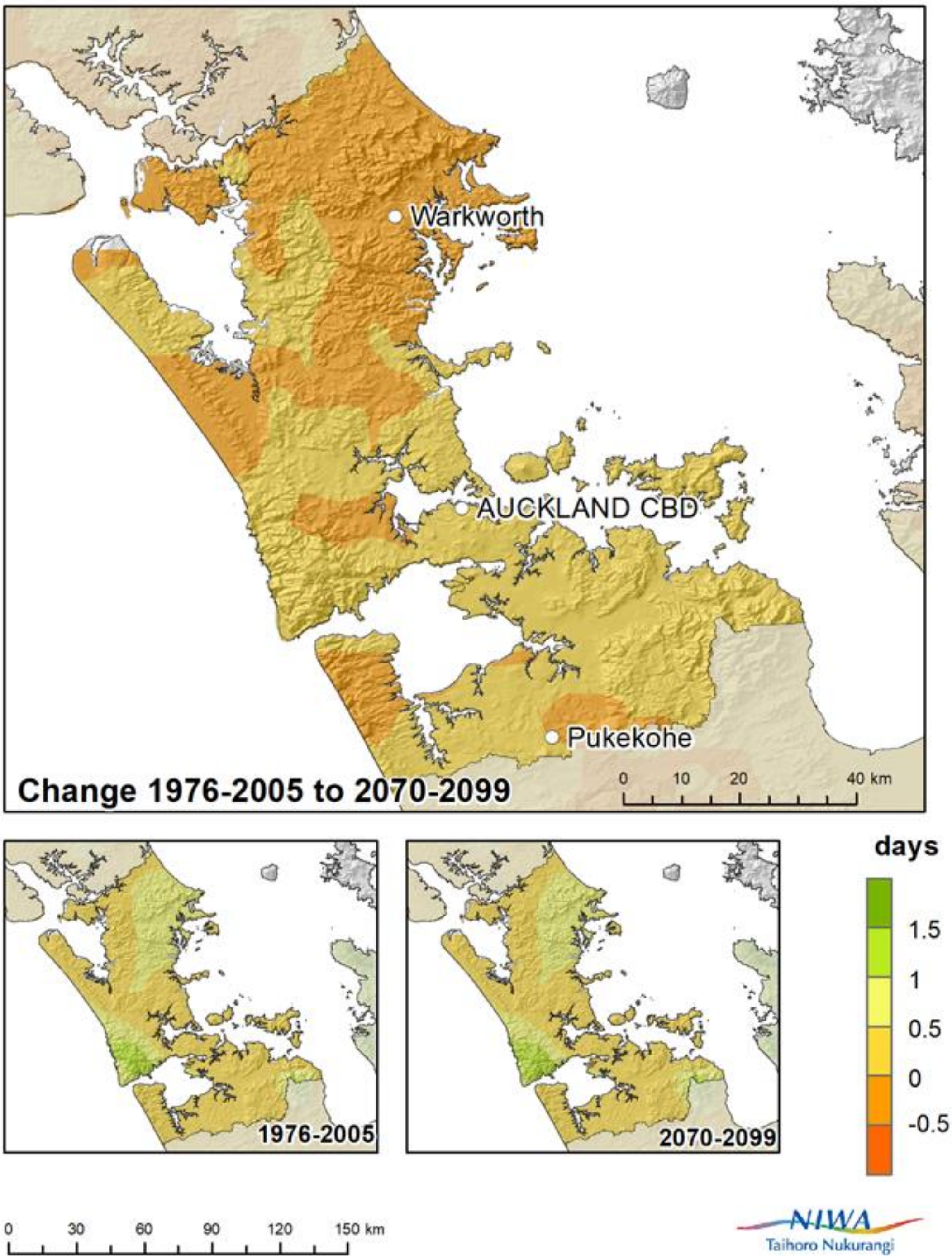

Figure 4-28: Average number of occurrences per year with 'consecutive' days of rainfall accumulations above 40 mm in the historical period (1976-2005, bottom left) and at the end of the century under RCP4.5 (2070-2099, bottom right), and the change between the two periods (top panel) for Auckland.

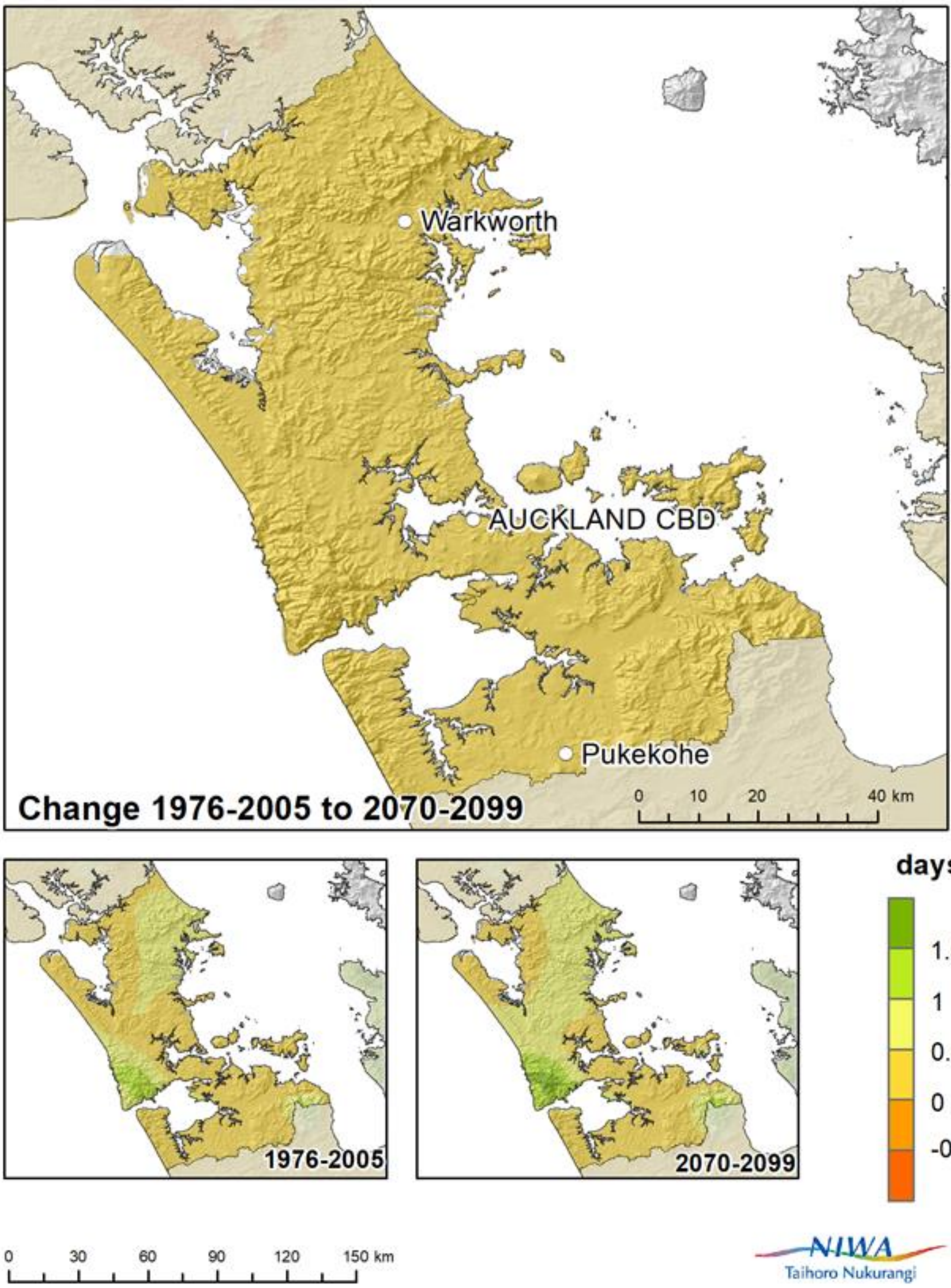

Figure 4-29: Average number of occurrences per year with 'consecutive' days of rainfall accumulations above 40 mm in the historical period (1976-2005, bottom left) and at the end of the century under RCP8.5 (2070-2099, bottom right), and the change between the two periods (top panel) for Auckland.

4.5 99th percentile of daily rainfall (1-2 wettest rain days of the year)

Key messages

- The 99th percentile of daily rainfall equates to about the 1-2 wettest rain days of the year in Auckland. The present-day annual average for the 99th percentile of daily rainfall at Auckland Airport is 48.2 mm.
- The magnitude of 99th percentile of daily rainfall is projected to increase for most parts of Auckland in the future.
- For RCP4.5 at 2110, 99th percentile of daily rainfall is projected to increase by up to 5% for most of the region and 10-15% for the southeast of the region.
- For RCP8.5 at 2110, 99th percentile of daily rainfall is projected to increase by more than 10% for most of the region, with some parts of the southeast projecting > 25% increase.

The 2016 national-scale climate change guidance (Mullan et al., 2016) presented extreme rainfall projections as the 99th percentile of daily rainfall (i.e. the top 1% of rain days (days over 1 mm of rainfall)). This equates to about the 1-2 wettest rain days of the year on average in Auckland, as many parts of the region experience about 150-200 days of rain per year (hence the top 1% is approximately the 1-2 wettest rain days of the year on average). Note that the 99th percentile is a relatively low threshold for engineering purposes (see Ministry for the Environment, 2008a). Projections for larger, rarer extreme rainfall events are presented in Section 4.6.

As a cautionary aside, the climate models being used do not have the resolution to realistically simulate the core centres of action for tropical cyclones, so extreme rainfall in Auckland from ex-tropical cyclones are likely to be underestimated in our results. See Section 5.5 for more information about storm projections.

4.5.1 Present

At present, Auckland Airport receives around 130 days of rain per year (1981-2010 average). Therefore, the 99th percentile equates to approximately the 1-2 wettest rain days per year on average. The average annual 99th percentile of daily rain from 1981-2010 was 48.2 mm. There is no statistical significance at or above the 95% confidence level of the small downward trend that is observed between 1963 and 2016 in the 99th percentile of daily rainfall at Auckland Airport (Figure 4-30).

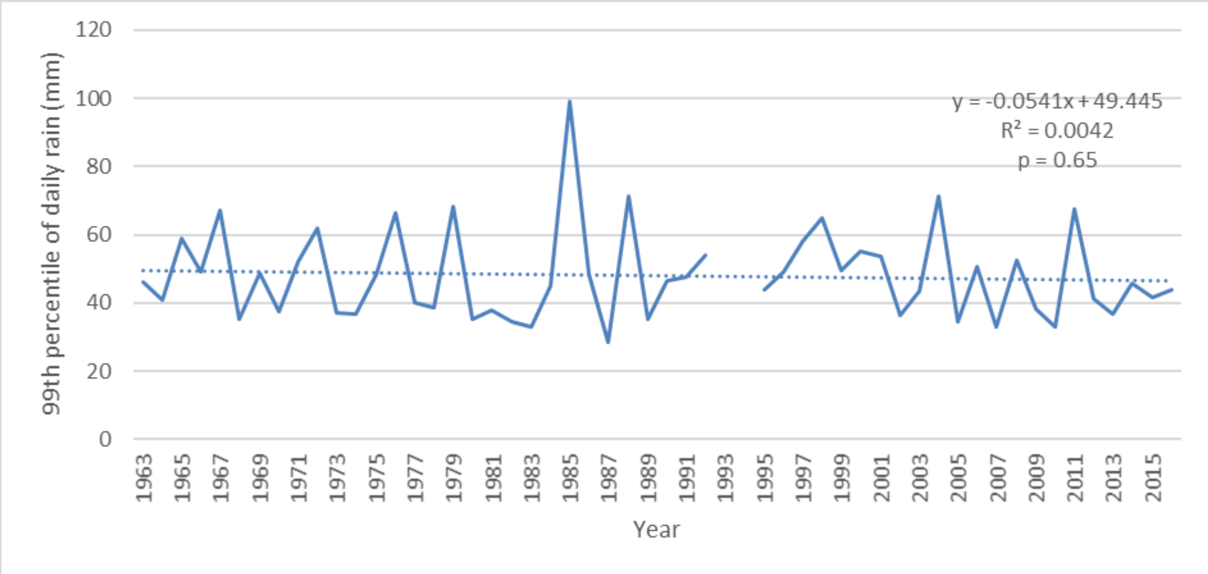

Figure 4-30: 99th percentile of daily rain (mm) at Auckland Airport, 1963-2016. There was a gap in observations at Auckland Airport in 1993 and 1994.

4.5.2 Future

Changes in the magnitude of the 99th percentile of daily rainfall across the Auckland Region have been dynamically downscaled using NIWA's Regional Climate Model in Figure 4-31, for RCP4.5 and RCP8.5 at 2040, 2090 and 2110. The ensemble-average of six models is presented. The 99th percentile of daily rainfall 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.

An example of how to interpret the results in this section is as follows: if a 99th percentile daily rain total at present produces 100 mm of rainfall, and the magnitude of that event is projected to increase by 20%, then that same event (i.e. the 99th percentile daily rain event) would expect to produce 120 mm of rain in the future.

Under RCP4.5 at 2040, most parts of the Auckland Region are expected to receive a 5% increase in 99th percentile daily rainfall, with up to a 10% increase projected for the southeast Auckland Region. Some small northern areas are projected to experience up to a 5% decrease in 99th percentile daily rainfall. This projection is similar by 2090 under RCP4.5, but the areas projecting a decrease in 99th percentile daily rainfall have almost disappeared. By 2110 under RCP4.5, 99th percentile daily rainfall is projected to increase by up to 5% for most of the region and by 10-15% for the southeast of the region.

Under RCP8.5 at 2040, southeast parts of the region are projected to experience an increase of 5-15% in the magnitude of 99th percentile daily rainfall. In the north of the region, some areas project an increase of up to 5% and others project a decrease of up to 5%. At 2090, most of the region projects an increase of over 5%, with localised southeast areas projecting a 20-25% increase in magnitude of 99th percentile daily rainfall. Western areas project increases of 10-15%. By 2110, the magnitude of 99th percentile daily rainfall is projected to increase by more than 10% for almost all the region, and up to 20% increase for some areas north of the isthmus. More than a 25% increase in magnitude of 99th percentile daily rainfall is projected for the southeast part of the region.

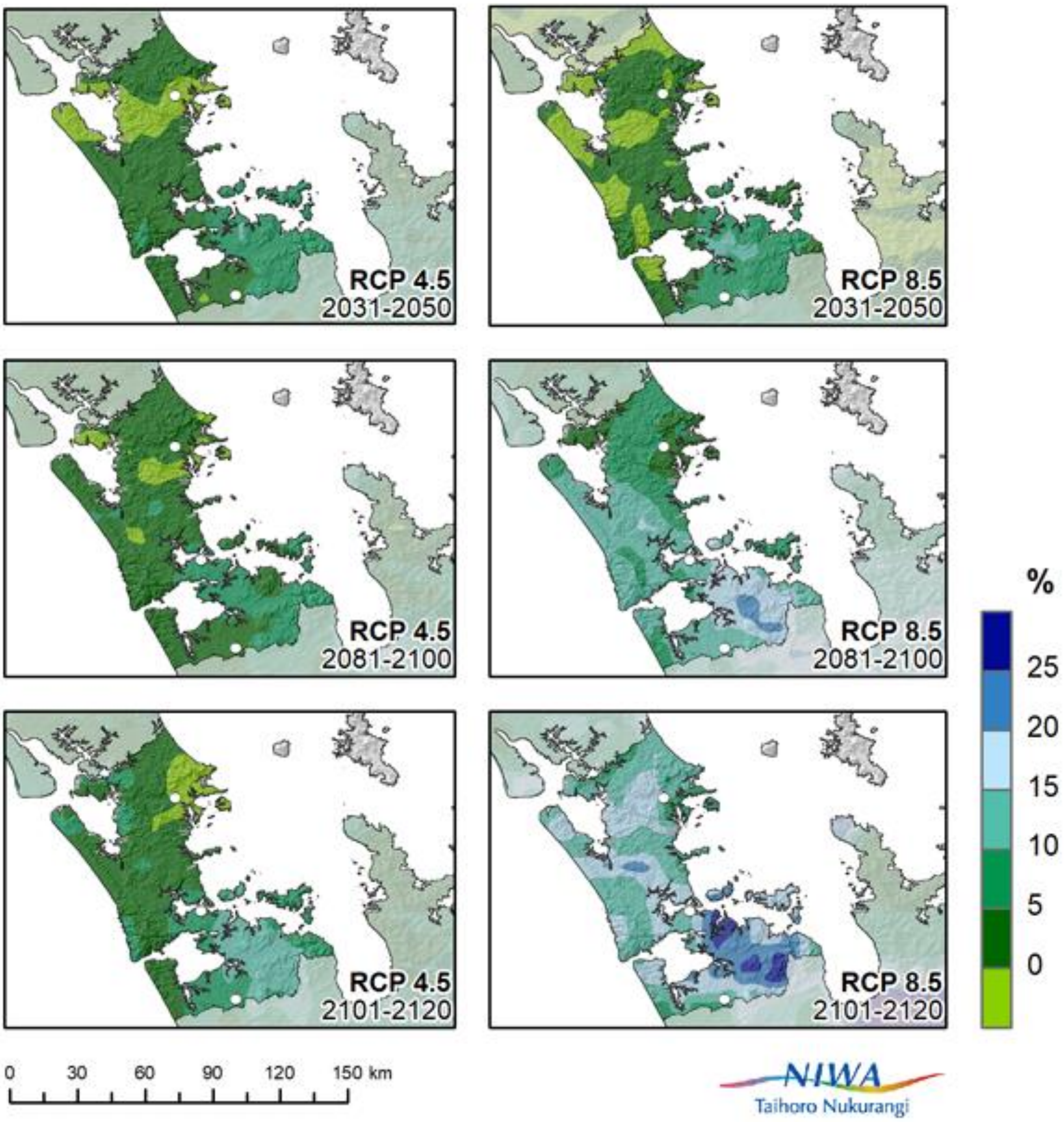

Figure 4-31: Change in the magnitude of the 99th percentile of daily rainfall (in %) for Auckland for RCP4.5 (left panels) and RCP8.5 (right panels), at 2040 (2031-2050), 2090 (2081-2100) and 2110 (2101-2120). Projected change in 99th percentile of daily rainfall is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km. White dots on map refer to (north-south) Warkworth, Auckland CBD, Pukekohe.

4.6 Extreme, rare rainfall events

Key messages

- Extreme, rare rainfall events are likely to increase in intensity in the Auckland Region because a warmer atmosphere can hold more moisture.
- Augmentation factors (percentage increase per degree of warming) are provided which allow calculation of increases in rainfall depths for events of different durations.
- Short duration, rare rainfall events have the largest relative increases which approach 14% increase per degree of warming, while the longest duration events increase by 5-6% per degree of warming.

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

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

The theoretical return period is the inverse of the probability that the event will be exceeded in any one year. For example, a 1-in-10-year rainfall event has a 1/10 = 0.1 or 10% chance of being exceeded in any one year and a 1-in-100-year rainfall event has a 1/100 = 0.01 or 1% chance of being exceeded in any one year. However, this does not mean that a 1-in-100-year flood will happen regularly every 100 years, or only once in 100 years.

This section presents maps for the amount of rainfall expected across the Auckland Region for different rainfall event durations (e.g. 1 hour, 24 hours) and different return periods (e.g. 1-in-2-year events, 1-in-100-year events, etc.). The events with larger return periods (i.e. 1-in-100-year events) have larger rainfall amounts for the same duration as events with smaller return periods (i.e. 1-in-2-year events) because larger events occur less frequently (on average).

4.6.1 Present

Maps of the rainfall expected in a present-day one-hour duration event for six different return periods ranging from 1-in-2 years to 1-in-100 years for the Auckland Region and surrounds are presented in Figure 4-32. These results are derived from the 2017 HIRDS (High Intensity Rainfall Design System) version 4 analysis. HIRDS uses a regionalized index-frequency method to predict rainfall intensities at ungauged locations (Carey-Smith et al., 2017). Note that additional quality control was carried out for Auckland stations in the HIRDS dataset, and additional data to early 2017 was included for the Auckland Region (the rest of New Zealand has data to 2015 or 2016). HIRDS version 4 is due to be released in early 2018.

All return periods for one-hour duration rainfall events show a consistent east-west gradient across the Auckland Region with the most extreme events in the east in Figure 4-32. Figure 4-33 shows the results for rainfall event durations of 24 hours, where the east-west gradient is more pronounced and there is also a larger orographic signal (more rain in higher elevation areas). This pattern may be interpreted to show that on average, extreme rainfall events occur in easterly flows with a low pressure system centered to the north of Auckland (with clockwise airflow around the low pressure system, and hence easterly flow over Auckland bringing rain predominantly to exposed eastern parts of the region).

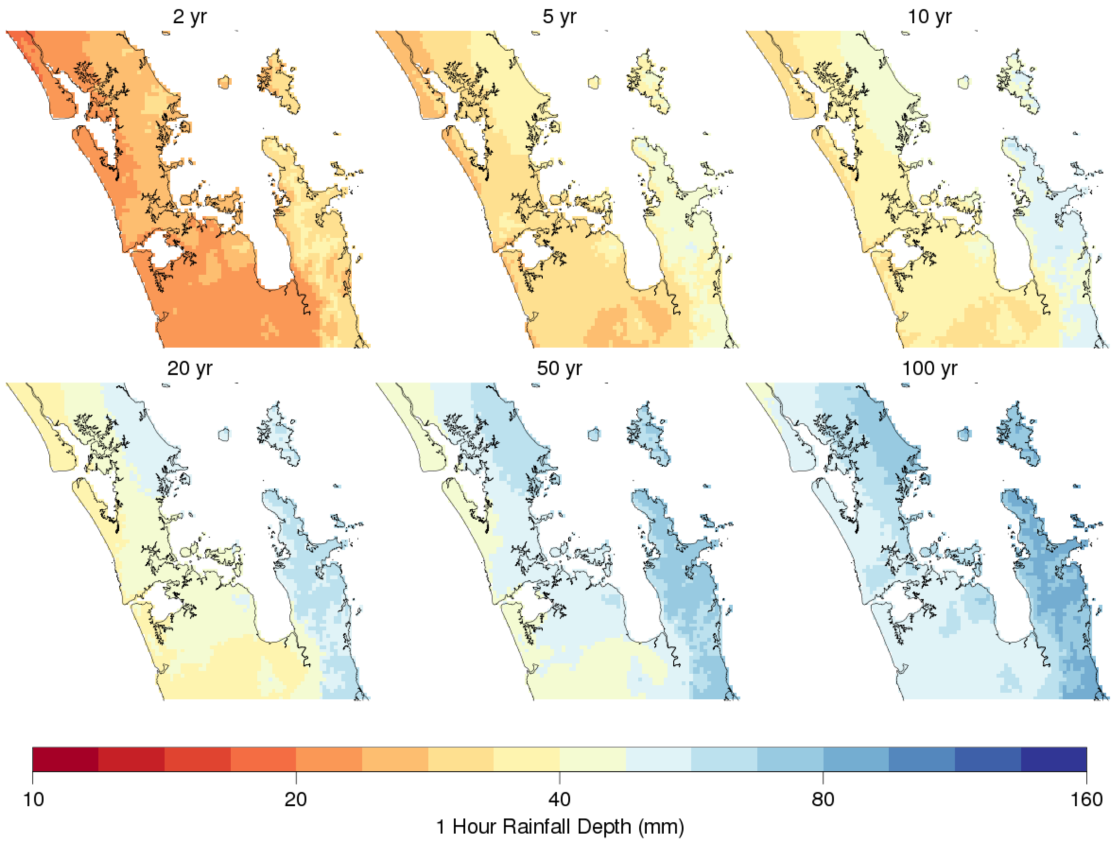

Figure 4-32: Present-day rainfall depth for a 1-hour duration event for 6 different return periods for the Auckland Region and surrounds, from 2017 HIRDS analysis. Rainfall depth is shown on using a logarithmic scale.

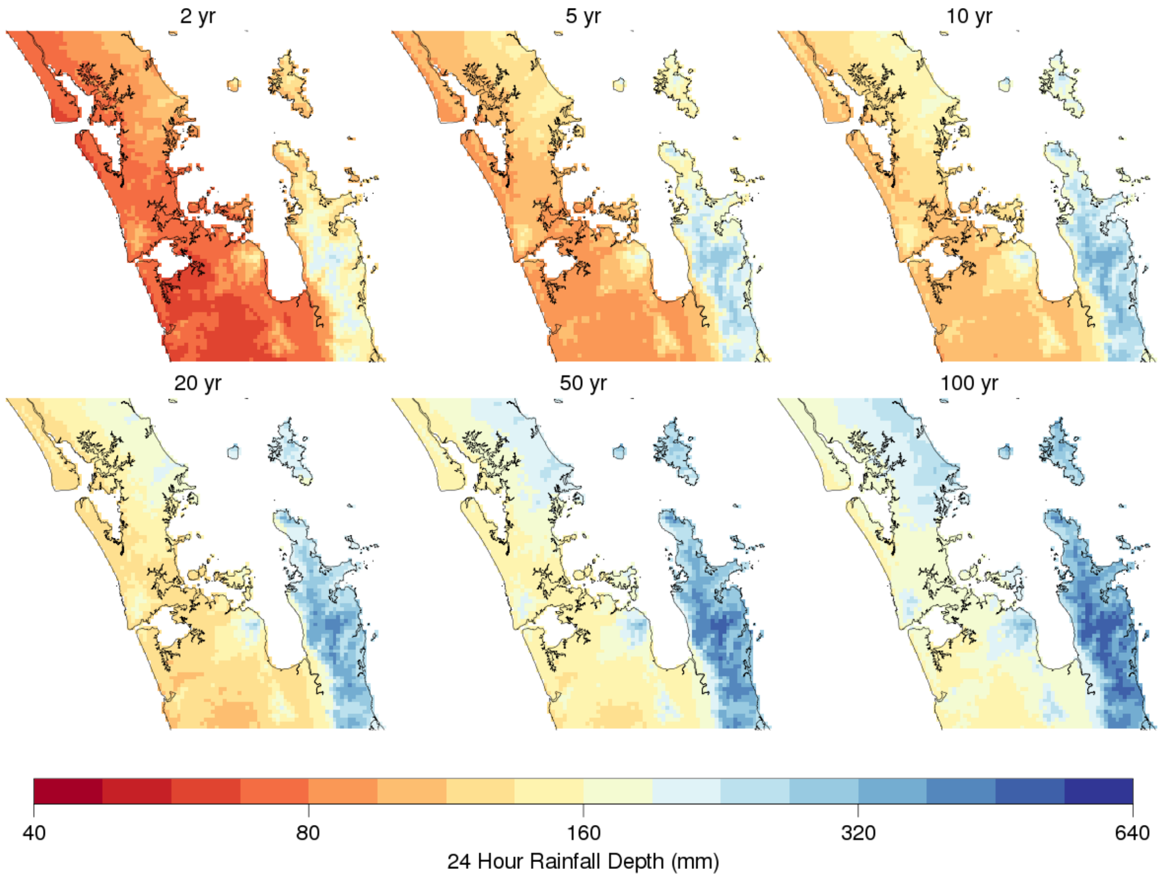

Figure 4-33: Present-day rainfall depth for a 24-hour duration event for six different return periods for the Auckland Region and surrounds, from 2017 HIRDS analysis. Rainfall depth is shown on using a logarithmic scale. Note the change in colour scale compared with the previous figure.

4.6.2 Future

A warmer atmosphere can hold more moisture, so there is potential for heavier extreme rainfall with global increases in temperatures under climate change (Fischer and Knutti, 2016, Trenberth, 1999). This general increase is due to the Clausius-Clapeyron (C-C) relationship, which states that amount of precipitable water the atmosphere can hold increases by approximately 7% per degree of warming. However, an increasing amount of research has shown that there are additional processes impacting on rainfall extremes that also need to be considered, and can result in increases above the 7% predicted by the C-C relationship. These include changes in dynamic processes such as vertical velocity (Pfahl et al., 2017) which can lead to the intensification of short duration convective storms (Feng et al., 2016). In the mid-latitudes, changes in rainfall intensity can be up to twice the C-C relationship for the most extreme events, i.e. the amount of precipitable water the atmosphere can hold may be up to 14% per degree of warming (Lenderink and Fowler, 2017). The frequency of heavy rainfall events is 'very likely' to increase over most mid-latitude land areas (this includes New Zealand; IPCC, 2013b). 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.

In the New Zealand context, Griffiths (2006) and Griffiths (2013) looked at trends in observed extreme rainfall, but found little statistical significance or obvious regional trends. Rosier et al. (2015) and Dean et al. (2013) detected the anthropogenic influence on some extreme rainfall events in New Zealand. However, very little work examining the relationship between extreme rainfall and region circulation indices has been undertaken in New Zealand. Carey-Smith et al. (2010) used regional and global climate model simulations to test the validity of the C-C relationship over New Zealand and using the limited simulations available at the time found the change in extreme rainfall to range between 5 and 12% per degree of regional warming. The 2008 Ministry for the Environment guidance manual provided climate change factors for extreme rainfall (Ministry for the Environment, 2008a), where the highest augmentation factor per degree of warming was 8%.

Due to the increase in availability of regional climate change information and advances in extreme rainfall research, this report provides an updated set of rainfall augmentation factors. These factors have been provided as a percent change per degree of warming, but can be converted to fixed percent changes for different future time slices and climate change scenarios (RCPs) by multiplying the augmentation factors by the relevant temperature change presented in Section 3.1.2. This aligns with the approach taken by the national-scale climate change guidance (Mullan et al., 2016) which limited its discussion of rainfall extremes to changes in the 99th percentile of daily rainfall. That previous work found a systematic rainfall extreme increase in much of the South Island, with both time and increasing greenhouse gas concentration, and a more varied signal in the North Island. Projections of 99th percentile daily rainfall are presented for Auckland in Section 4.5.

Analysis of extreme rainfall

Six global climate models were dynamically downscaled for the climate projections in this report. While there exists a bias-corrected version of this data at 5 km^2 resolution with a daily time-step (which was used for most of the other climate variables presented here, including the 99th percentile of daily rainfall), this has not been used for this section as the bias correction methodology excludes the most extreme events from its adjustment and does not provide sub-daily information. For this section, only *relative changes* in extreme rainfall within a simulation are assessed and used, so the effect of biases in absolute values of rainfall are minimised.

The impact of climate change on extreme rainfall was assessed using regional climate model (RCM) simulations spanning from 1971 to 2100. For each RCM simulation, hourly estimates of rainfall were used to calculate annual maxima series for all standard durations (1 hour through 5 days) at each model grid square. The generalised extreme value (GEV) distribution was then fitted at each grid square separately using the method described in Appendix II. To assess the change in extreme rainfall due to the warming climate, the parameters of the GEV distribution were allowed to change as a function of temperature. The temperature variable used for this trend analysis was each RCM's land-average annual temperature anomaly (relative to 1986-2005). Once fitted, the GEV parameters were used to calculate depth-duration-frequency tables at each grid square for the current climate and a future climate with one degree of warming. The percentage difference per degree of warming between the current and a future climate could then be estimated.

Future extreme rainfall

Despite the known biases in RCM rainfall, there is a high degree of similarity between the HIRDS-derived rainfall depth surfaces (Figure 4-32 and Figure 4-33) and those derived from the climate model simulations in Figure 4-34. The result of the ensemble-average model results for 24-hour duration rainfall events at 2-year and 100-year return periods, for RCP8.5, is shown in Figure 4-34. This figure uses the same colour scale as Figure 4-33 for ease of comparison.

While the largest rainfall depths estimated from the 1986-2005 period (left panels) are not as large as those from the HIRDS analysis above (and the smallest depths not small enough), the spatial characteristics are broadly consistent. The two future periods are also consistent and while on this logarithmic scale the differences appear small, the depths generally increase with time. It is important to note that it is the *change* between the different time slices, i.e. the relative increase in rainfall depth over time, that is fundamental, rather than the absolute values presented in these modelled results.

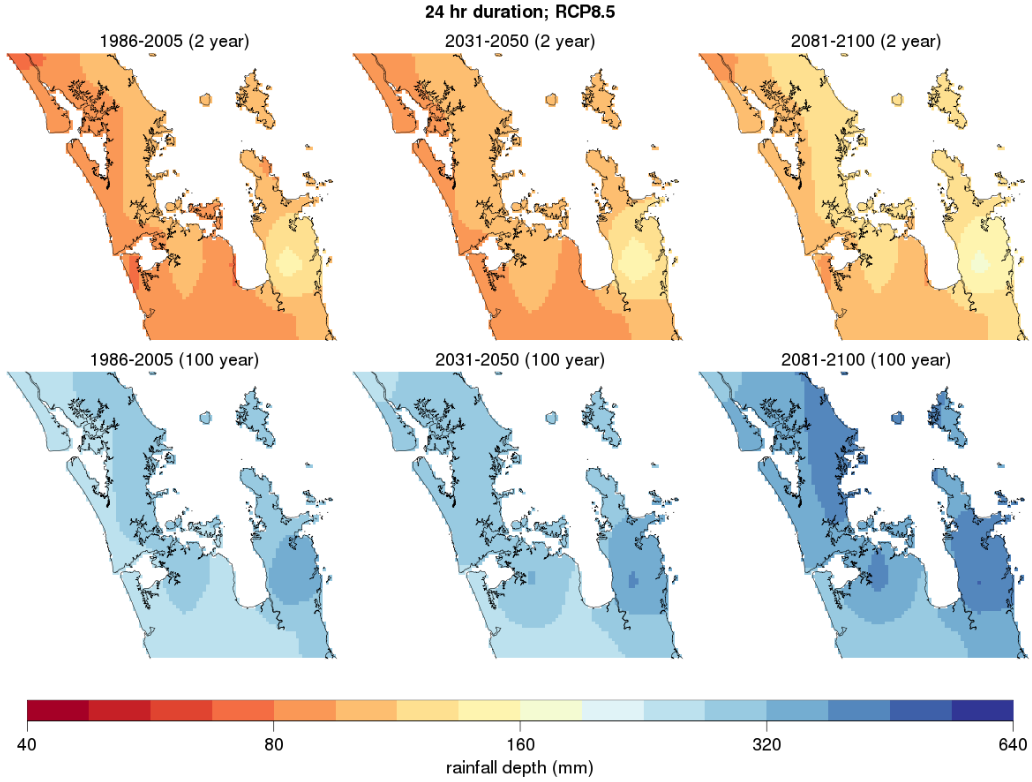

Figure 4-34: The RCM derived 2-year and 100-year event magnitude for a 24-hour duration event for the Auckland Region and surrounds. The simulation based on the current climate is shown in the left panels while the centre and right panels show the mid- and late-century projections based on the RCP8.5 scenario. Each map is an ensemble-average over 6 separate RCM simulations.

However, *changes* in rainfall depth due to climate change show regional patterns that vary considerably depending on the driving model. This is because the 24 different RCM simulations (6 driving models with 4 RCPs each) have boundary conditions that come from different global climate simulations, and therefore, they each have different extreme events that occur at different times into the future.

Some of this variability can be reduced by combining the 4 different RCPs and assessing each driving GCM model as a whole, as shown for all New Zealand in Figure 4-35. The increase in rainfall depth is clear, especially for short duration events. However, the spatial patterns in rainfall depth are still quite variable.

What this figure shows is that there appears to be no clear regional pattern to the percentage change in extreme rainfall, regardless of the event duration. That there are no regions of New Zealand with a clearly different trend from anywhere else suggests that, given the available RCM projections, it is appropriate to use a uniform estimate of the percentage increase in rainfall (for each event duration and return period) to be used over the whole country.

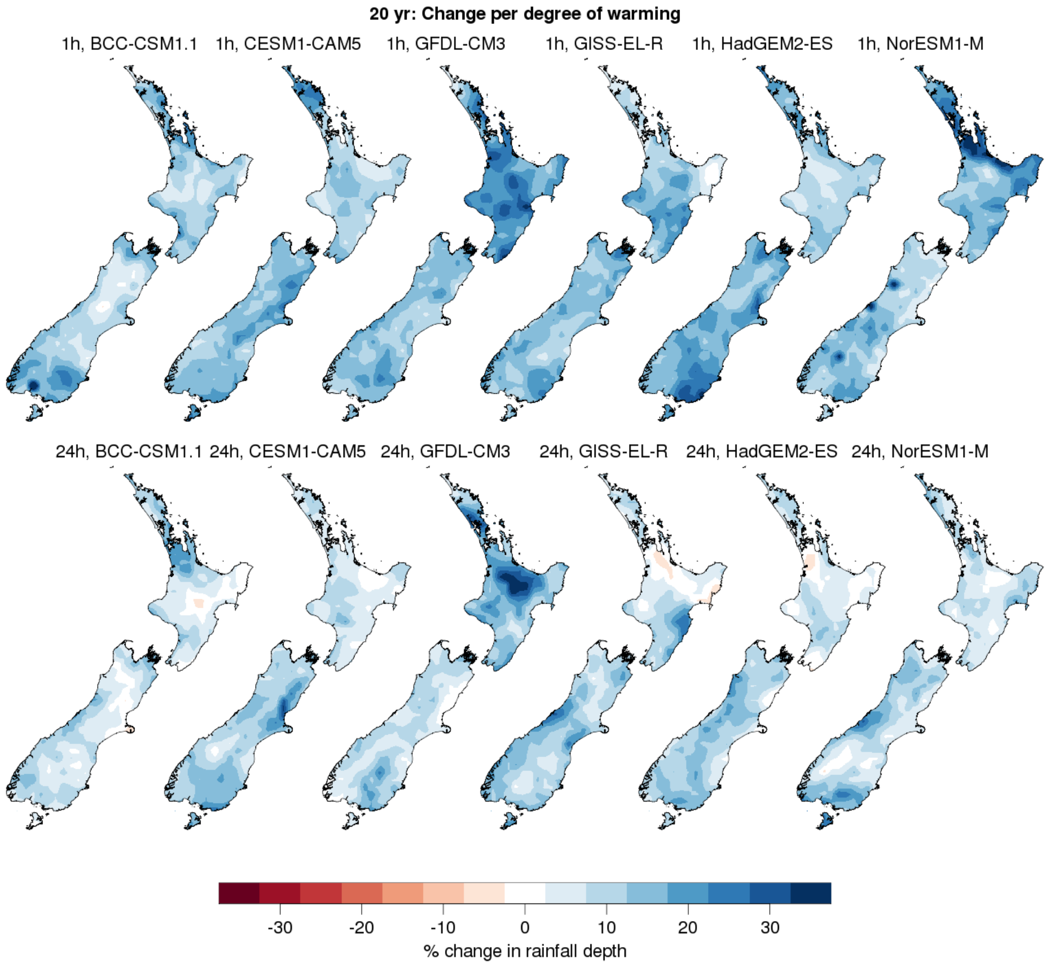

Figure 4-35: Percentage changes in the 20-year event magnitude per degree of warming for each driving model and for two different event durations. Each map combines the 4 different RCPs and shows the change resulting from 1 degree of warming. The top row shows the 1-hour duration for each model while the bottom row shows the 1-day (24h) event duration.

Climate change augmentation factors

Augmentation factors to incorporate the effect of climate change on extreme rainfall have been estimated from RCM results by taking an average over the whole of the New Zealand mainland. That is, for each event duration and return period, a uniform percentage change (along with an uncertainty estimate) has been made by taking the median of the relevant field (and 5th/95th percentile) over the country of the percentage increase in event magnitude derived from all the RCP ensemble members.

These New Zealand-average values are shown in Figure 4-36 and Table 4-3, for a 1°C temperature rise relative to 1986-2005. The short duration, rare events have the largest relative increases of around 14%, while the longest duration events increase by about 5 to 6%.

To create a change factor for a specific RCP scenario and time slice, the temperature changes from the "Annual" column in Table 3-1 or Table 3-2 can be used. For example, to obtain the augmentation factors for RCP2.6 for the 2081-2100 period, the factors in Table 4-3 should be multiplied by 0.7.

The consistent increase in the augmentation factors with reducing duration suggests that durations shorter than 1 hour (for which we have no direct results) will have even larger augmentation factors.

However, due to the lack of direct information it is recommended that the change factors listed here for the 1-hour rainfall event duration be also applied to events of shorter duration. Similarly, the factors shown here for 100-year return periods should also be applied for events with longer return periods.

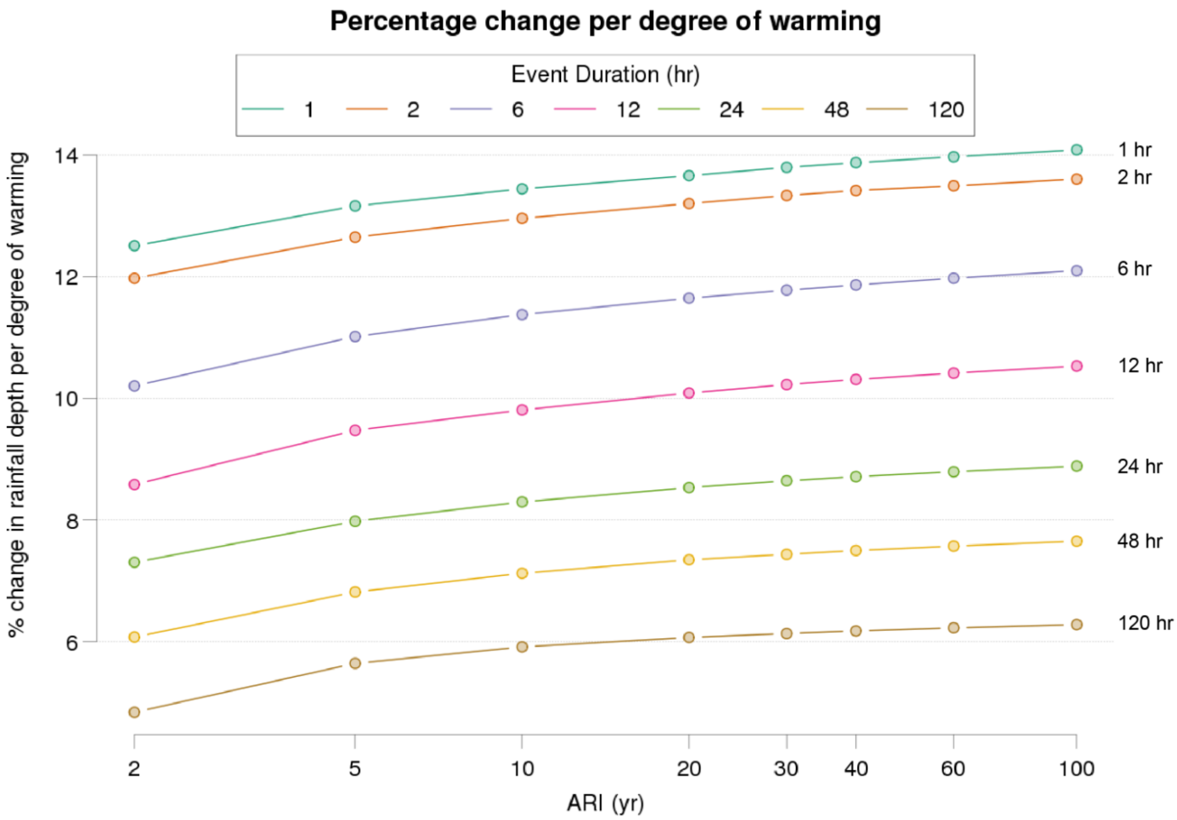

Figure 4-36: Extreme rainfall change factors for one degree of warming relative to 1986-2005 plotted as a function of return period. The different lines represent different event durations, which are labelled to the right of the line and in the legend.

Table 4-3: Percentage change factors per degree of warming to project rainfall depths based on the current climate to a future climate change scenario. The first number in each cell represents the best estimate based on the currently available information. The numbers in brackets show the range of possible values based on the regional variability found in regional climate modelling results. Use temperature projections from Table 3-1 or Table 3-2 to calculate the projected increase in extreme rainfall for each RCP and time slice for Auckland.

DURATION/ ARI	2 YR	5 YR	10 YR	20 YR	30 YR	50 YR	100 YR
1 HOUR	12.5 (9.7, 17.4)	13.1 (10.5, 18.1)	13.3 (10.6, 18.5)	13.5 (10.6, 18.8)	13.6 (10.6, 19.0)	13.7 (10.5, 19.2)	13.9 (10.5, 19.4)
2 HOURS	11.9 (8.8, 16.9)	12.5 (9.7, 17.6)	12.8 (9.8, 18.0)	13.0 (9.8, 18.4)	13.1 (9.8, 18.6)	13.2 (9.8, 18.9)	13.3 (9.8, 19.1)
6 HOURS	10.2 (7.4, 15.2)	10.9 (8.1, 16.0)	11.2 (8.3, 16.5)	11.5 (8.4, 16.8)	11.6 (8.4, 17.0)	11.7 (8.4, 17.2)	11.8 (8.4, 17.5)
12 HOURS	8.6 (5.9, 13.6)	9.3 (6.6, 14.5)	9.6 (6.8, 14.9)	9.8 (7.0, 15.3)	9.9 (7.0, 15.5)	10.0 (7.1, 15.7)	10.2 (7.1, 15.9)
24 HOURS	7.3 (4.2, 12.2)	7.9 (4.6, 12.8)	8.1 (4.8, 13.0)	8.3 (4.9, 13.2)	8.4 (4.9, 13.3)	8.5 (5.0, 13.4)	8.6 (5.0, 13.5)
48 HOURS	6.1 (3.0, 11.4)	6.7 (3.1, 11.9)	6.9 (3.2, 12.1)	7.1 (3.2, 12.3)	7.1 (3.2, 12.4)	7.2 (3.3, 12.5)	7.3 (3.3, 12.6)
72 HOURS	5.5 (2.4, 10.8)	6.1 (2.6, 11.2)	6.3 (2.6, 11.4)	6.5 (2.7, 11.6)	6.5 (2.7, 11.7)	6.6 (2.7, 11.8)	6.7 (2.7, 11.9)
96 HOURS	5.0 (2.0, 10.4)	5.8 (2.2, 10.9)	6.0 (2.3, 11.2)	6.1 (2.3, 11.4)	6.2 (2.3, 11.5)	6.3 (2.3, 11.7)	6.3 (2.3, 11.8)
120 HOURS	4.8 (1.7, 10.0)	5.5 (1.9, 10.3)	5.7 (2.0, 10.5)	5.9 (2.0, 10.8)	5.9 (2.0, 10.9)	6.0 (2.0, 11.0)	6.0 (2.0, 11.1)

Note that the numbers presented in Figure 4-36 and Table 4-3 may change prior to the release of HIRDS version 4, which is planned for early 2018. An updated version of this report will be provided to Auckland Council if there are changes.

4.7 Dry days (< 1 mm)

Key messages

- The average number of dry days (days with < 1 mm of rainfall) at Auckland Airport is 237 days per year.
- An increase in the number of annual dry days is projected for most of the Auckland Region in the future. Spring is generally the season where the largest increase in dry days is projected.
- By 2110 under RCP4.5, most of the Auckland Region is projected to experience six to nine more dry days per year.
- By 2110 under RCP8.5, most of the Auckland Region is projected to experience 12-21 more dry days per year.

4.7.1 Present

Dry days are defined in this report as days with less than 1 mm of rainfall, i.e. the inverse of rain days presented in Section 4.2. The average present number of dry days per year at Auckland Airport is 237 (1981-2010 average). There is no statistically significant trend at or above the 95% confidence level in the number of dry days per year between 1963 and 2016 (Figure 4-37).

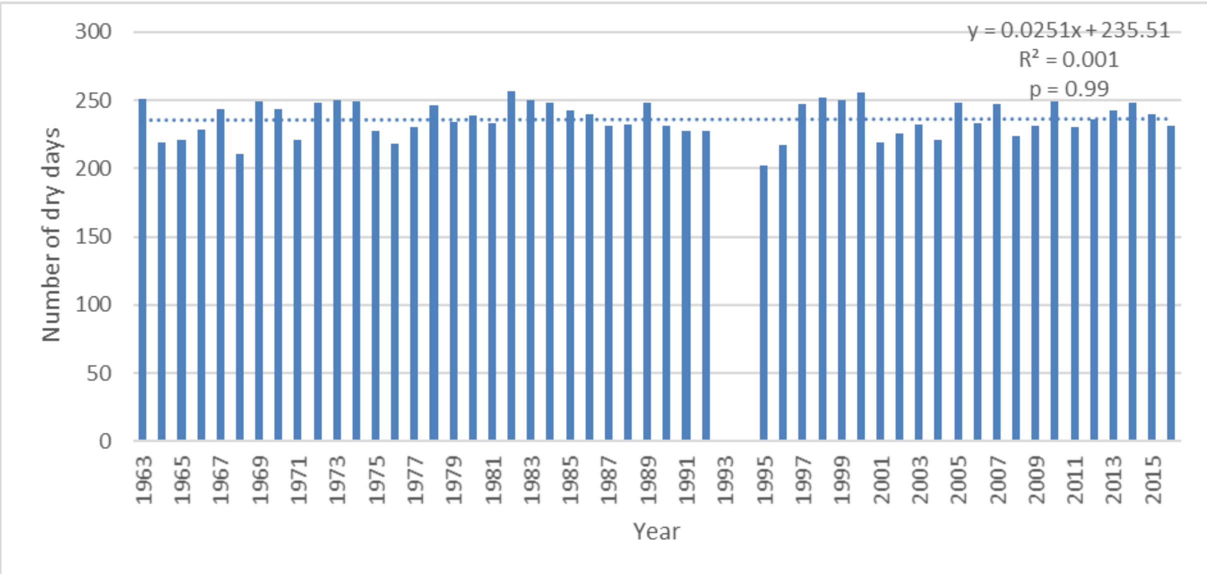

Figure 4-37: Number of dry days per year (< 1mm rainfall) at Auckland Airport, 1963-2016. There was a gap in observations at Auckland Airport in 1993 and 1994.

4.7.2 Future

The projected changes in dry days for the Auckland Region are presented for RCP4.5 and RCP8.5 at 2040, 2090 and 2110 in Figure 4-38 to Figure 4-43, derived from the ensemble average of six dynamically downscaled models.

Projections for dry days at 2040 are similar for both RCP4.5 (Figure 4-38) and RCP8.5 (Figure 4-41). An increase of three to nine dry days per year is projected for most of the Auckland Region for 2040. Small decreases in the number of dry days per year (0-3 days per year) are projected for Waiheke Island and the Waitakere Ranges. At the seasonal timescale for 2040 under RCP4.5 (Figure 4-38), increases of zero to three dry days per year are projected for most of the region, with small decreases projected for the Waitakere Ranges and in the southeast of the region. For RCP8.5 at 2040 (Figure 4-41), a larger increase in dry days is projected across the region for spring (three to six days) than the other seasons (zero to three days).

At 2090 under RCP4.5 (Figure 4-39), six to 12 more dry days per year are projected for the northern Auckland Region and the isthmus (Figure 4-39). Decreases of zero to six dry days per year are projected for Waiheke Island and the Waitakere Ranges at 2090 under RCP4.5. Spring is the season with the largest increases in dry days, with three to six more dry days projected across most of the region for this season under RCP4.5 at 2090. By 2110 under RCP4.5 (Figure 4-40), most of the Auckland Region is projected to experience six to nine more dry days per year, and zero to three more dry days per year are projected for the Waitakere Ranges and Waiheke Island.

At 2090 under RCP8.5 (Figure 4-42), 12-21 more dry days per year are projected for most of the region. The west of the region (including the Waitakere Ranges) and Waiheke Island project smaller increases of zero to six dry days per year. Spring is the season with the largest increase in dry days, with six to nine more dry days projected for most of the region at 2090 under RCP8.5. By 2110 under RCP8.5 (Figure 4-43), the projected pattern of dry days is similar to that at 2090 under RCP8.5, although the extent of the area projecting 18-21 more dry days per year is reduced.

Model agreement is good for dry day projections across both RCPs at 2090 and 2110 as most models project an increase in dry days.

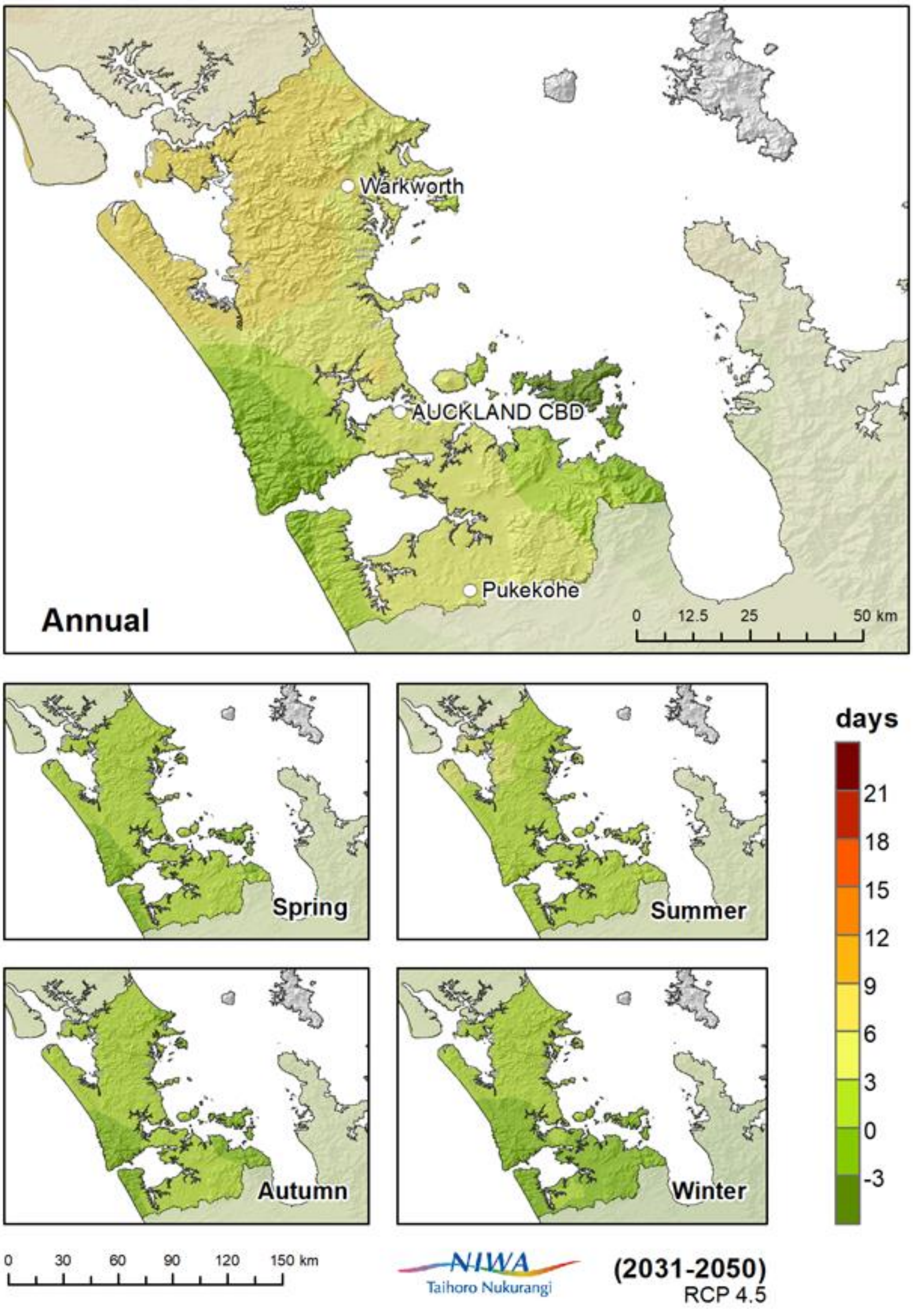

Figure 4-38: Projected annual and seasonal dry day changes (days where rain <1mm; in number of days) at 2040 (2031-2050 average) for Auckland for RCP4.5. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

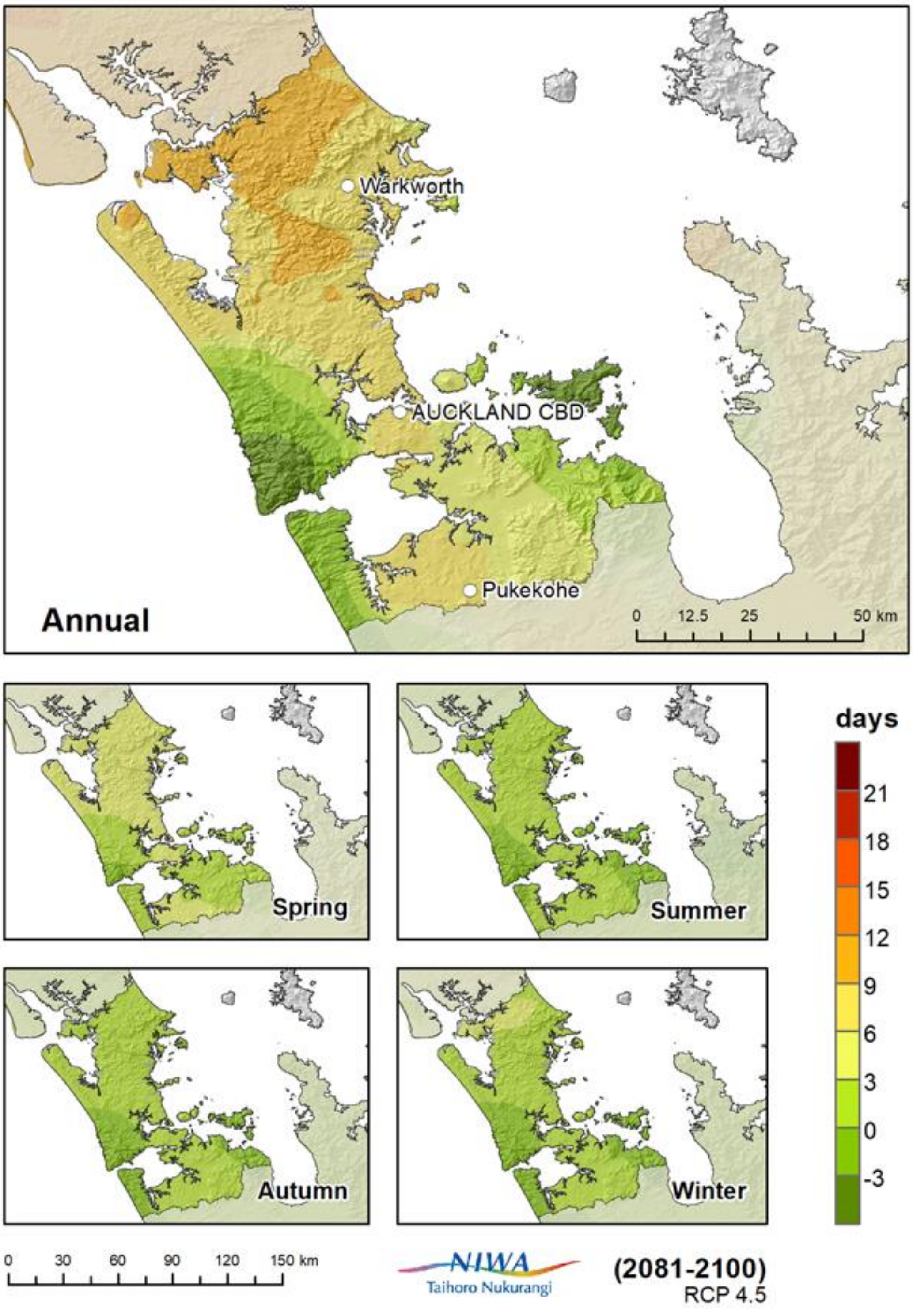

Figure 4-39: Projected annual and seasonal dry day changes (days where rain <1mm; in number of days) at 2090 (2081-2100 average) for Auckland for RCP4.5. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

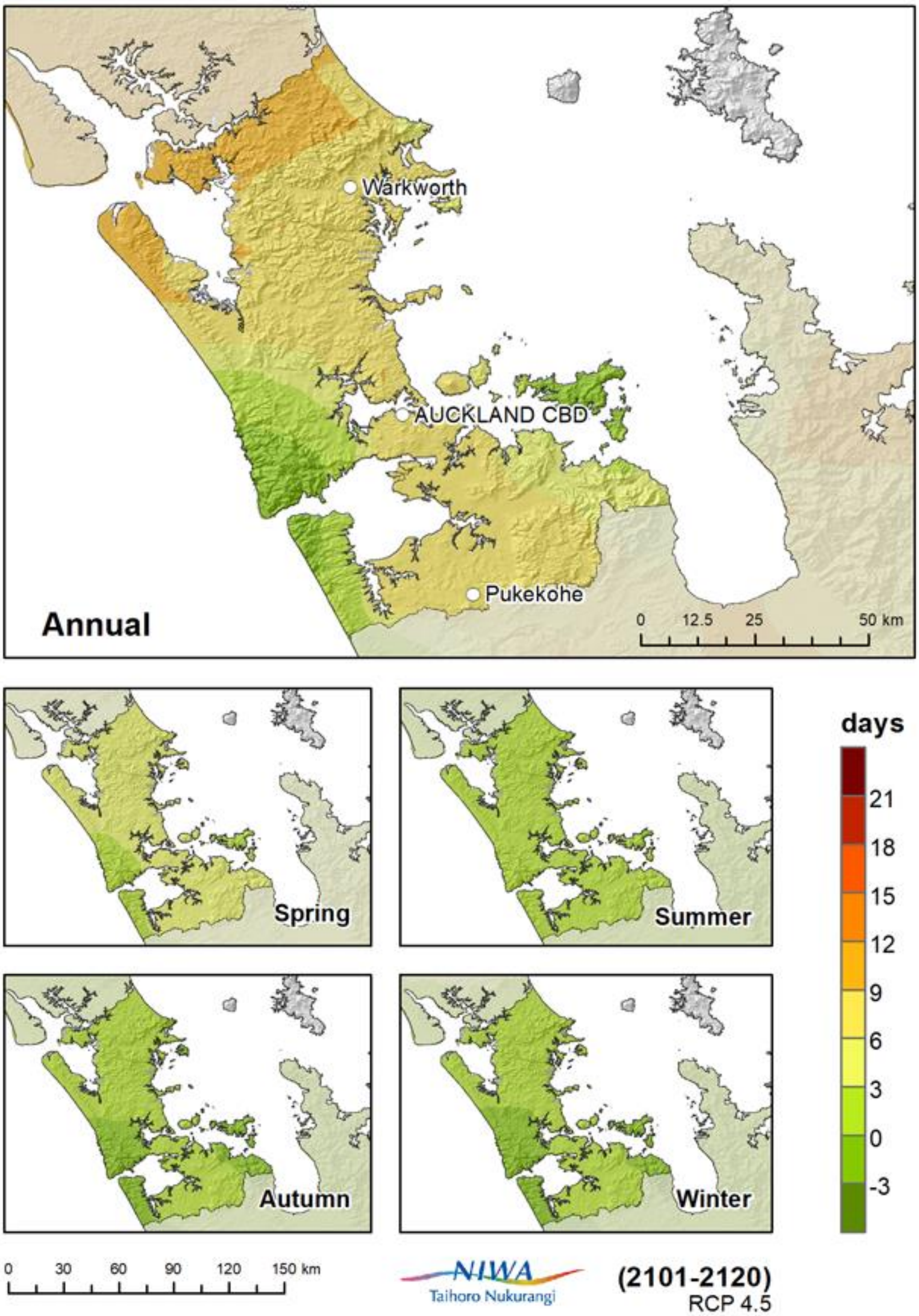

Figure 4-40: Projected annual and seasonal dry day changes (days where rain <1mm; in number of days) at 2110 (2101-2120 average) for Auckland for RCP4.5. Projected change in is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

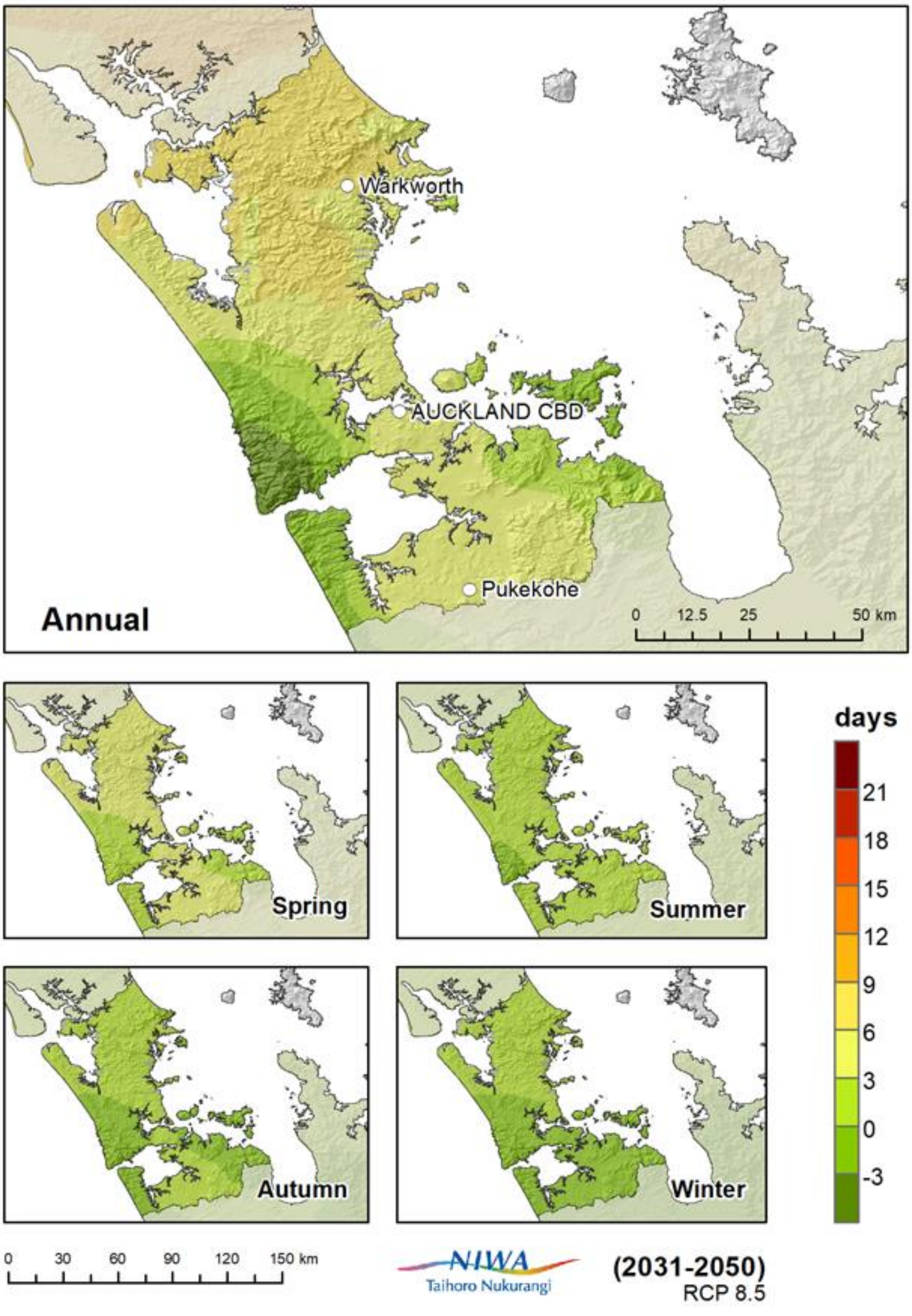

Figure 4-41: Projected annual and seasonal dry day changes (days where rain <1mm; in number of days) at 2040 (2031-2050 average) for Auckland for RCP8.5. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

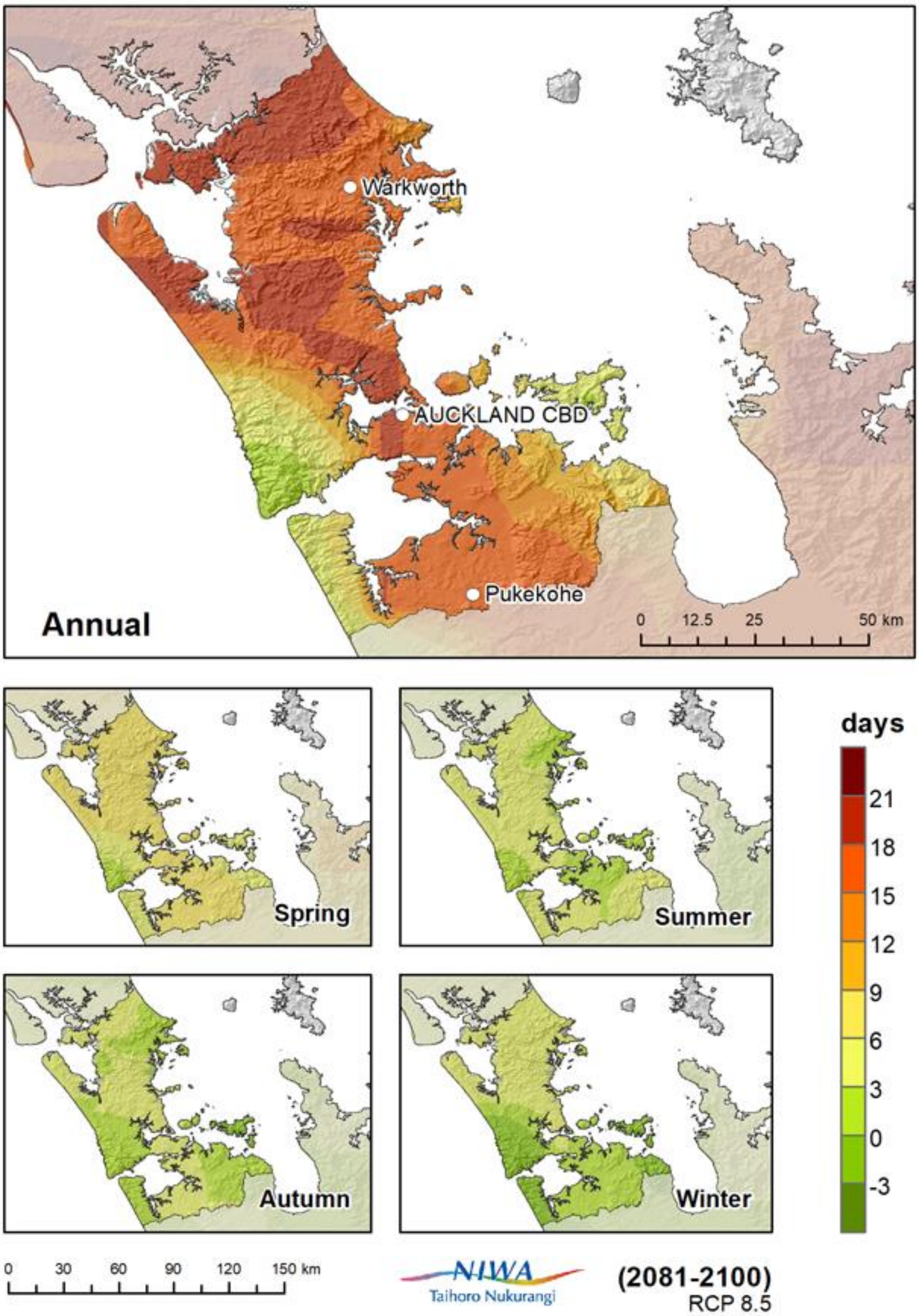

Figure 4-42: Projected annual and seasonal dry day changes (days where rain <1mm; in number of days) at 2090 (2081-2100 average) for Auckland for RCP8.5. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

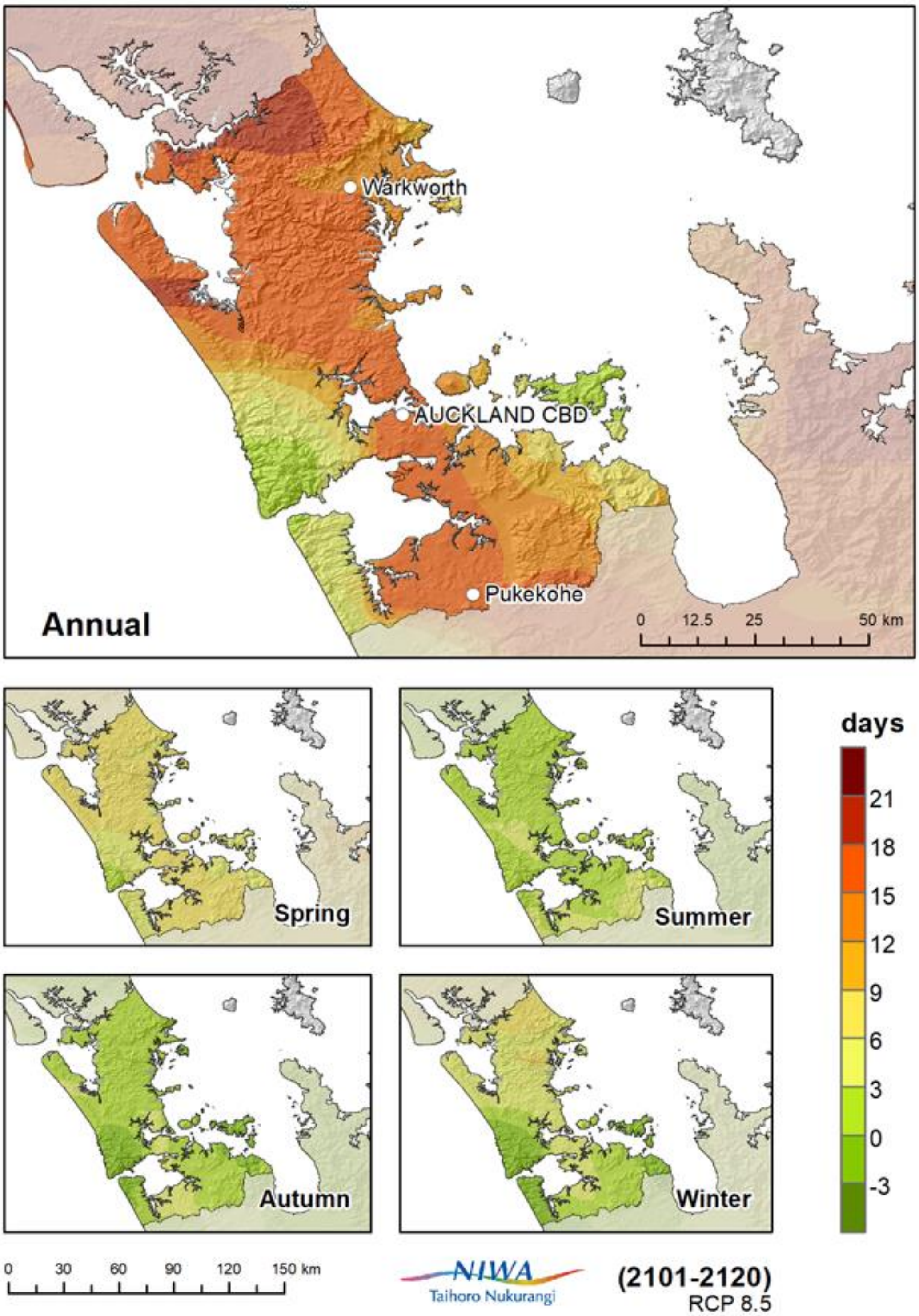

Figure 4-43: Projected annual and seasonal dry day changes (days where rain <1mm; in number of days) at 2110 (2101-2120 average) for Auckland for RCP8.5. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

4.8 Potential Evapotranspiration Deficit

Key messages

- Potential evapotranspiration deficit (PED) is the gap between water demand and water availability. It affects soil moisture retention and plant growth. > 300 mm of accumulated PED indicates very dry conditions.
- Present-day PED is lowest in the Hunua Ranges and Waitakere Ranges (< 225 mm per year) and highest on the east coast of the Auckland Region (> 375 mm per year).
- PED is projected to increase everywhere in the Auckland Region in the future; i.e. Auckland is projected to become more drought-prone. The largest increases are projected for Waiheke Island and the southeast.
- Waiheke Island and the southeast Auckland Region project an increase in the number of days of PED > 300 mm in the future, indicating longer dry spells.

Parts of the Auckland Region are particularly prone to meteorological drought[6] conditions. Due to the importance of primary production to New Zealand's economy, the occurrence of drought is of major concern. The measure of meteorological drought that is used in this section is 'potential evapotranspiration deficit' (PED). Evapotranspiration is the process where water held in the soil is gradually released to the atmosphere through a combination of direct evaporation and transpiration from plants. As the growing season advances (the growing season starts in July and ends in June), the amount of water lost from the soil through evapotranspiration typically exceeds rainfall, giving rise to an increase in soil moisture deficit. As soil moisture decreases, pasture production becomes moisture-constrained and evapotranspiration can no longer meet atmospheric demand.

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

PED is calculated as the 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 missing rainfall needed in order to keep pastures growing at optimum levels. Higher PED totals indicate drier soils. An increase in PED of 30 mm or more corresponds to an extra week of reduced grass growth. Accumulations of PED greater than 300 mm indicate very dry conditions.

Measures and projections of hydrologic drought are presented in Section 8.1.

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

4.8.1 Present

The higher the PED accumulation, the drier the soils are, with accumulations of > 300 mm indicating very dry conditions. Present-day annual average potential evapotranspiration deficit (PED) is lowest in the Hunua Ranges in the southeast of the Auckland Region and Waitakere Ranges in the west of the region, with less than 225 mm accumulated PED per year on average (Figure 4-44). PED is highest on the east coast as well as the Hauraki Gulf islands (excluding Great Barrier Island), and in the northwest of the region, with over 375 mm of accumulated PED per year on average.

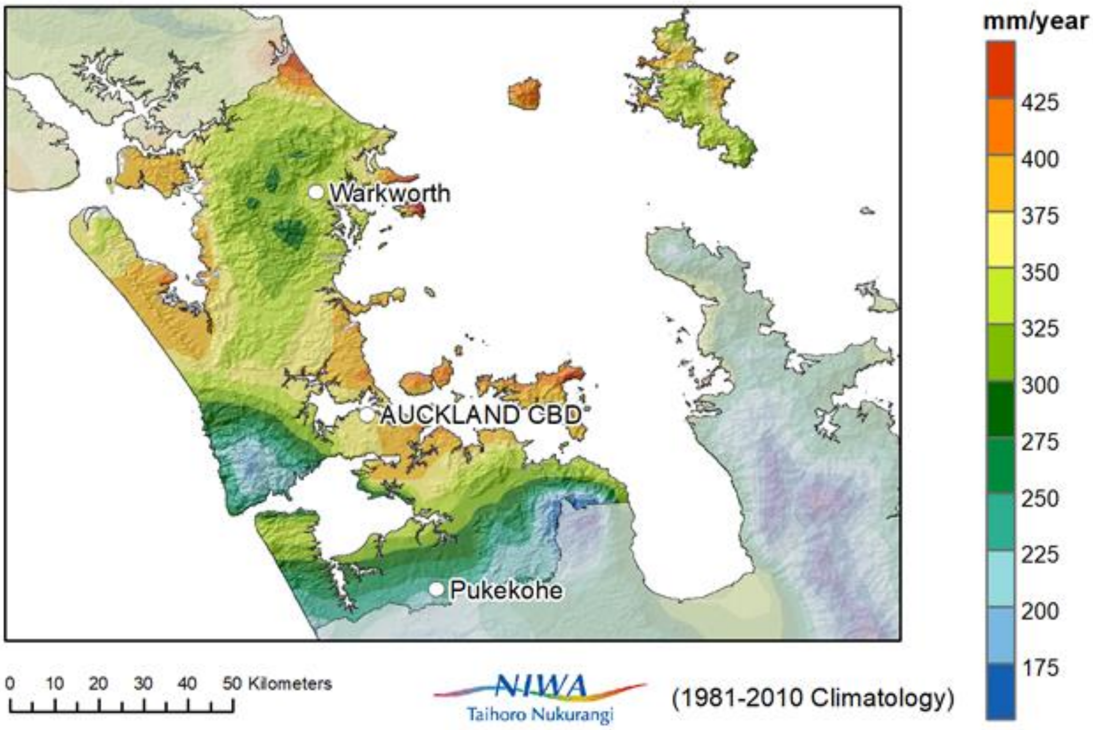

Figure 4-44: Annual average Potential Evapotranspiration Deficit (PED) accumulation (mm) in the Auckland Region. Climatology period 1981-2010. This map shows data from NIWA's Virtual Climate Station Network.

Figure 4-45 shows PED accumulations over growing years (July-June) throughout the historical record for Auckland. The higher the PED accumulation, the drier the soils were on average during that year. Auckland Airport has highly variable PED accumulation from year to year. The highest PED accumulations (i.e. driest conditions) occurred in 1973-1974 (449 mm), 2012-2013 (448 mm) and 1972-1973 (429 mm). These three years were significant drought years for the Auckland Region, and local-scale PED accumulations would be higher than the regional average. There is a positive trend in PED in Auckland over the historical period, indicating slight drying conditions over time. This trend is statistically significant above the 95% confidence level.

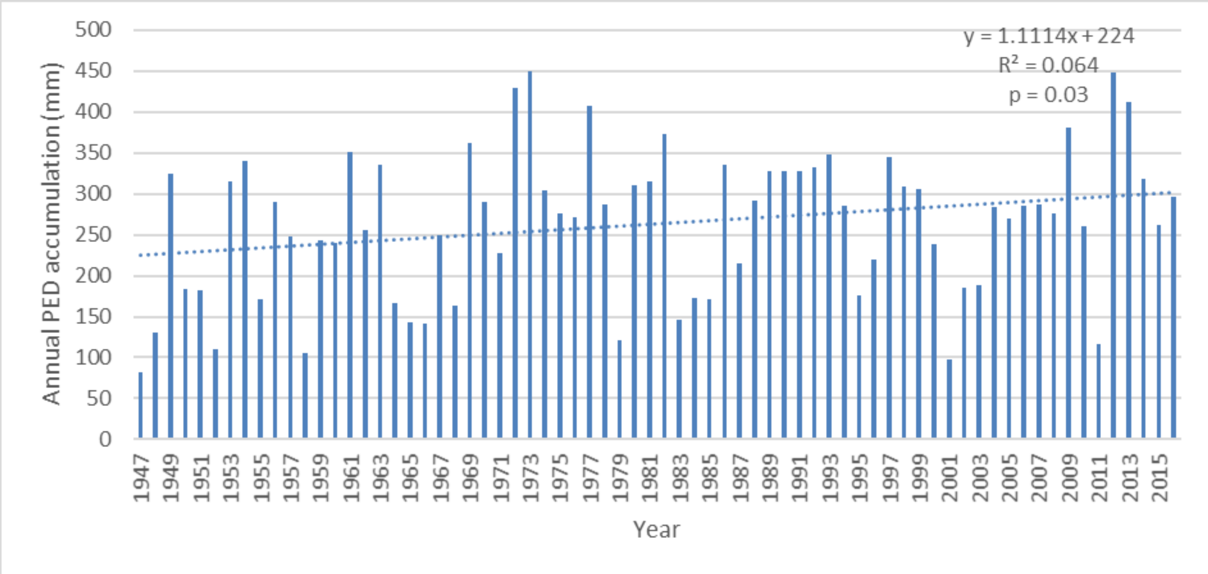

Figure 4-45: Annual PED accumulation from 1947/48-2016/17 (July-June years) for Auckland. Annual accumulated PED is averaged over all available climate stations in the Auckland Region. Trend indicates an increase in PED of approximately 1 mm per year.

4.8.2 Future

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

A regional map for projected changes in PED is presented in Figure 4-46 for RCP4.5 and RCP8.5 at 2040, 2090 and 2110. The maps are plotted with an annual accumulated PED anomaly with respect to the historical annual average (1986-2005 average). The ensemble average of six dynamically downscaled models is presented.

As shown by Figure 4-46, the east coast of the northern Auckland Region, parts of the isthmus, Waiheke Island, and the southeast part of the region are projected to experience the largest increases in PED (i.e. the largest drying trend) in the future across all time slices for both RCPs. Under RCP4.5 at all three time slices, as well as RCP8.5 at 2040, most of the region is projected to experience increases of 60-100 mm of PED and localised areas up to 120 mm. Some areas north of the isthmus project smaller increases in PED of 40-60 mm per year. The projections for 2090 and 2110 under RCP8.5 are quite similar, which show increases of over 140 mm per year for coastal areas in the northeast of the region, as well as Waiheke Island and the southeast coast, and over 100 mm increase in PED per year for most of the remainder of the region.

These projections indicate that the entire Auckland Region is projected to experience > 300 mm of PED per year (total; historic average + projected change) under both scenarios at all time slices. 300 mm is the current PED threshold for very dry conditions, so this indicates the entire Auckland Region is likely to become more drought prone in the future. Waiheke Island and the southeast coast of the region are projected to experience the largest increases in PED.

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

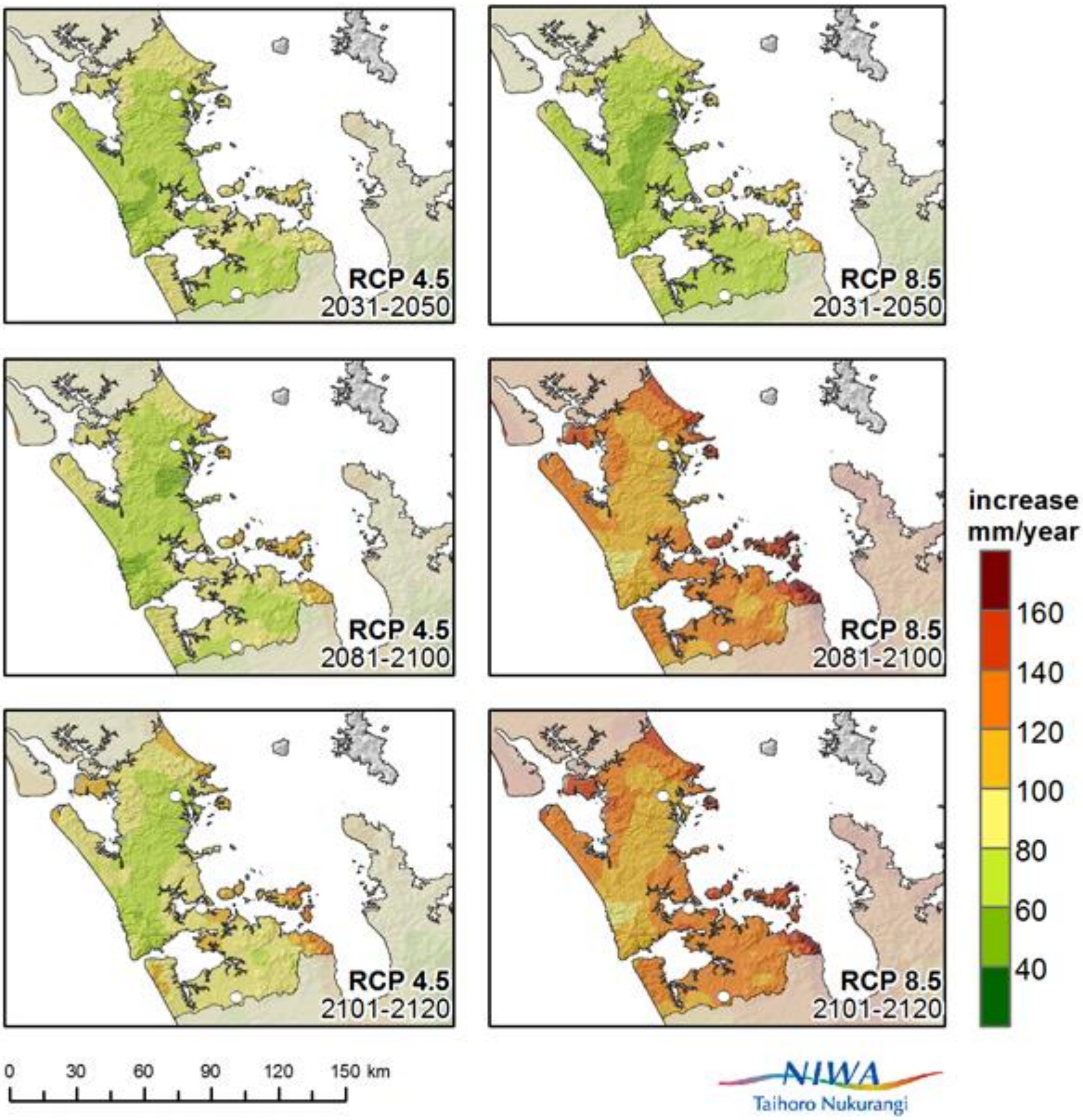

Figure 4-46: Projected changes in Potential Evapotranspiration Deficit (PED, in mm accumulation over the July-June 'hydrologic year') for the Auckland Region, for RCP4.5 (left panels) and RCP8.5 (right panels), at 2040 (2031-2050), 2090 (2081-2100) and 2110 (2101-2120). Projected change in PED is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km. The white dots correspond to (north-south) Warkworth, Auckland CBD, Pukekohe.

Calculating the change in the number of days per year with accumulated PED over 300 mm shows areas which are projected to experience more severe and long-lived droughts in the future. The projections for the number of days where PED is greater than 300 mm (Figure 4-47) show that under RCP4.5 at 2040 and 2090 there is no change from present (grey shades) and by 2110 under RCP4.5 there is a small part of eastern Waiheke Island and the southeast coast of the region that is projected to experience an increase of between three and nine days with PED > 300 mm per year. For RCP8.5 at 2040, an increase of between three and six days per year is projected for eastern Waiheke Island and the southeast coast. Projections for RCP8.5 at 2090 show increases of three to six days per year of PED > 300 mm on the northeast coast of the Auckland Region and more than 15 additional days of PED > 300 mm per year for eastern Waiheke Island and the southeast coast of the region. The change in the number of days with PED > 300 mm for 2110 under RCP8.5 is slightly lower than at 2090 under RCP8.5, but the pattern is the same – the largest increases are for Waiheke Island and the southeast coast of the region, which projects increases of 9-15 days per year. The lower projections for 2110 compared with 2090 under RCP8.5 is possibly due to the smaller ensemble of models used for projections at 2110 (i.e. the more extreme model from 2090 may not be included at 2110).

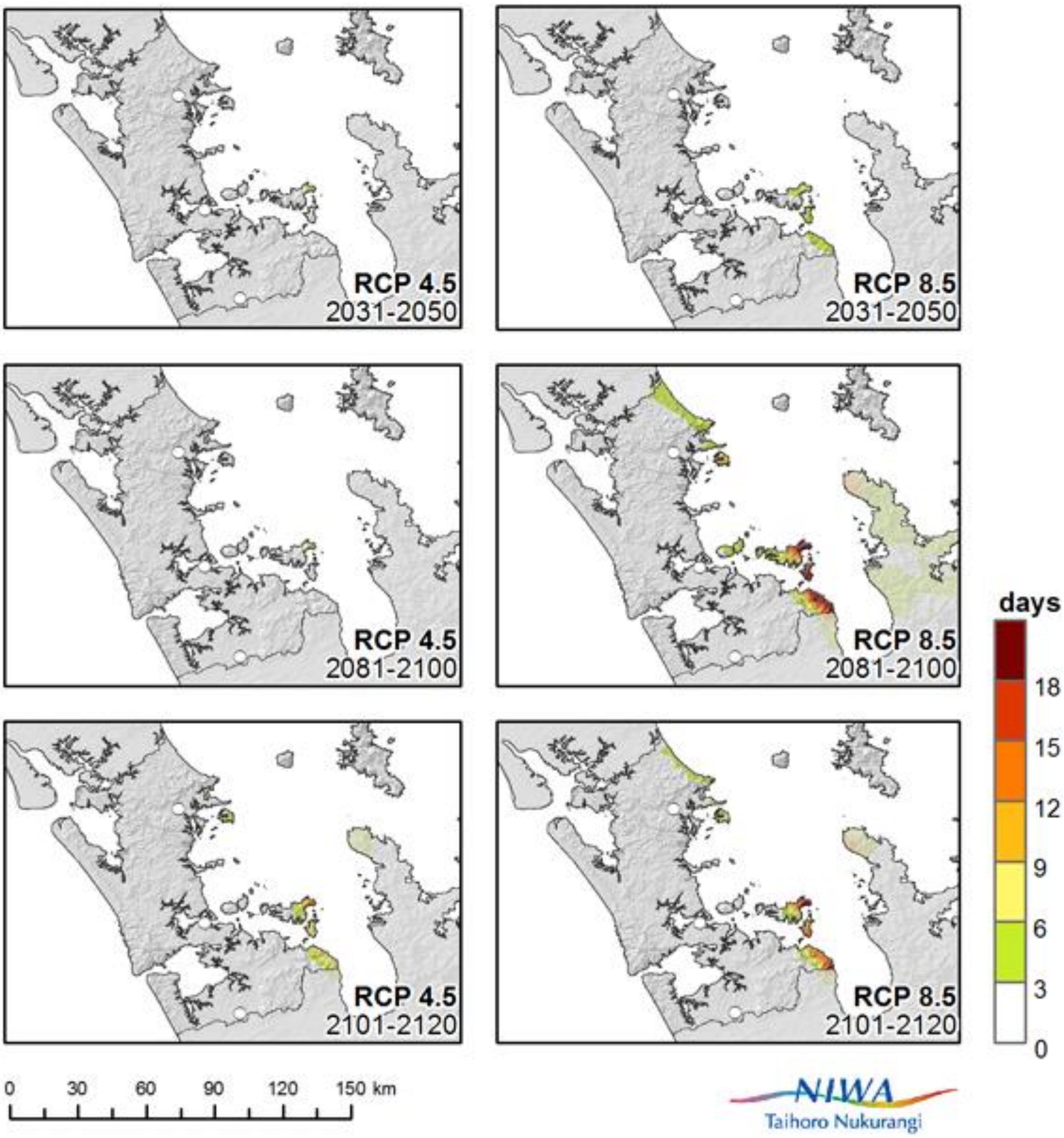

Figure 4-47: Projected changes in the number of days per year of Potential Evapotranspiration Deficit (PED) accumulation over 300 mm (accumulation over the July-June 'hydrologic year') for the Auckland Region, for RCP4.5 (left panels) and RCP8.5 (right panels) at 2040 (2031-2050), 2090 (2081-2100) and 2110 (2101-2120). Projected change in PED is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km. The white dots correspond to (north-south) Warkworth, Auckland CBD, Pukekohe.

4.9 Soil moisture deficit days

Key messages

- Most of the Auckland Region currently experiences 50-70 days of soil moisture deficit per year, with the most SMD days observed in summer and least in winter.
- The amount of days of SMD generally increases with time and RCP forcing.
- By 2110 under RCP4.5, most of the Auckland Region projects an increase of 8-16 days of SMD per year.
- By 2110 under RCP8.5, most of the region projects an increase of 16-24 days of SMD per year, with more than 28 extra SMD days projected for some northern parts of the region.

Soil moisture deficit (SMD) is calculated based on incoming daily rainfall (mm), outgoing daily potential evapotranspiration (PET), and a fixed available water capacity of 150 mm (the amount of water in the soil 'reservoir' that plants can use). In the calculation, evapotranspiration continues at its potential rate until about half of the water available to plants is used up (75 mm out of the total 150 mm available). Subsequently, the rate of evapotranspiration 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 (i.e. all 150 mm). A day of SMD is considered in this report to be when soil moisture is below 75 mm of available soil water capacity. The timing of changes in the days of soil moisture deficit projections indicates how droughts may change in timing throughout the year. Soil moisture deficit and PED are similar measures of dryness, but in this report SMD is measured in days and PED is measured in mm of accumulation, so PED is a more sensitive measure of drought intensity than SMD.

4.9.1 Present

The present number of days of soil moisture deficit (SMD) in the Auckland Region is presented in Figure 4-48. Days of SMD are highest in the northeast of the region and the Auckland Isthmus, with over 70 days of SMD per year on average. The southern part of the region experiences the lowest number of days of SMD, with less than 40 days per year. The largest number of days of SMD occurs in summer, when most of the region experiences 40-50 days of SMD (Figure 4-49). In winter, the whole region experiences no days of SMD, on average.

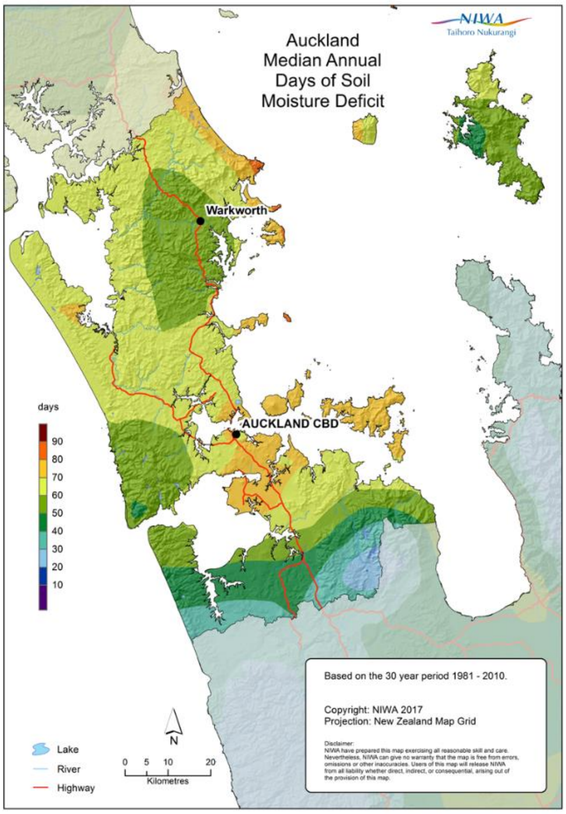

Figure 4-48: Median annual days of soil moisture deficit for Auckland (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

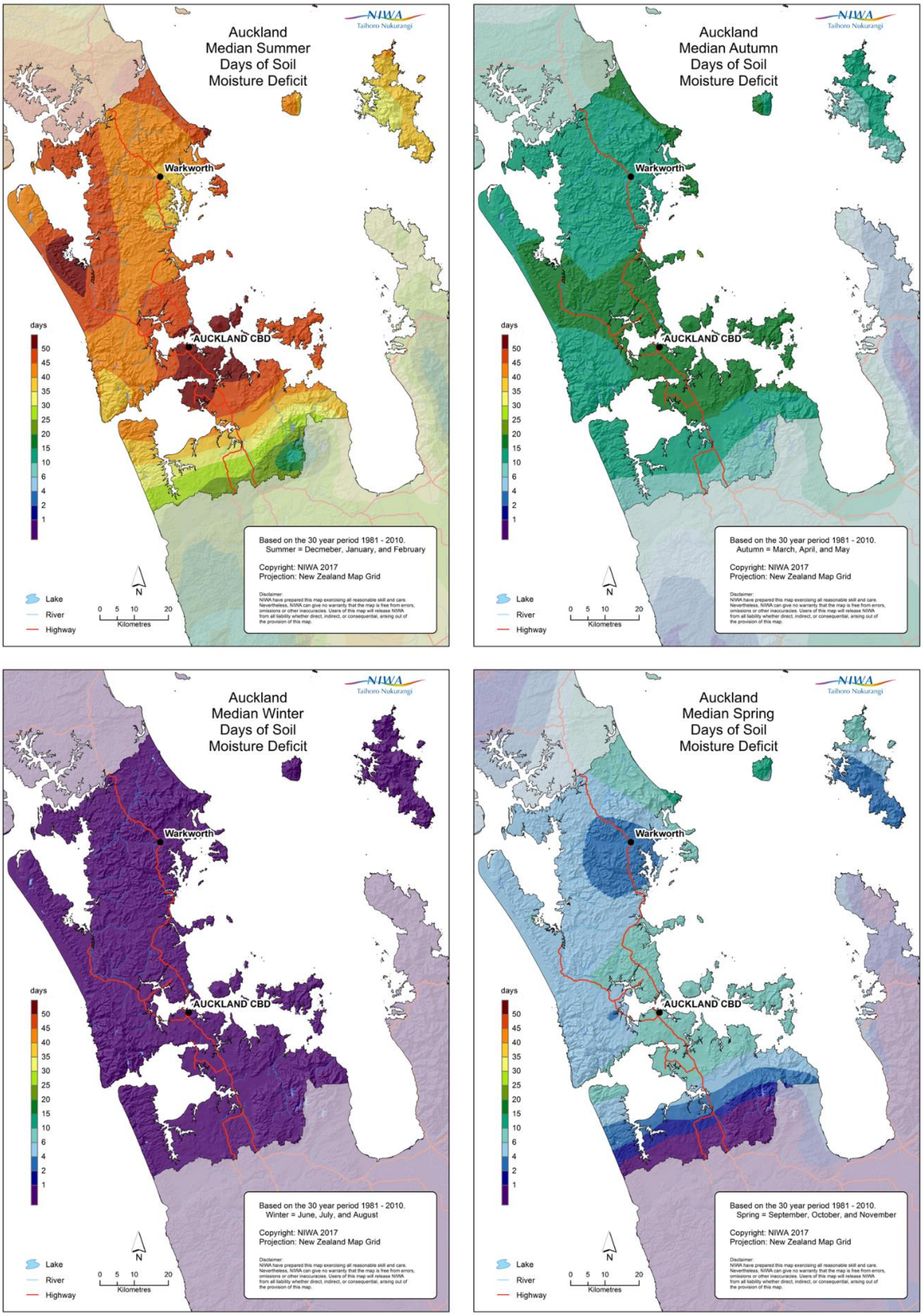

Figure 4-49: Median seasonal days of soil moisture deficit for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

4.9.2 Future

The seasonal and annual change of days of soil moisture deficit (SMD) is presented in Figure 4-50 to Figure 4-55 for RCP4.5 and RCP8.5 at 2040, 2090, and 2110, based on the ensemble average of six dynamically downscaled models. Note that more soil moisture projections are presented in Section 8.1.5 for hydrologic drought, which are consistent with these projections.

The amount of days of SMD generally increases with time slice and RCP forcing, but there are some areas that project a decrease in days of SMD.

Under RCP4.5 at 2040, eight to 12 more days of SMD per year are projected in the northeast of the region, and up to eight more days of SMD are projected for most of the rest of the region. Waiheke Island and the southeast part of the region project decreases of up to eight days of SMD per year. Summer at 2040 under RCP4.5 has the largest increase in days of SMD (four to eight days per summer for the whole region), and small decreases of days of SMD are projected for parts of the region in autumn and winter at 2040 under RCP4.5.

At 2090 under RCP4.5, an increase of 16-20 days of SMD per year is projected for northeast Auckland Region, and most of the region projects an increase of more than eight days of SMD per year. Spring, summer and winter project small increases of days of SMD, but in autumn some of the region projects small decreases in days of SMD (zero to four days per season). The projections for days of SMD under RCP4.5 at 2110 are similar to 2090, but with some larger increases in spring and more widespread small decreases in autumn.

Under RCP8.5 at 2040, an increase of more than eight days per year is projected for most northern and central parts of the region. An increase of >12 days per year is projected for the northeast of the region near Warkworth. Spring is the season with the largest increase in days of SMD (four to eight more days of SMD per spring season).

At 2090 under RCP8.5, considerably more days of SMD are projected at the annual scale. For parts of northeast Auckland, >32 more days of SMD per year are projected, and much of northern Auckland projects an increase of >28 days of SMD per year. Waiheke Island and the southeast part of the region project an increase of eight to 12 more days of SMD per year. The largest seasonal increase is projected for spring (increases of 12-20 days of SMD across most of the region). Some small decreases are projected for autumn in isolated northern areas. At 2110, the increases in days of SMD are not as large as at 2090, possibly due to the smaller ensemble of models used for projections at 2110 (i.e. the more extreme model from 2090 may not be included at 2110).

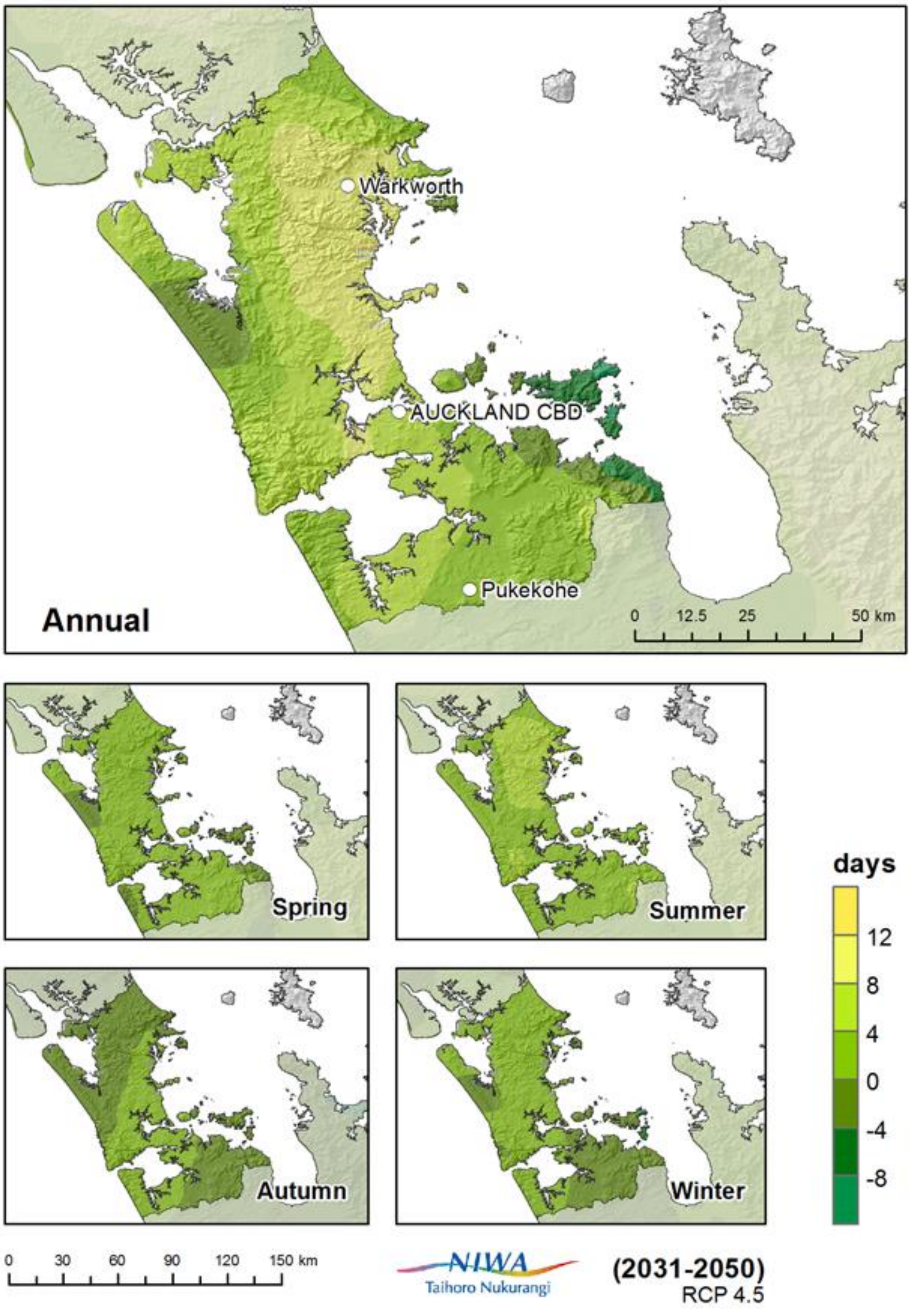

Figure 4-50: Projected annual and seasonal changes in the number of days of soil moisture deficit (accumulation over the July-June 'hydrologic year') for the Auckland Region, for RCP4.5 at 2040 (2031-2050). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

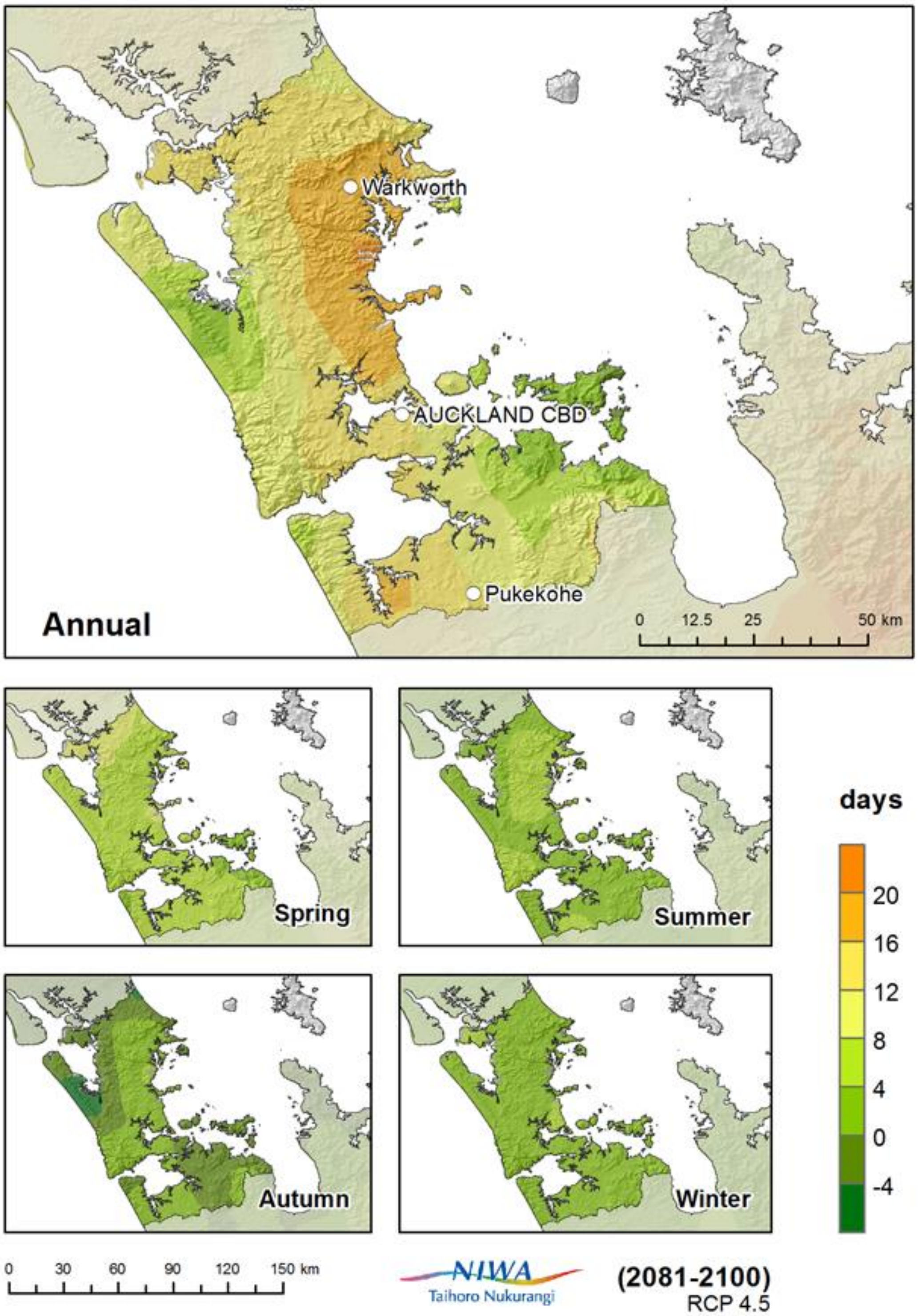

Figure 4-51: Projected annual and seasonal changes in the number of days of soil moisture deficit (accumulation over the July-June 'hydrologic year') for the Auckland Region, for RCP4.5 at 2090 (2081-2100). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

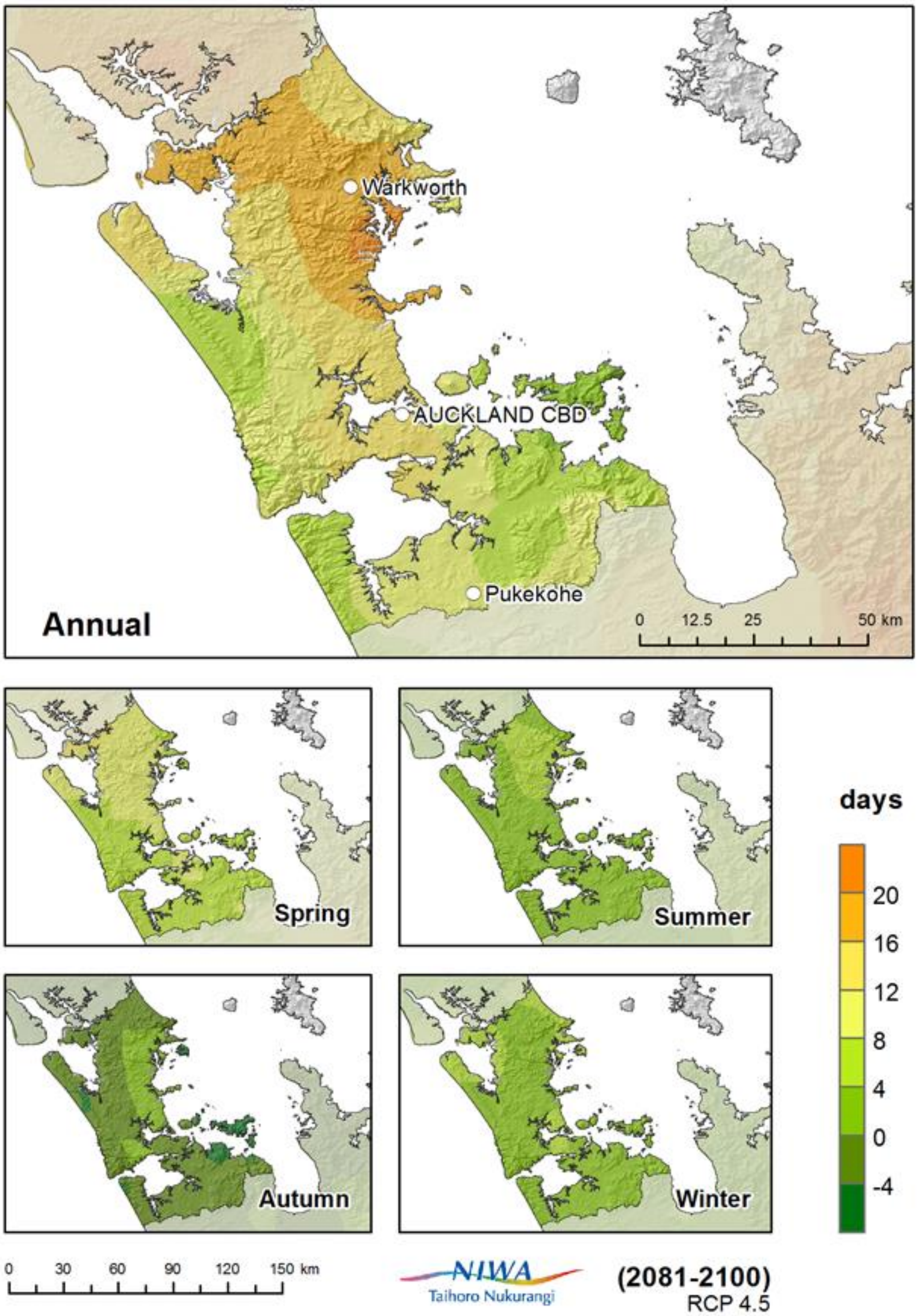

Figure 4-52: Projected annual and seasonal changes in the number of days of soil moisture deficit (accumulation over the July-June 'hydrologic year') for the Auckland Region, for RCP4.5 at 2090 (2101-2120). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

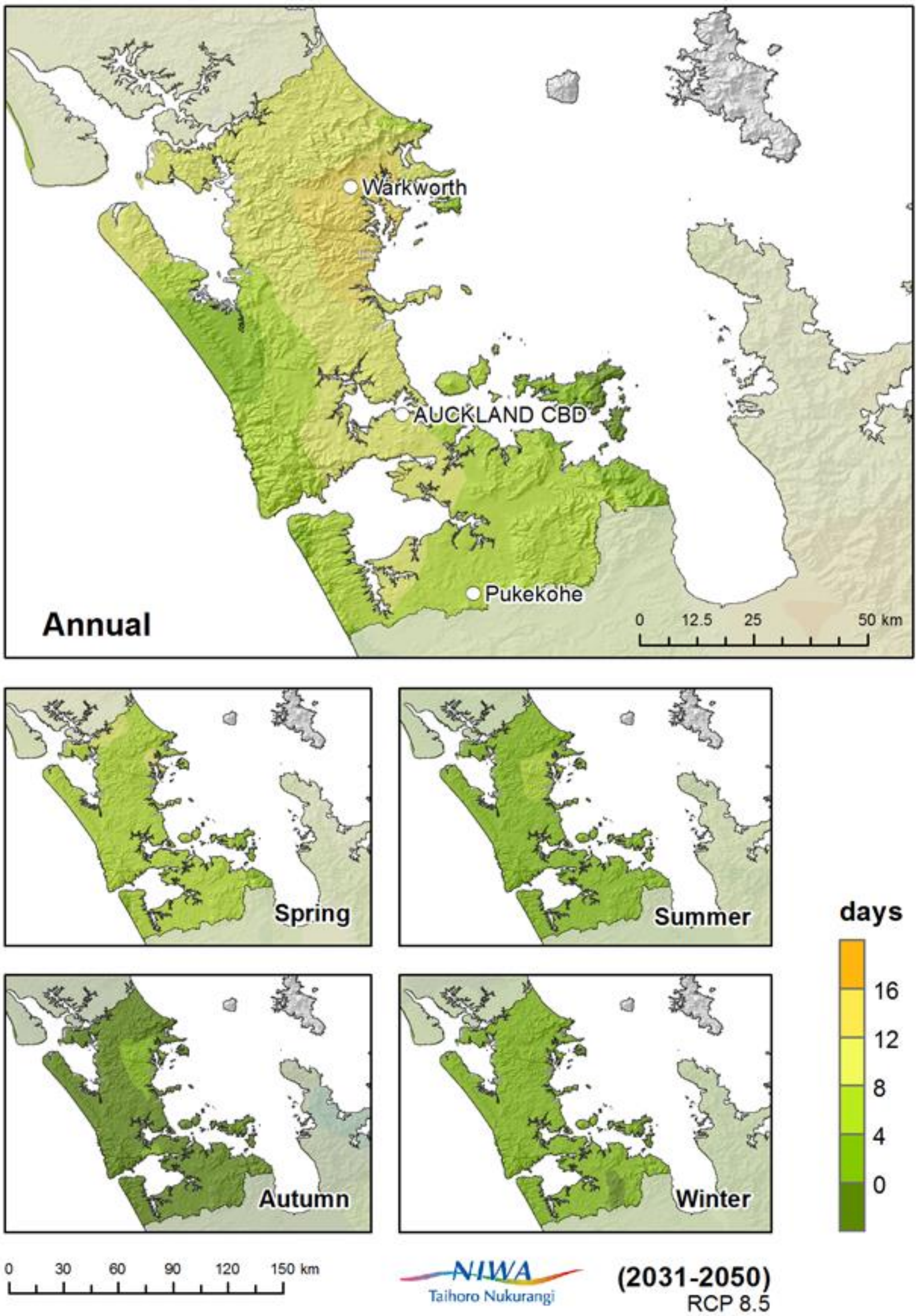

Figure 4-53: Projected annual and seasonal changes in the number of days of soil moisture deficit (accumulation over the July-June 'hydrologic year') for the Auckland Region, for RCP8.5 at 2040 (2031-2050). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

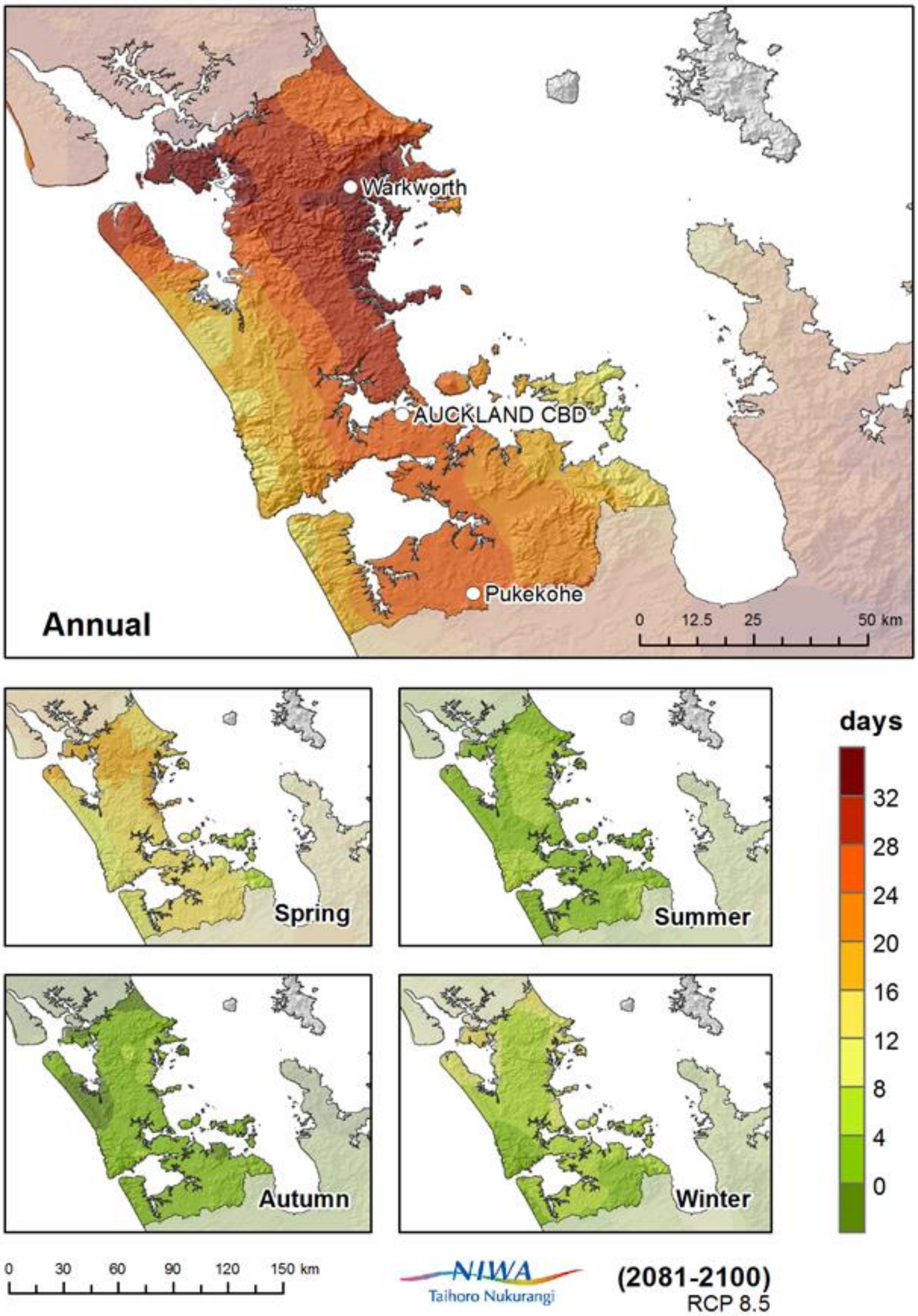

Figure 4-54: Projected annual and seasonal changes in the number of days of soil moisture deficit (accumulation over the July-June 'hydrologic year') for the Auckland Region, for RCP8.5 at 2090 (2081-2100). Projected change in days of SMD is relative to 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model, based on the average of six global climate models. Resolution of projection is 5km x 5km. © NIWA.

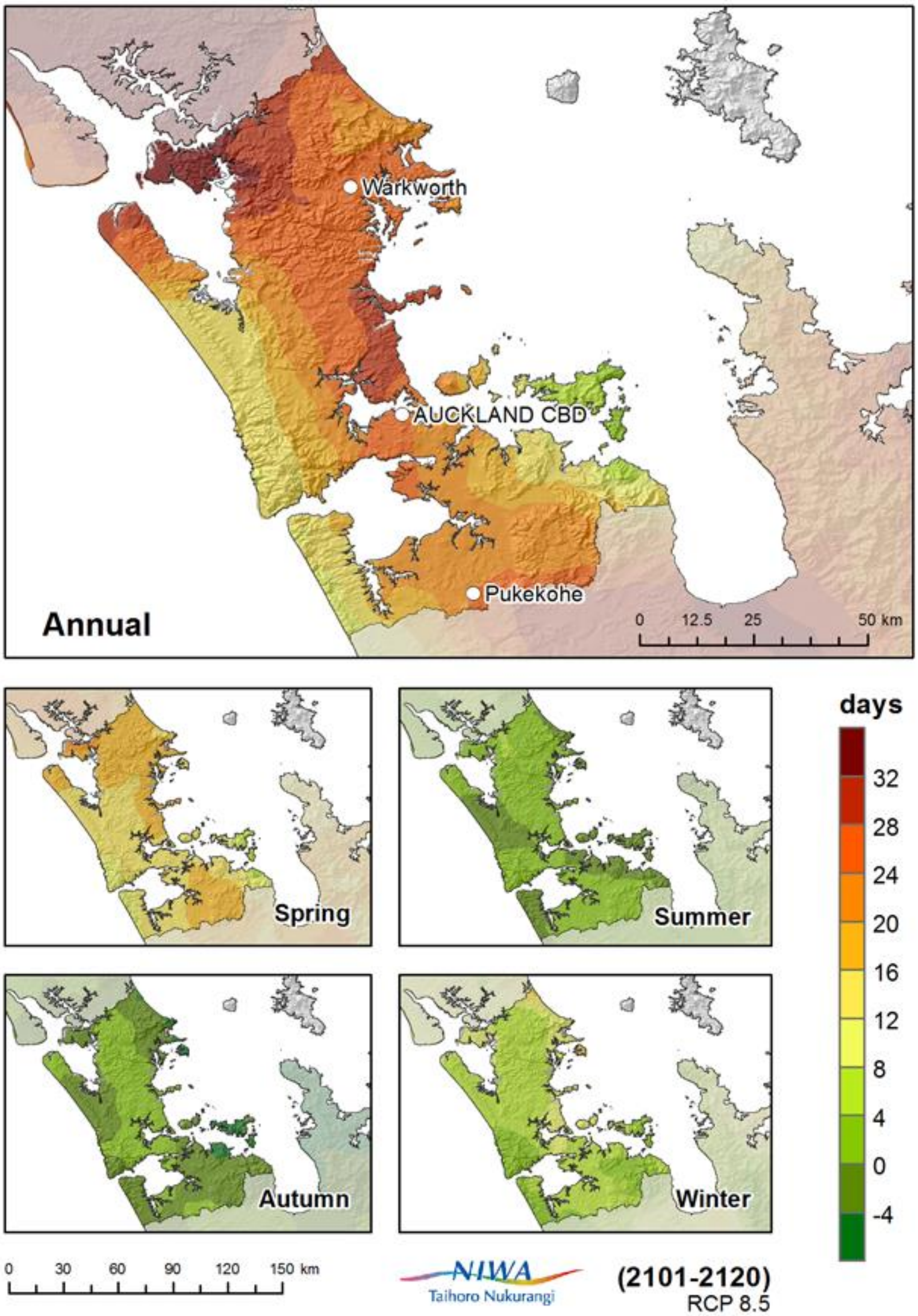

Figure 4-55: Projected annual and seasonal changes in the number of days of soil moisture deficit (accumulation over the July-June 'hydrologic year') for the Auckland Region, for RCP8.5 at 2110 (2101-2120). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

4.10 Rainfall projection comparisons within RCPs

Key messages

- There is no agreement on the direction of rainfall change among all models for all RCPs at 2040, 2090 and 2110, i.e. some models project positive changes and others project negative changes in rainfall.
- The spread of the models is large, from -20% to +30% change in rainfall for some RCPs and seasons.
- Most ensemble averages are near 0% change in rainfall, except for spring at later time slices and higher RCP forcing which projects a decline in ensemble-average rainfall.

The average picture of projected rainfall changes in the tables and maps in this chapter obscures significant variations between the individual models run under each RCP on the projected seasonal changes. Figure 4-56 to Figure 4-58 show seasonal and annual rainfall projections from all the models individually individually for one grid point from the Auckland Region (Mangere) for 2040, 2090, and 2110, respectively. The coloured vertical bars, and inset stars, show the individual models, so the complete range is displayed (unlike Table 4-1 where the 5th to 95th percentile range has been calculated). Figure 4-56 to Figure 4-58 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.

In general, there is no agreement among all the models as to the direction of projected rainfall changes, as identified in Table 4-1 and Table 4-2 for the different RCPs. For all RCPs, the ensemble-average rainfall projections for all seasons and the annual period at 2040 are close to zero (Figure 4-56). The spread of the models under each RCP is quite large; results are spread across approximately -20% to +30% rainfall change for autumn. For 2090 (Figure 4-57), the model spread under each RCP is much larger than at 2040. Summer has the greatest spread in the model results and spring shows the most consistent change in direction, with the ensemble mean showing decreases in rainfall for all RCPs except RCP2.6 (0% change). For 2110 (Figure 4-58), there is again a large spread of model results within the RCPs. Most RCPs and seasons project an ensemble-average of less than 10% change (increase or decrease), except for spring which shows more significant decreases in rainfall (> -10%). As with temperature, caution is advised in comparing projections from 2110 to the other time slices as the number of models are fewer, and therefore the ensemble-average results at 2110 may be skewed (if, for example, the missing model(s) at 2110 were the highest or lowest at 2090).

Note that Figure 4-56 to Figure 4-58 show the model variability at one grid point only (Mangere), rather than a regional average (like what has been shown for temperature in Figure 3-45). This is because rainfall is more spatially variable than temperature.

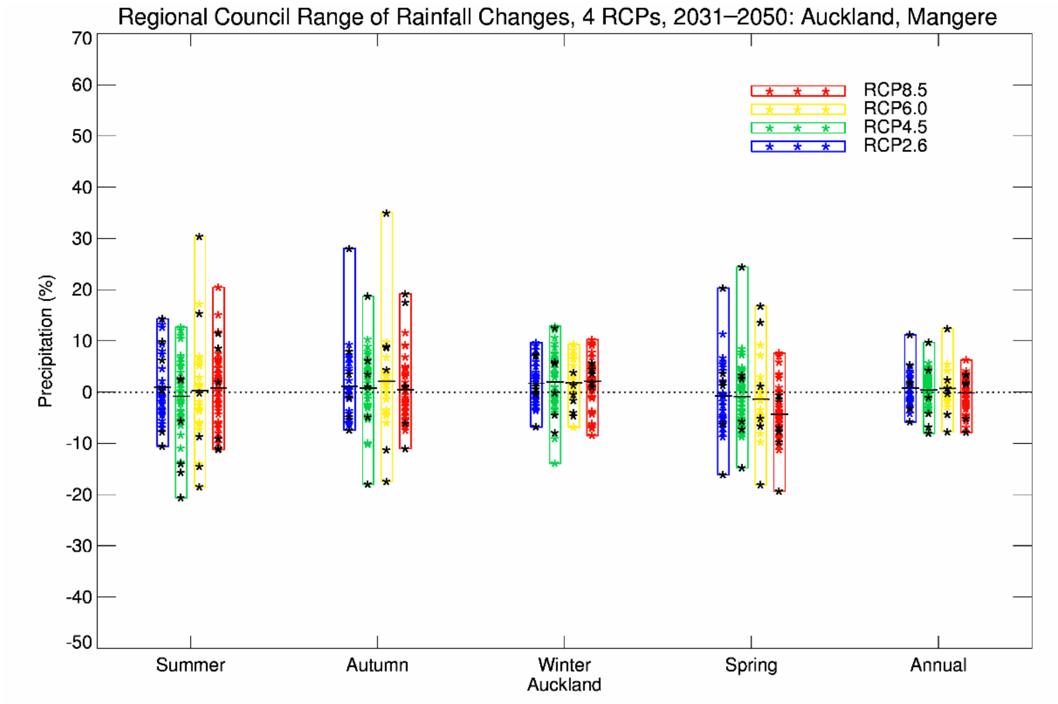

Figure 4-56: Projected seasonal rainfall changes by 2040 (2031-2050) for Auckland (Mangere grid point) for the four RCPs. The vertical coloured bars show the range over all climate models used. The coloured stars show the projected changes for each statistically downscaled model, and the black stars represent the projected changes for each of the six dynamically downscaled models. The short black 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.

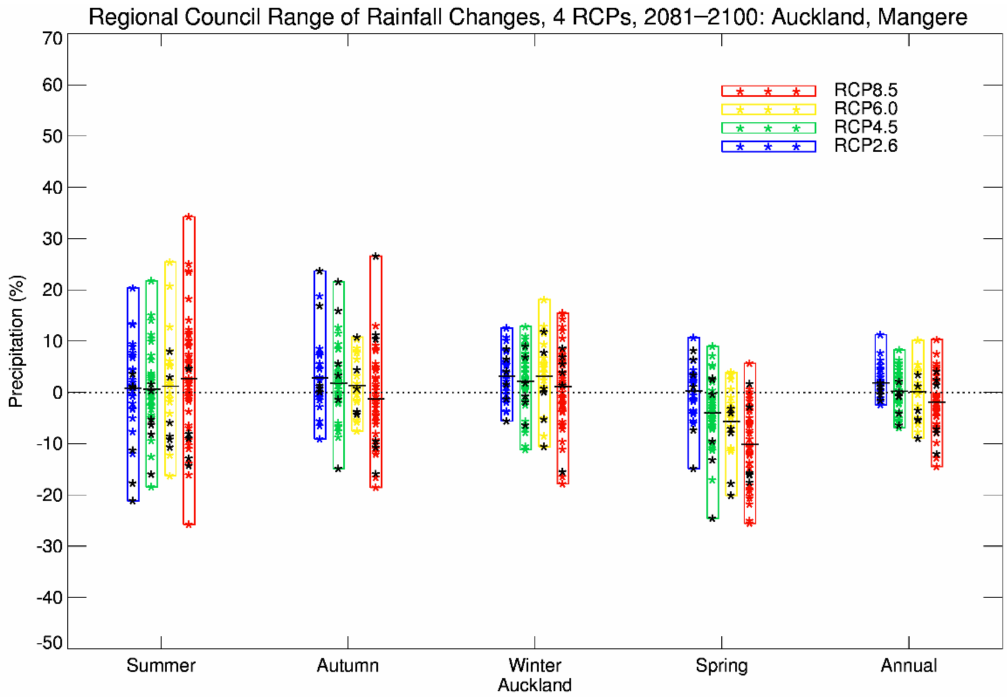

Figure 4-57: Projected seasonal rainfall changes by 2090 (2081-2100) for Auckland (Mangere grid point) for the four RCPs. The vertical coloured bars show the range over all climate models used. The coloured stars show the projected changes for each statistically downscaled model, and the black stars represent the projected changes for each of the six dynamically downscaled models. The short black 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.

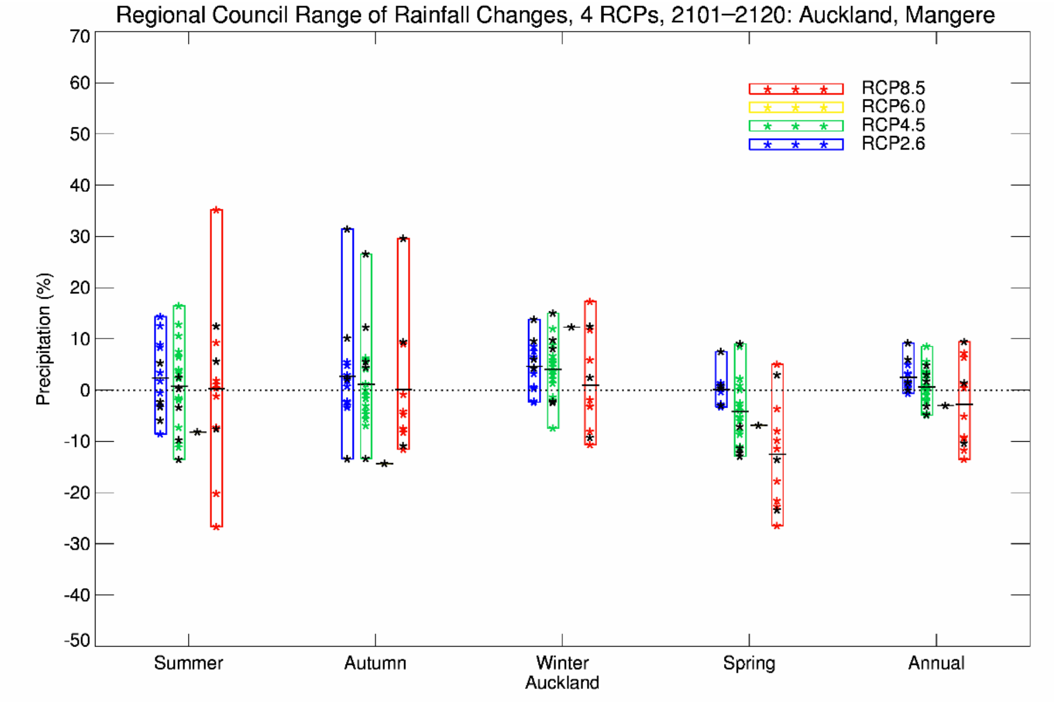

Figure 4-58: Projected seasonal rainfall changes by 2110 (2101-2120) for Auckland (Mangere grid point) for three RCPs. The vertical coloured bars show the range over all climate models used. The coloured stars show the projected changes for each statistically downscaled model, and the black stars represent the projected changes for each of the six dynamically downscaled models. The short black horizontal line is the model-average rainfall over all statistical and dynamical models. Note that there are limited models available for RCP6.0 hence no bar is displayed here. Blue = RCP2.6, 9 models; green = RCP4.5, 16 models; red = RCP8.5, 9 models. © NIWA.

5 Air pressure, wind and storms

Key messages

- Mean sea level pressure is projected to increase in summer, associated with more anticyclonic patterns over northern New Zealand.
- Annual mean wind speed has been decreasing over time in Auckland by ~20% if the historic trend was extrapolated to 100 years. Mean annual wind speeds are projected to decrease by a few percent into the future, which is a much slower rate than observed changes.
- The striking contrast between past wind speed trends and future trends in Auckland could be due to a slowing in the positive trend of the Southern Annular Mode in the future compared to over the last few decades, due to recovery of the ozone hole and the influence of anthropogenic greenhouse gas emissions.
- A projected reduction in mean sea level pressure in winter is likely to result in increased westerly winds over central and southern New Zealand, which is reflected with projections of small increases in Auckland's winter mean wind speed by 2090 and 2110 under RCP8.5.
- The number of windy days (> 10 m/s) have been declining over time in Auckland, and this is projected to continue.
- The magnitude of the 99th percentile of daily mean wind speed is projected to decline in the Auckland Region.
- Ex-tropical cyclones that approach Auckland in the future may be stronger due to retaining tropical cyclone characteristics further south than at present.

Variables presented here include air pressure, mean wind speed, windy days (days with mean wind speed > 10 m/s), extreme wind (99th percentile of daily mean wind speed) and commentary on storms. Present-day conditions are summarised for all variables, and for mean wind speed, windy days and extreme wind, future projections are presented for RCP4.5 and RCP8.5 at 2040, 2090 and 2110.

5.1 Air pressure

Key messages

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

5.1.1 Present

Mean sea level pressure (MSLP) varies over New Zealand from day to day as different weather systems pass over the country. Figure 5-1 shows average seasonal MSLP over the Southwest Pacific, including New Zealand. During summer months over the northern North Island, north easterly wind flows are dominant. In all other seasons, westerly or south westerly wind flows dominate over the northern North Island.

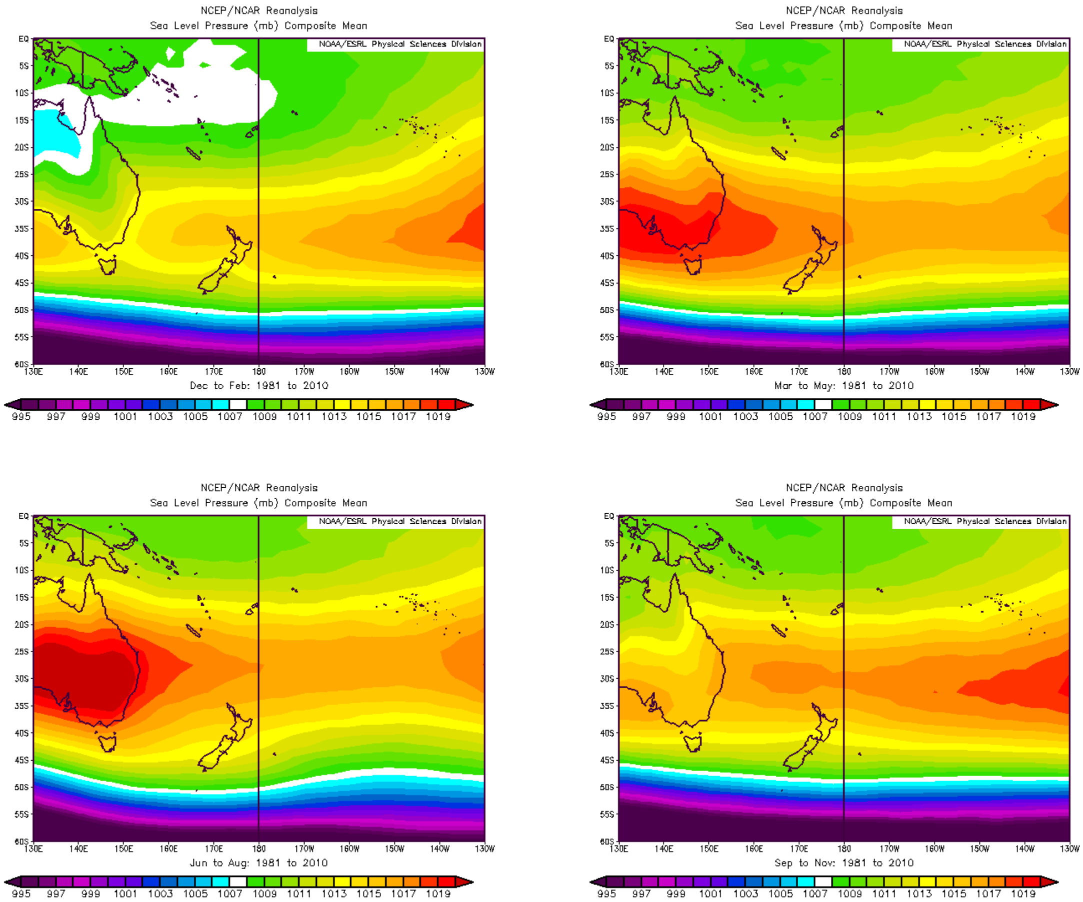

Figure 5-1: Average seasonal mean sea level pressure over the Southwest Pacific, 1981-2010. Top left: summer, top right: autumn, bottom left: winter, bottom right: spring. From https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl

5.1.2 Future

Mean sea-level pressure projections have been derived from the Regional Climate Model (RCM) simulations. The key projected changes in mean sea-level pressure (MSLP) and mean winds are as follows (more detail can be found in Mullan et al. (2016)):

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

5.2 Mean wind speed

Key messages

- Annual mean wind speed has been decreasing over time at Auckland Airport, by about 20% if the trend was extrapolated to 100 years. Present-day annual mean wind speed is 4.9 m/s at Auckland Airport.
- Decreases in mean annual wind speeds are projected for all of the Auckland Region under RCP4.5 and RCP8.5 at 2040, 2090 and 2110.
- By 2110 under RCP4.5, mean annual wind speed is projected to decrease by up to 2% across most of the region.
- By 2110 under RCP8.5, mean annual wind speed is projected to decrease by 4% across most of the region.
- Winter mean wind speeds are projected to slightly increase under RCP8.5 at 2090 and 2110.
- The striking contrast between past wind speed trends (~20% decline per century) and future trends (up to 4% decline per century) may occur with a slowing of the positive trend of the Southern Annular Mode.

5.2.1 Present

Average wind speed varies throughout the year, with the highest median average annual wind speeds generally recorded in the northeast and west of the region, as well as the Hauraki Gulf Islands (> 4 m/s). The lowest median annual average wind speeds are recorded in the south of the region (1-2 m/s) (Figure 5-2). Average wind speed is relatively constant throughout the year, with slightly lighter winds in general in autumn and slightly higher winds in spring (Figure 5-3). The long-term average annual wind speed is 4.9 m/s at Auckland Airport. Annual mean wind speed has exhibited a statistically significant decreasing trend above the 95% confidence level since the 1960s when measurements began at Auckland Airport as seen in Figure 5-4. If the observed trend was extrapolated to 100 years, the decrease in average annual wind speed from a century ago to present would be about 20%.

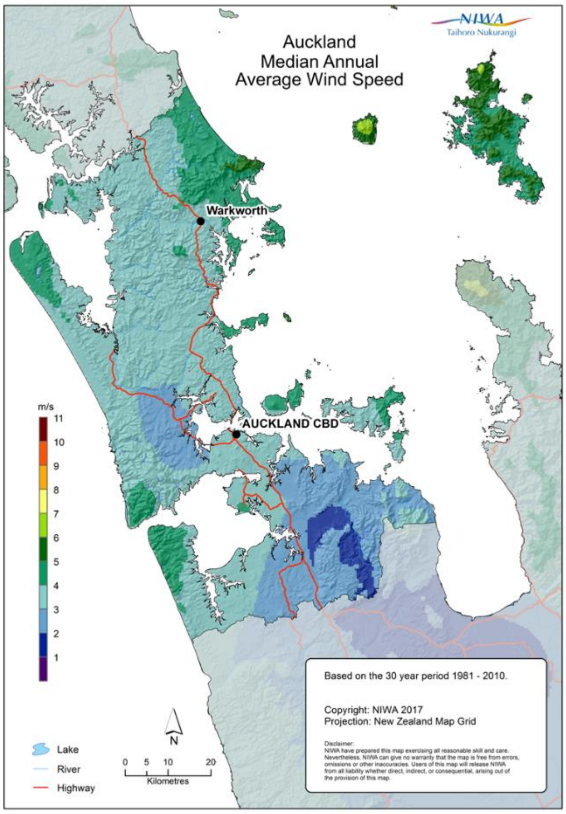

Figure 5-2: Median annual average wind speed for the Auckland Region, 1981-2010 (m/s). Based on data from NIWA's Virtual Climate Station Network.

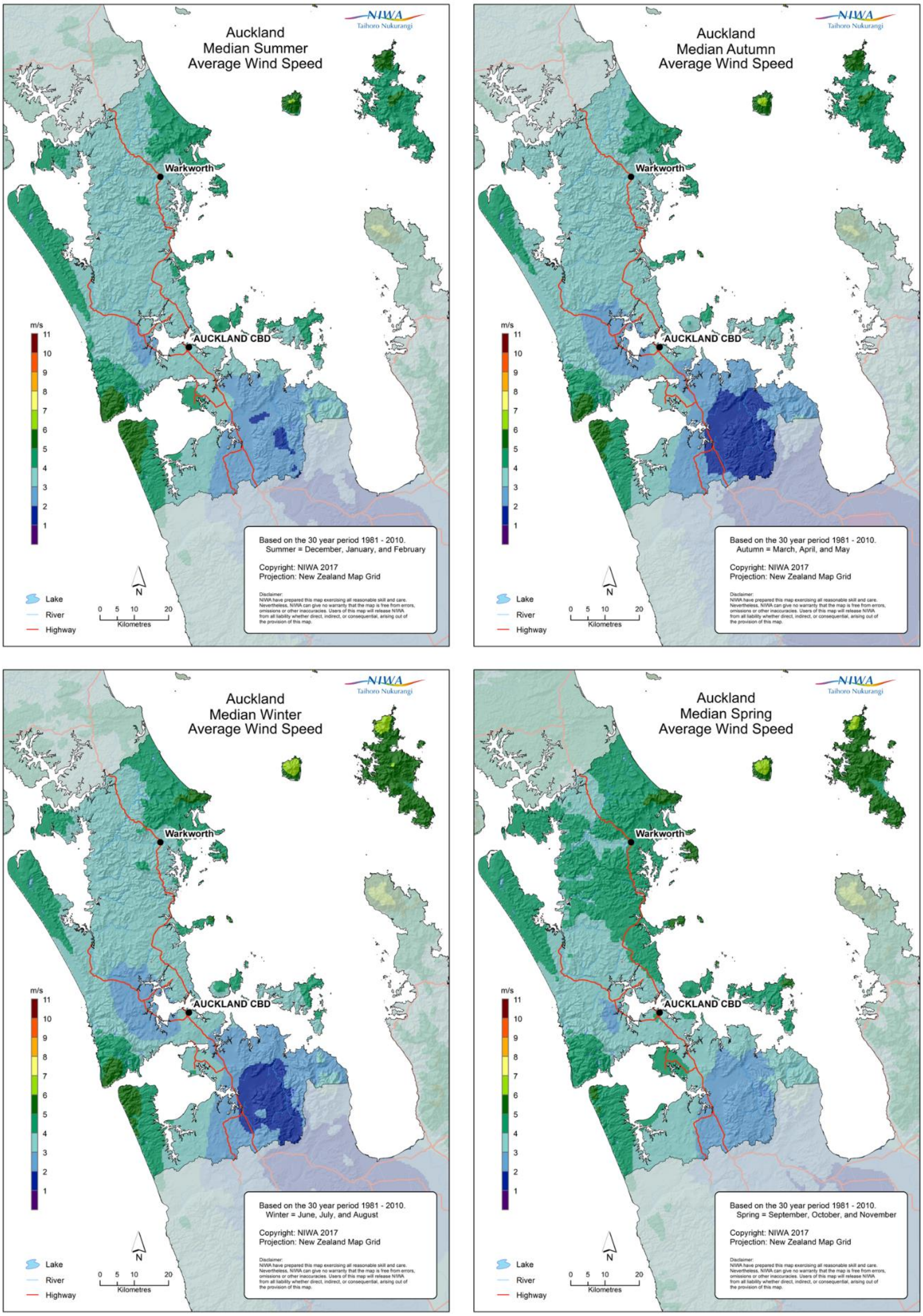

Figure 5-3: Median seasonal average wind speed for the Auckland Region, 1981-2010 (m/s). Based on data from NIWA's Virtual Climate Station Network.

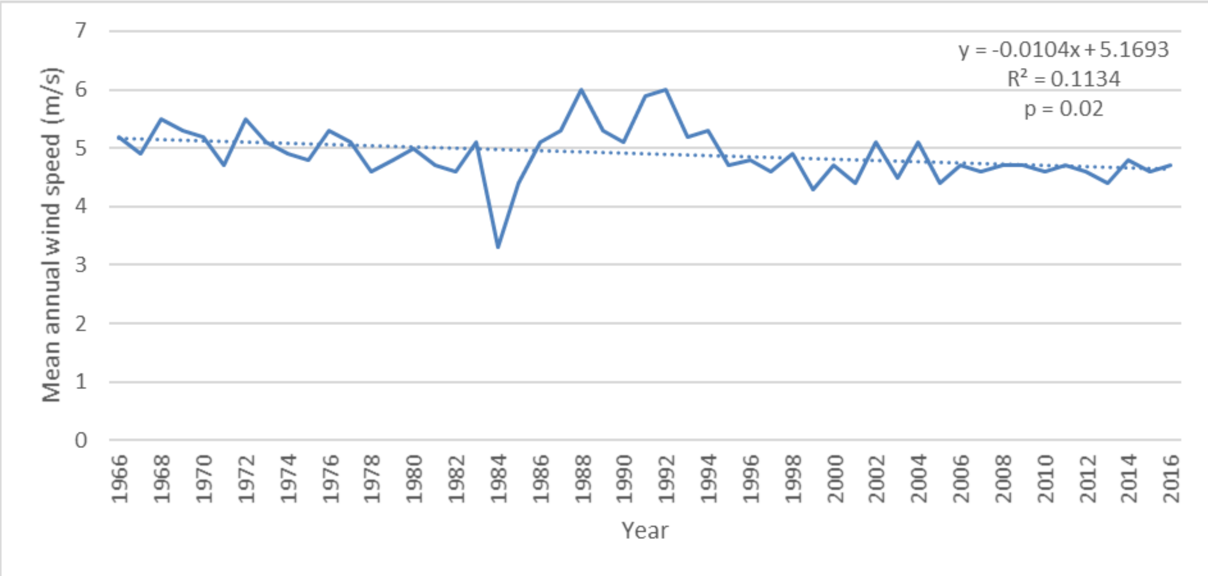

Figure 5-4: Annual mean wind speed (m/s) for Auckland Airport, 1966-2016. Trend indicates a decrease in annual mean wind speed of approximately 0.1 m/s per decade.

5.2.2 Future

Projections of changes to annual and seasonal mean wind speed are presented for 2040, 2090 and 2110, compared to 1995 under RCP4.5 and RCP8.5 in Figure 5-5 to Figure 5-10, based on based on the ensemble average of six dynamically downscaled models.

Under RCP4.5, annual mean wind speed decreases by 1% at 2040 (Figure 5-5) and by up to 2% at both 2090 (Figure 5-6) and 2110 (Figure 5-7). At the seasonal timescale, projections for 2040 show a small increase (up to 1%) for spring and decreases of up to 4% for summer. For 2090, small decreases are projected for all seasons. For 2110, small increases of up to 1% are projected for the southern half of the region in winter, but decreases of up to 2% are projected for all other seasons.

Under RCP8.5, decreases in mean wind speed are more pronounced. At 2040, decreases of 1-2% are projected at the annual scale, with decreases of up to 3% projected for summer and autumn (Figure 5-8). At 2090, annual mean wind speed is projected to decrease by 3% across the whole region (Figure 5-9). Summer at 2090 is projected to experience up to 7% lower mean wind speeds in the south of the region, and autumn projects 5% lower mean wind speeds throughout the region. Increases up to 2% are projected for the southwest part of the region in winter at 2090. By 2110, annual mean wind speed is projected to decrease by 4% across most of the region (Figure 5-10). Autumn mean wind speeds are projected to decrease by 6-7% across most of the region and spring mean wind speeds are projected to decrease by 3-5% across the region. In contrast, winter mean wind speeds are projected to increase by up to 2% across the southern half of the region.

These projected decreases in mean wind speed, particularly in summer, are consistent with projections of mean sea level pressure becoming more anticyclonic over the northern part of New Zealand in the summer (Section 5.1.2). Anticyclonic conditions (or high pressure systems) are generally associated with lower mean wind speeds than cyclonic conditions (or low pressure systems).

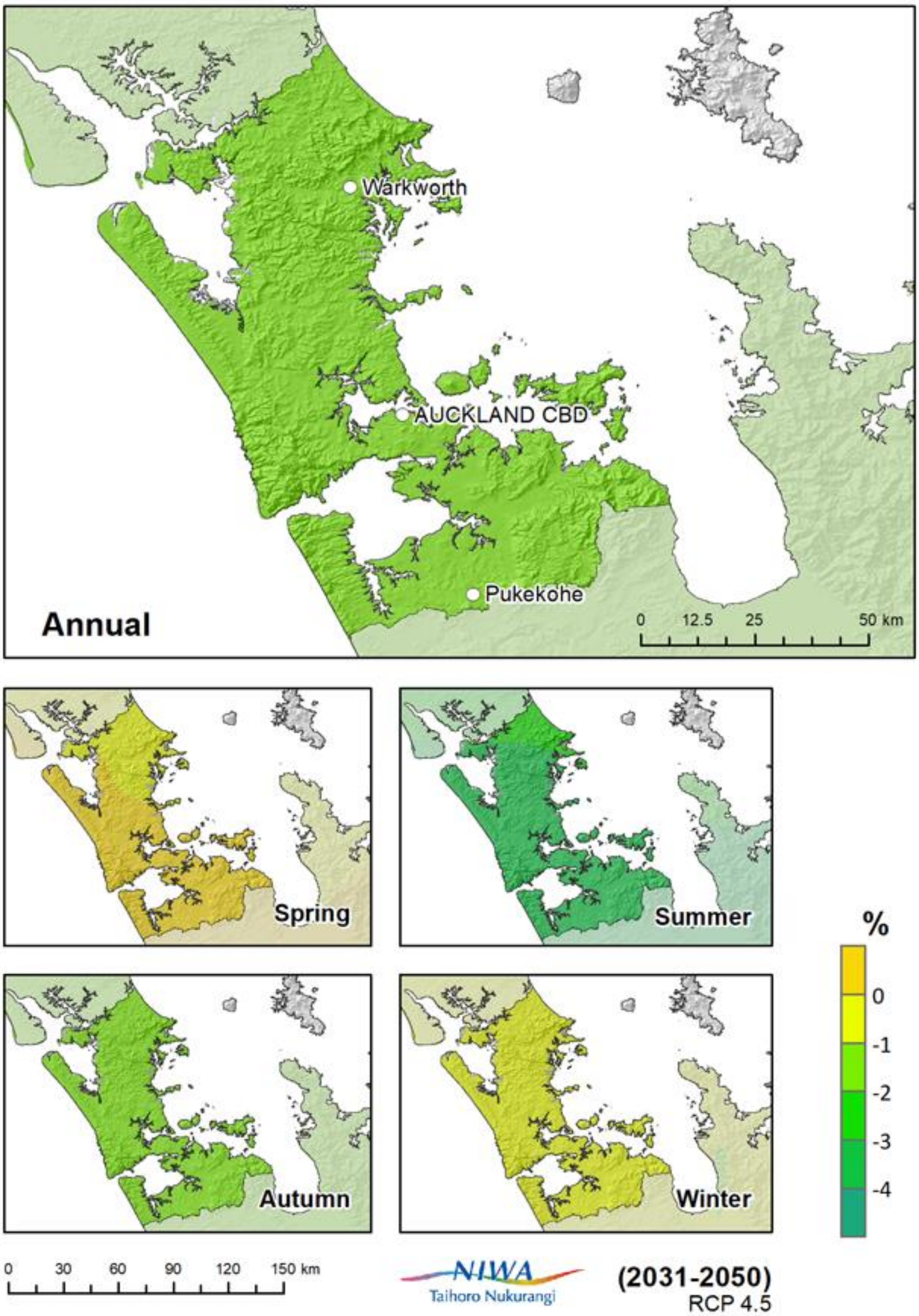

Figure 5-5: Change in annual and seasonal mean wind speed (%) for Auckland for RCP4.5 at 2040 (2031-2050). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

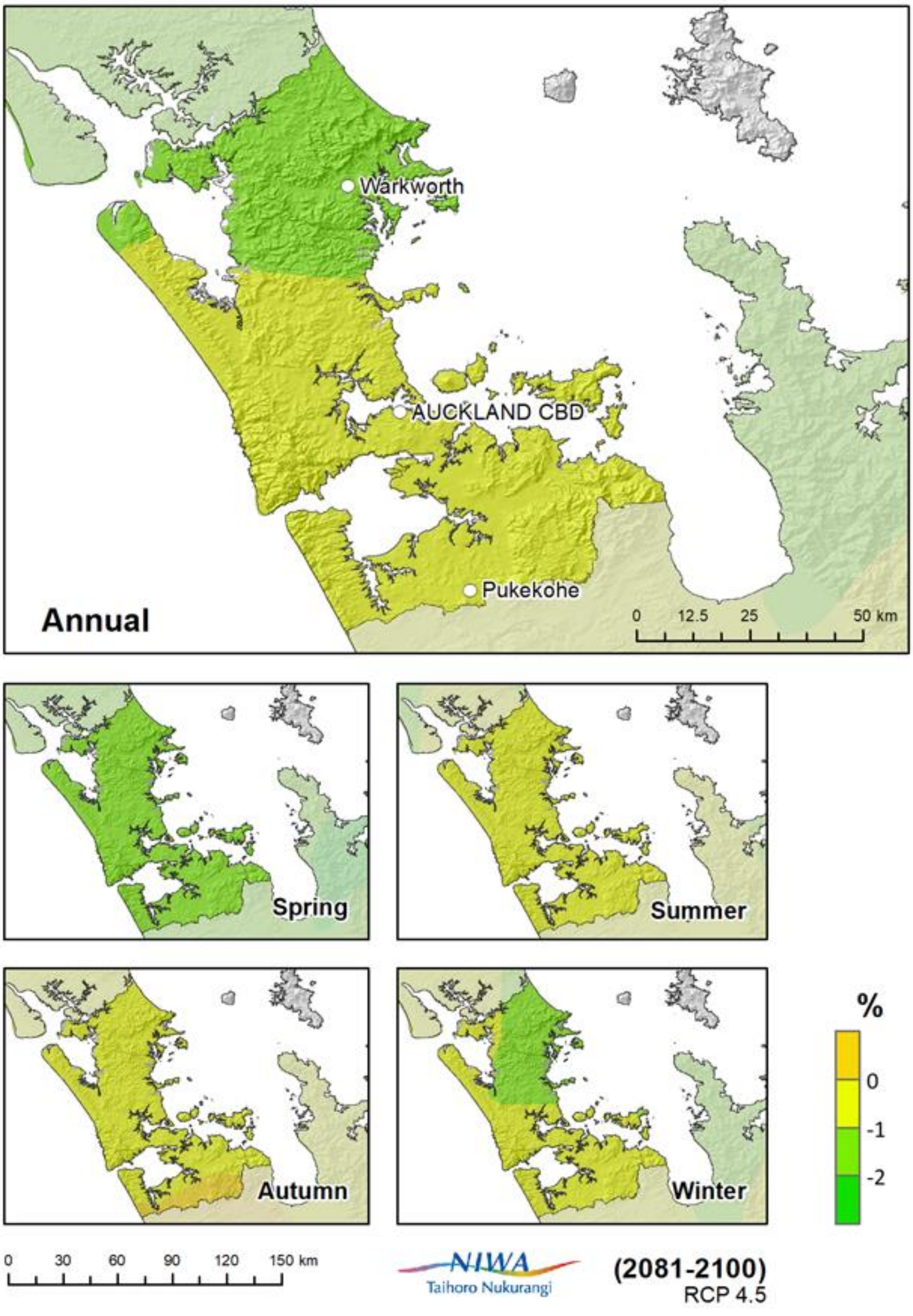

Figure 5-6: Change in annual and seasonal mean wind speed (%) for Auckland for RCP4.5 at 2090 (2081-2100). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

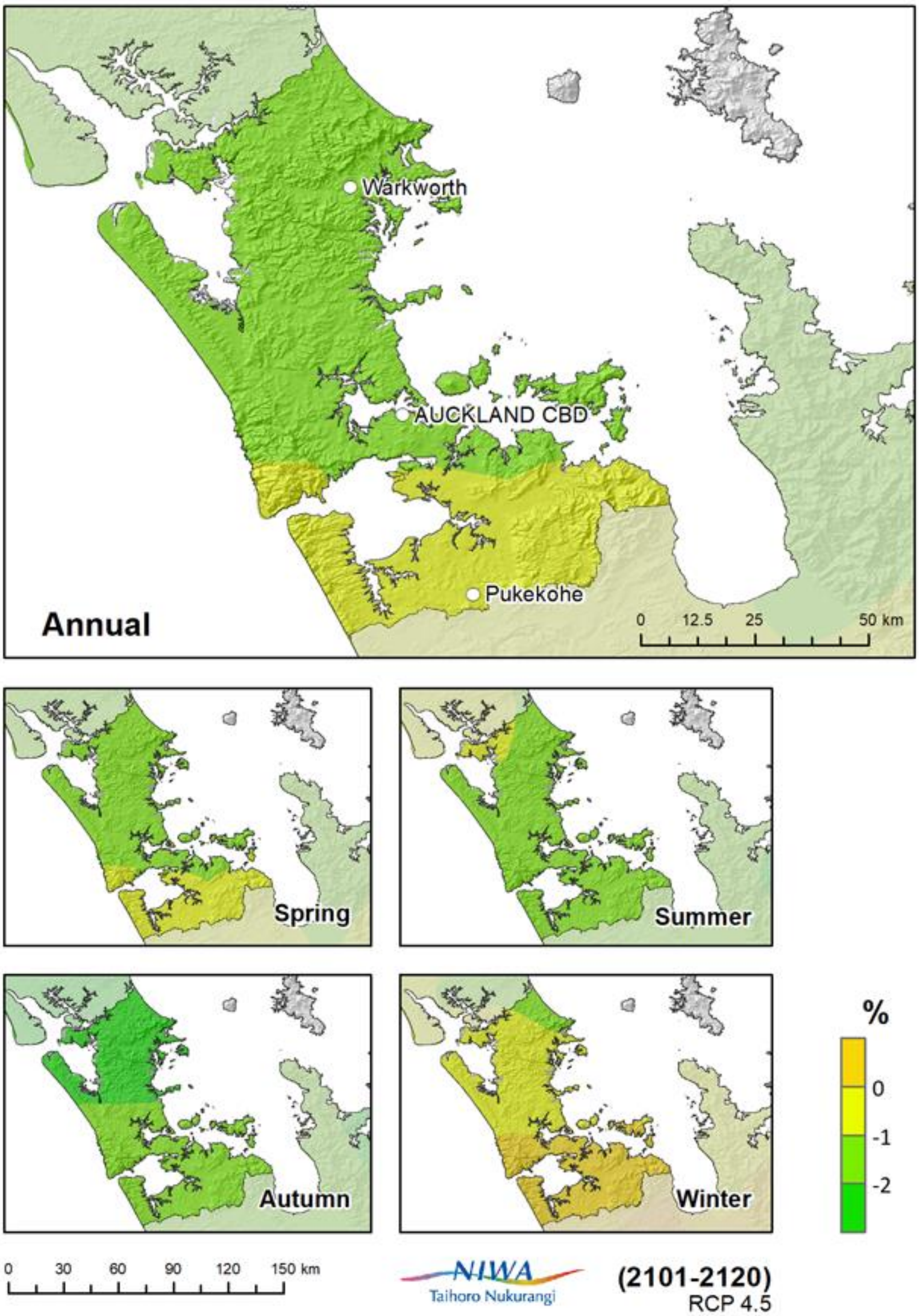

Figure 5-7: Change in annual and seasonal mean wind speed (%) for Auckland for RCP4.5 at 2110 (2101-2120). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

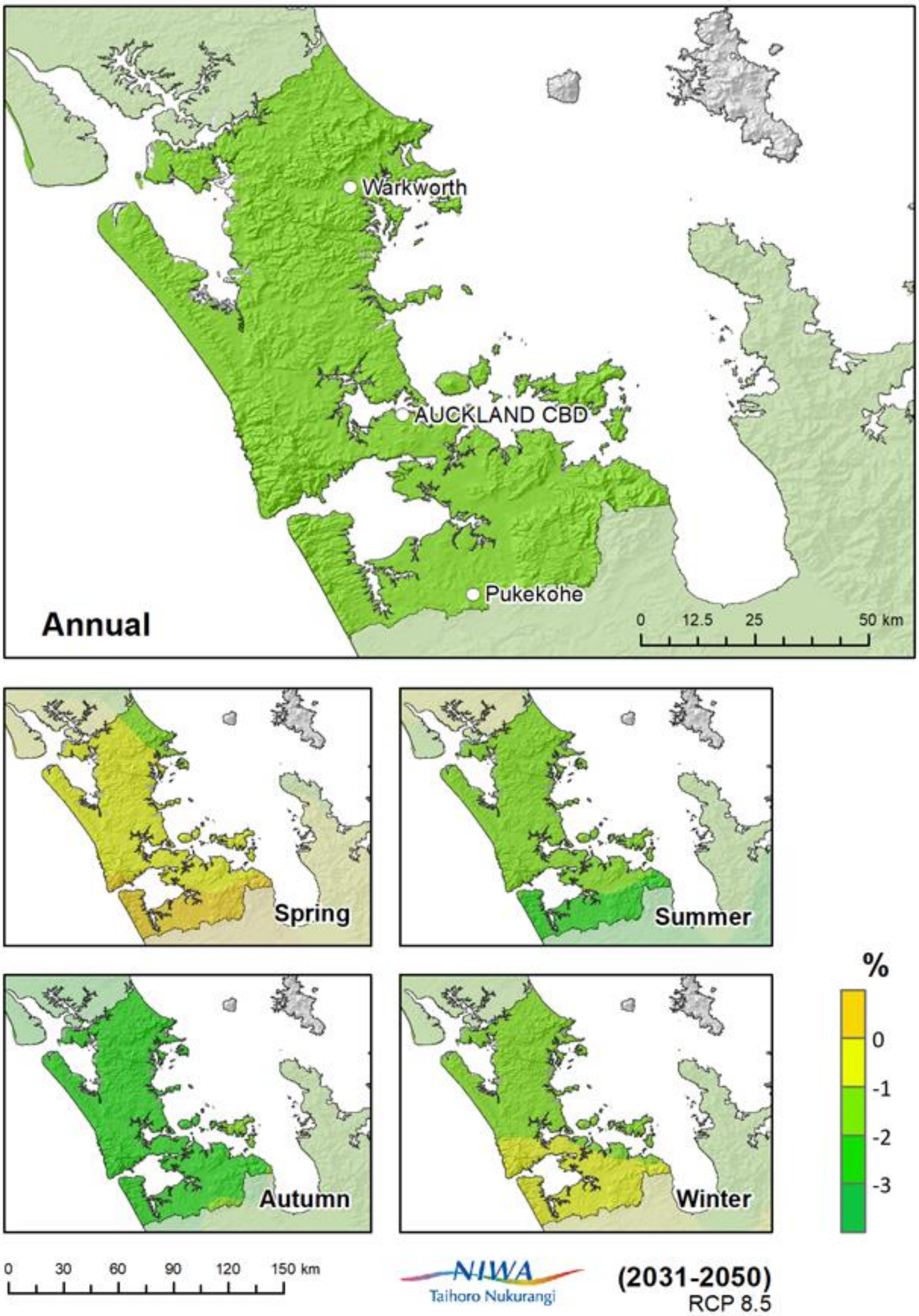

Figure 5-8: Change in annual and seasonal mean wind speed (%) for Auckland for RCP8.5 at 2040 (2031-2050). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

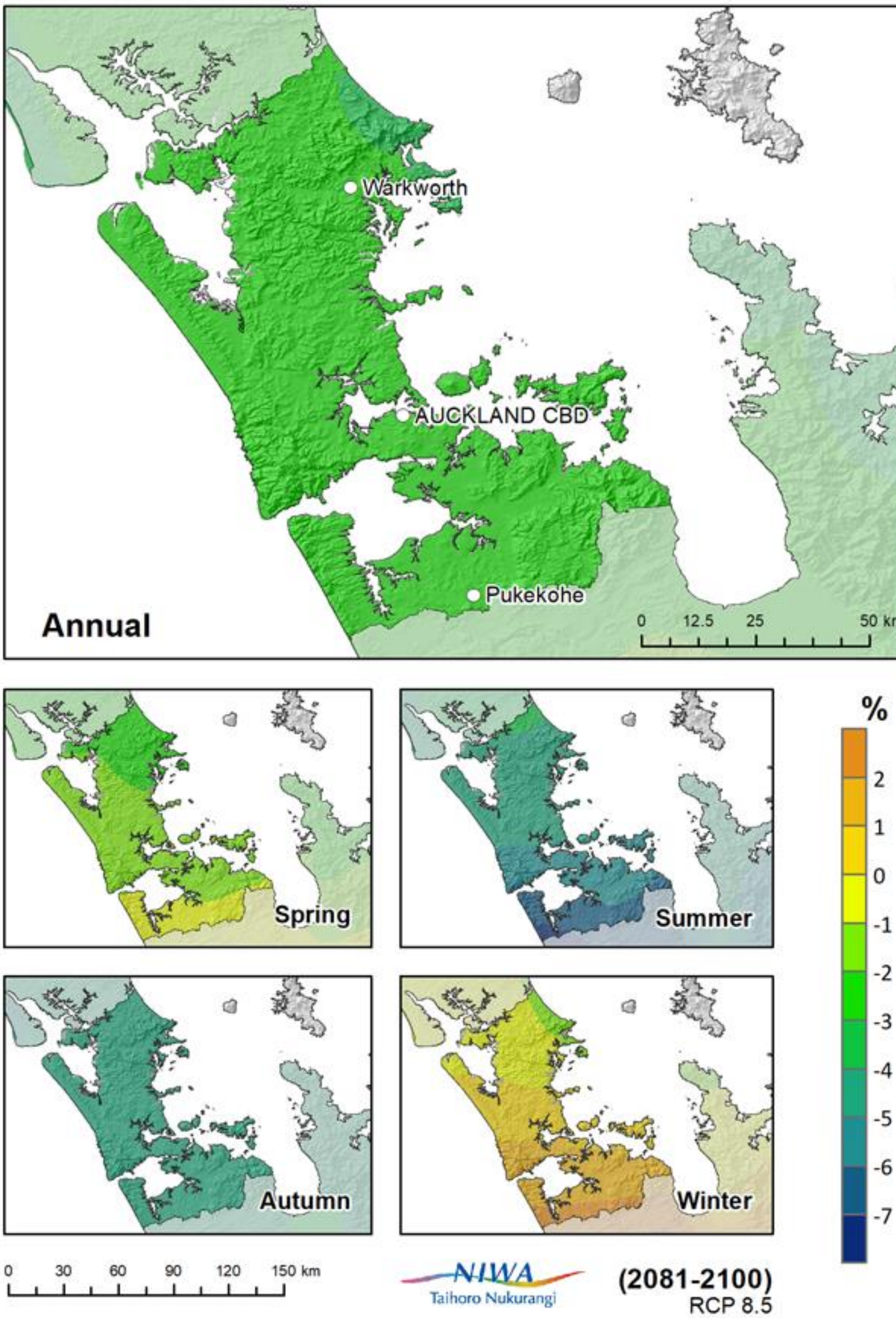

Figure 5-9: Change in annual and seasonal mean wind speed (%) for Auckland for RCP8.5 at 2090 (2081-2100). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

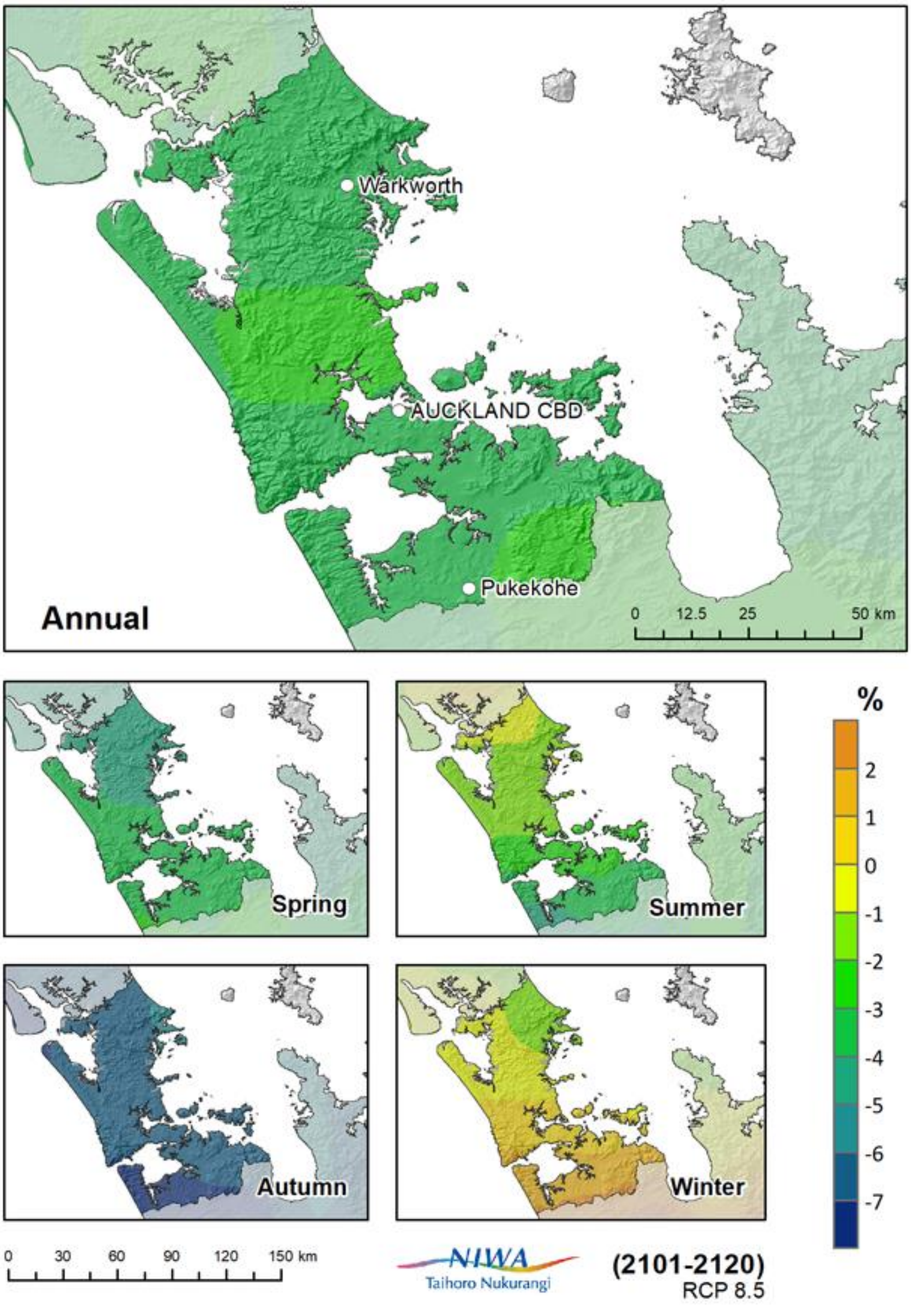

Figure 5-10: Change in annual and seasonal mean wind speed (%) for Auckland for RCP8.5 at 2110 (2101-2120). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

The observed (historic) decrease in mean wind speed at Auckland Airport of about 20% per century (if the trend was extended over 100 years) is possibly due to trends in the Southern Annular Mode (SAM, Section 1.4.3). The SAM is influenced by the size of the ozone hole, with past increases in ozone-depleting substances giving rise to a positive trend in the phase of the SAM (Thompson et al., 2011). This trend produced more settled weather and light winds over New Zealand (hence the statistically significant negative trend in wind speed for Auckland since the 1960s). With the recovery of the ozone hole and reduction of ozone-depleting substances projected into the future, the trend of summertime SAM is expected to decline. Average SAM index values are projected to stabilise slightly above zero (i.e. it is expected that there will be slightly more positive SAM phases than negative phases). However, increasing atmospheric concentration of greenhouse gases will have the opposite effect, by increasing the positive trend in the SAM. The net result for SAM behaviour, because of both ozone recovery and greenhouse gas increases, is therefore likely to be relatively little change from present by 2100. This means that the positive SAM trend seen in the past decades is likely to slow, and therefore the statistically significant rate of decline in Auckland's mean wind speed may also reduce in the future. The projected trends in Auckland's mean annual wind speed are smaller than the observed trends (of about a 20% decrease if extrapolated over a century) by about a factor of 10 for RCP4.5 at 2110 (2% decrease compared with the baseline) and about a factor of 5 for RCP8.5 at 2110 (4% decrease compared with the baseline).

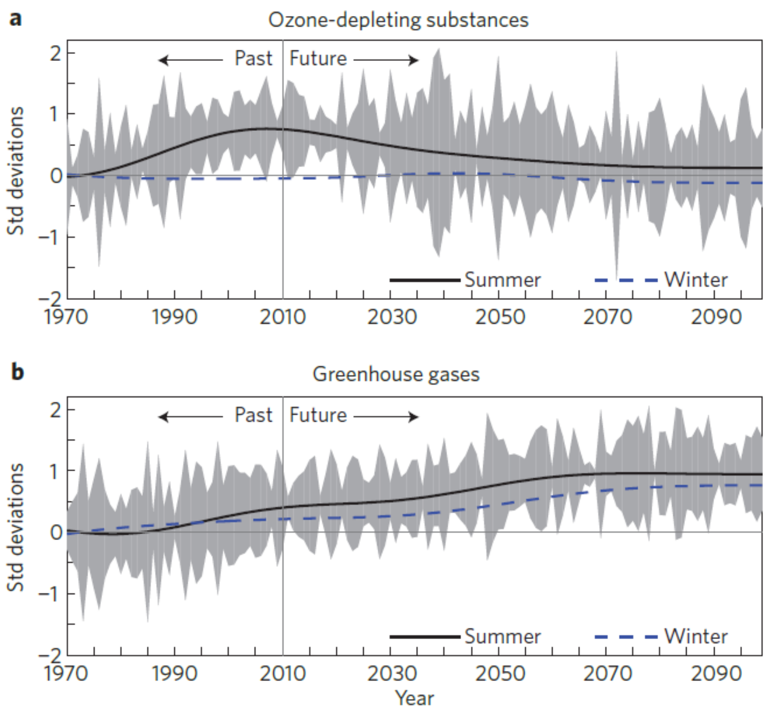

Figure 5-11: Time series of the Southern Annular Mode from transient experiments forced with time-varying ozone-depleting substances and greenhouse gases. a. Forcing with ozone-depleting substances; b. forcing with greenhouse gases. The SAM index is defined as the leading principal component time series 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. From Thompson et al. (2011).

5.3 Windy days

Key messages

- The annual number of windy days (> 10 m/s) has been decreasing over time at Auckland Airport. The present-day average annual number of windy days at Auckland Airport is 18.6 days.
- The number of windy days per year is expected to slightly decrease across the Auckland Region at all three time slices for both scenarios.
- By 2110 under RCP4.5, up to three fewer windy days per year are projected in the north and east of the region.
- By 2110 under RCP8.5, up to four fewer windy days per year are projected for most of the region.

5.3.1 Present

A 'windy day' is considered to have a daily mean wind speed of 10 m/s or more. Auckland Airport has observed a long-term decline in the number of windy days since 1966 (Figure 5-12). This trend is statistically significant above the 95% confidence level. The long-term average (1981-2010) is 18.6 windy days per year but this ranges from five to 45 windy days per year in the historical record. If the observed trend of a decrease of around four days per decade continues, it would lead to a complete absence of windy days (with a daily mean wind speed at least 10 m/s on average) by around 2050. The past trend in windy days for Auckland is consistent with the trends in average wind speed and the potential influence of the trend of the Southern Annular Mode, as discussed in Section 5.2.

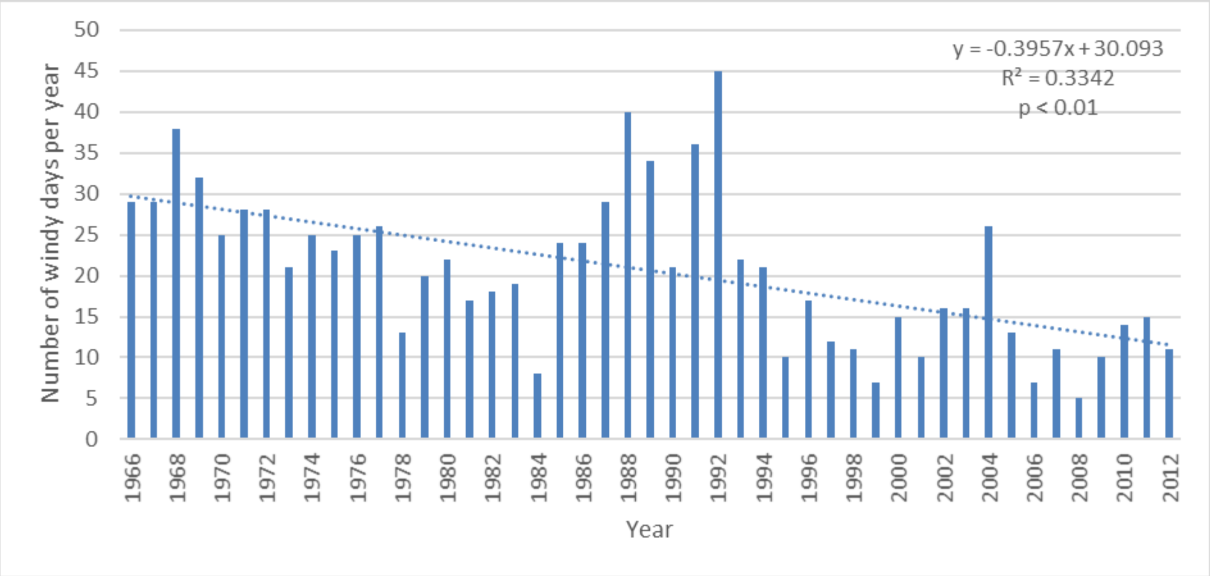

Figure 5-12: Annual number of windy days (mean daily wind speed >10m/s) for Auckland Airport, 1966-2012. Trend indicates a decrease in the annual number of windy days of approximately 4 days per decade.

5.3.2 Future

The annual and seasonal change in the number of windy days for the Auckland Region was calculated from the ensemble average of six dynamically downscaled models, for 2040, 2090 and 2110 under RCP4.5 and RCP8.5 and is presented in Figure 5-13 to Figure 5-18.

The number of windy days per year is expected to slightly decrease across the Auckland Region at all three time slices for both scenarios.

Under RCP4.5 at 2040, zero to two fewer windy days per year are projected across the region (Figure 5-13). A slight increase in windy days is projected for winter (zero to one more windy days per winter). At 2090 and 2110 under RCP4.5 (Figure 5-14 and Figure 5-15), two to three fewer windy days per year are projected for the north and east of the region, and zero to two fewer windy days per year are projected in the south and west.

Under RCP8.5 at 2040, zero to two fewer windy days per year are projected across the region (Figure 5-16). There are small increases in windy days for parts of the region in summer and winter (zero to one windy days per season). At 2090 (Figure 5-17), three to four fewer windy days per year are projected for the east of the region, and 2-3 fewer windy days are projected for the remainder of the region. At 2110 under RCP8.5 (Figure 5-18), three to four fewer windy days per year are projected for most of the Auckland Region. Future changes in windy days are projected to be slower than past observed changes, like for mean wind speed in Section 5.2. This is also possibly because of a slowing in the positive trend of the Southern Annular Mode (see Section 5.3.2 for more details).

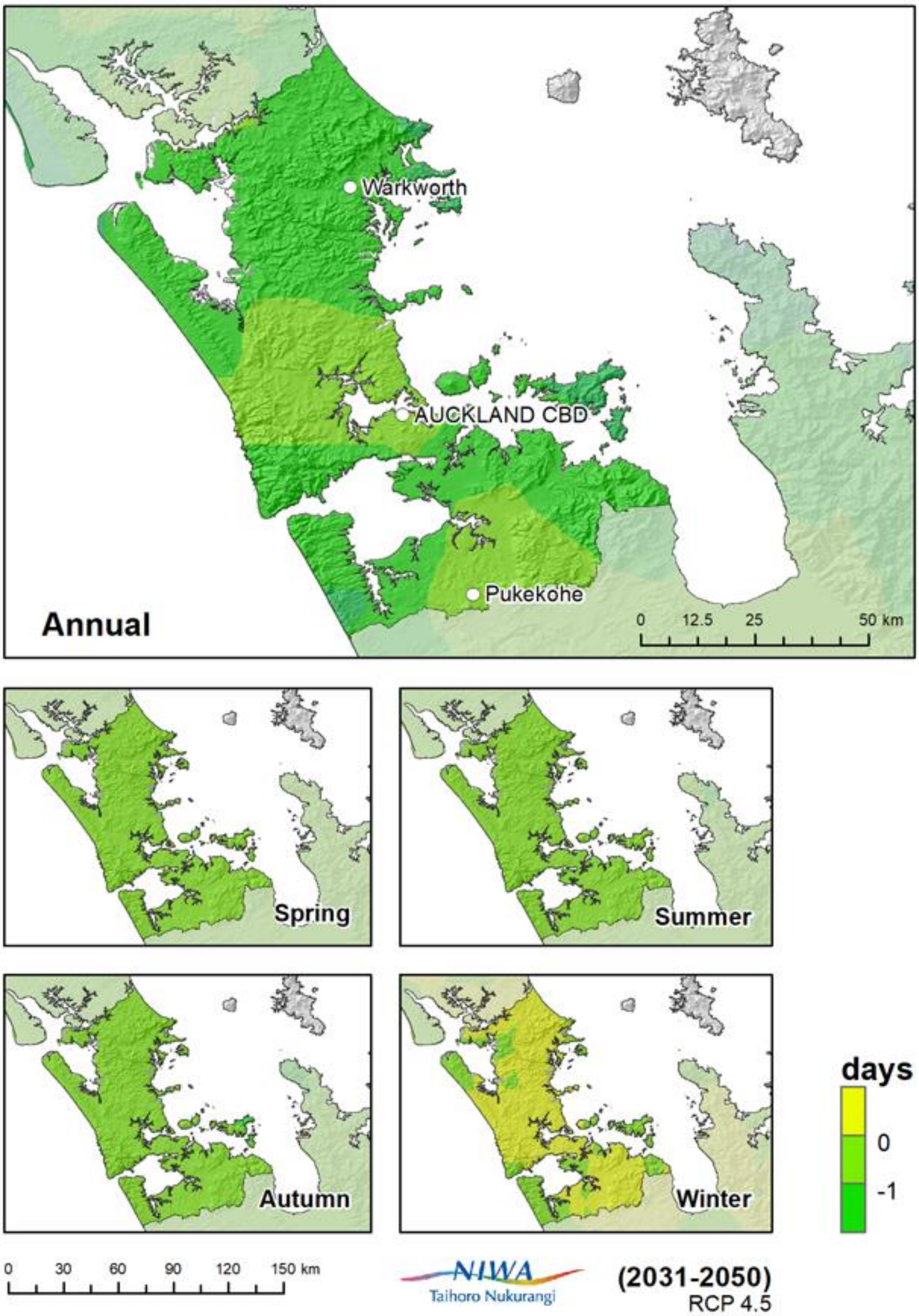

Figure 5-13: Change in the annual and seasonal number of windy days (>10m/s), for Auckland for RCP4.5 at 2040 (2031-2050). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

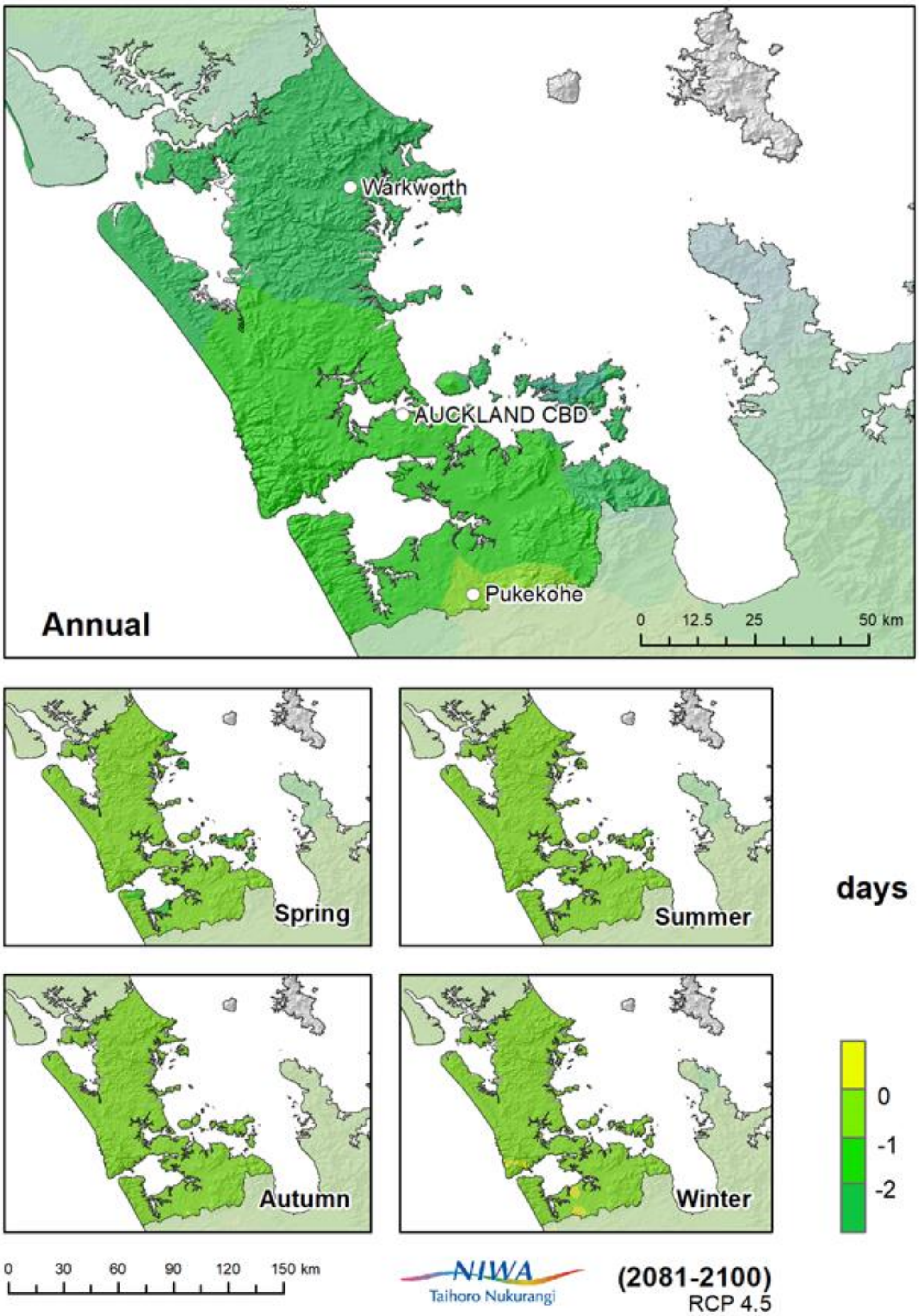

Figure 5-14: Change in the annual and seasonal number of windy days (>10m/s), for Auckland for RCP4.5 at 2090 (2081-2100). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

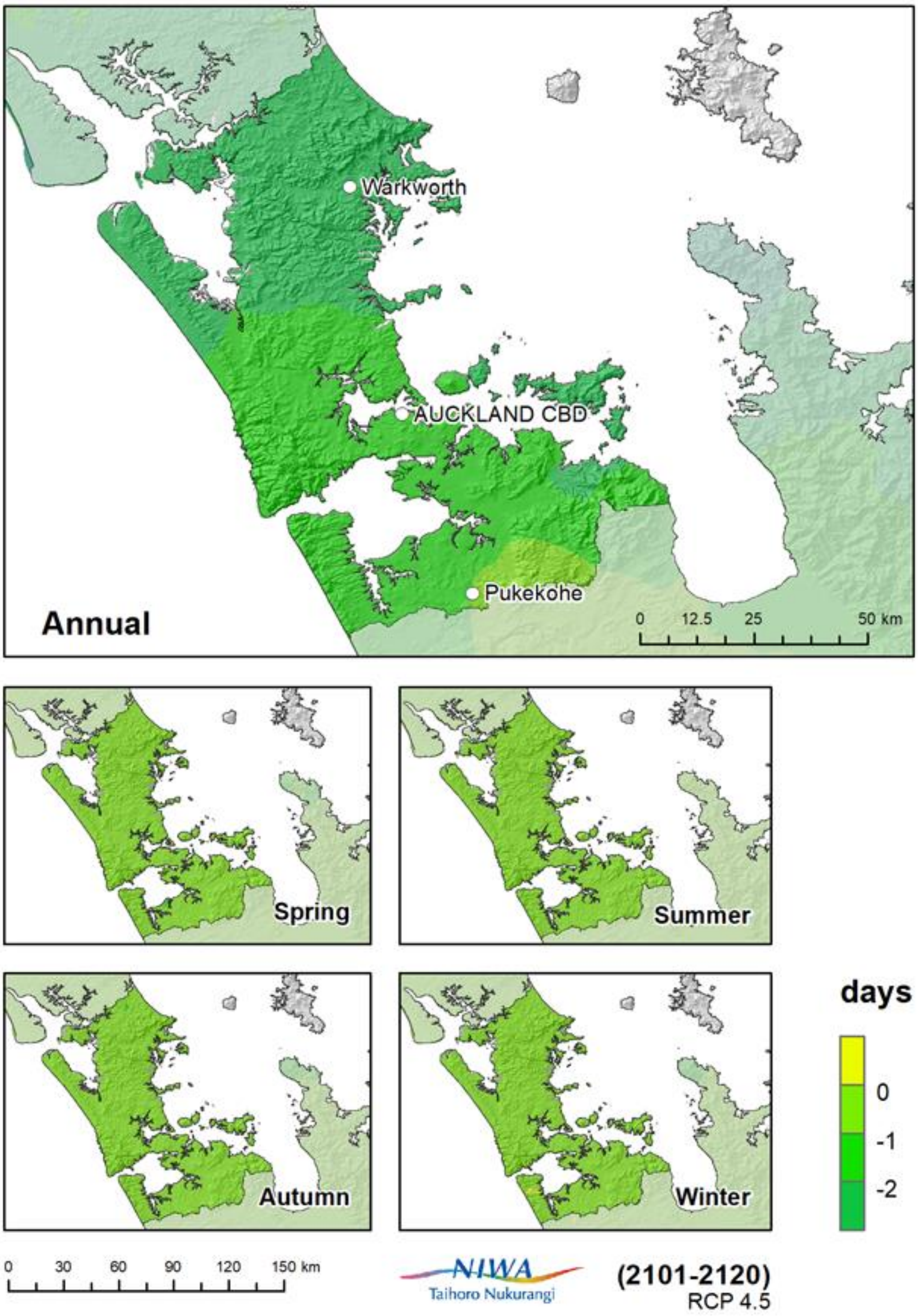

Figure 5-15: Change in the annual and seasonal number of windy days (>10m/s), for Auckland for RCP4.5 at 2110 (2101-2120). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

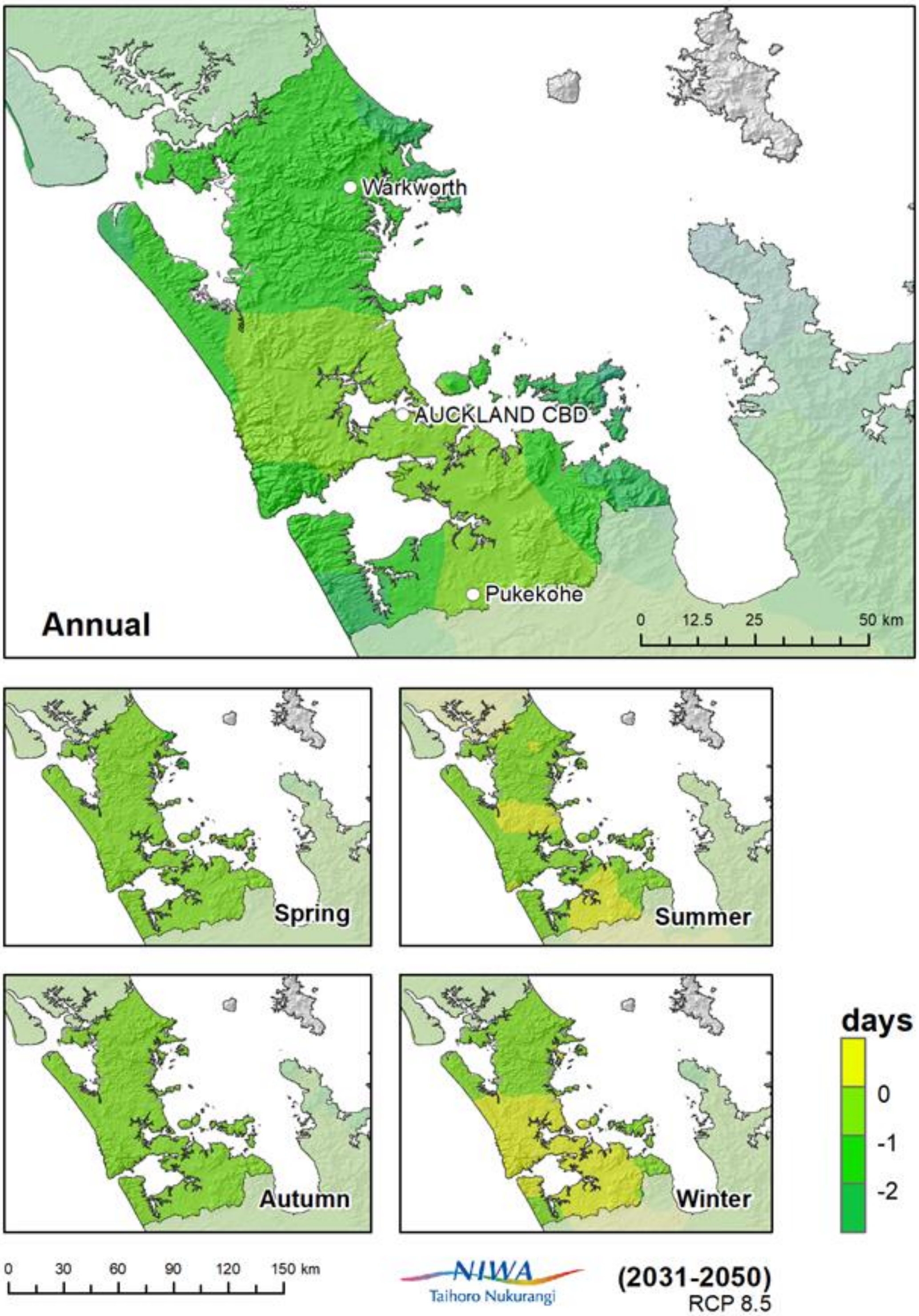

Figure 5-16: Change in the annual and seasonal number of windy days (>10m/s), for Auckland for RCP8.5 at 2040 (2031-2050). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

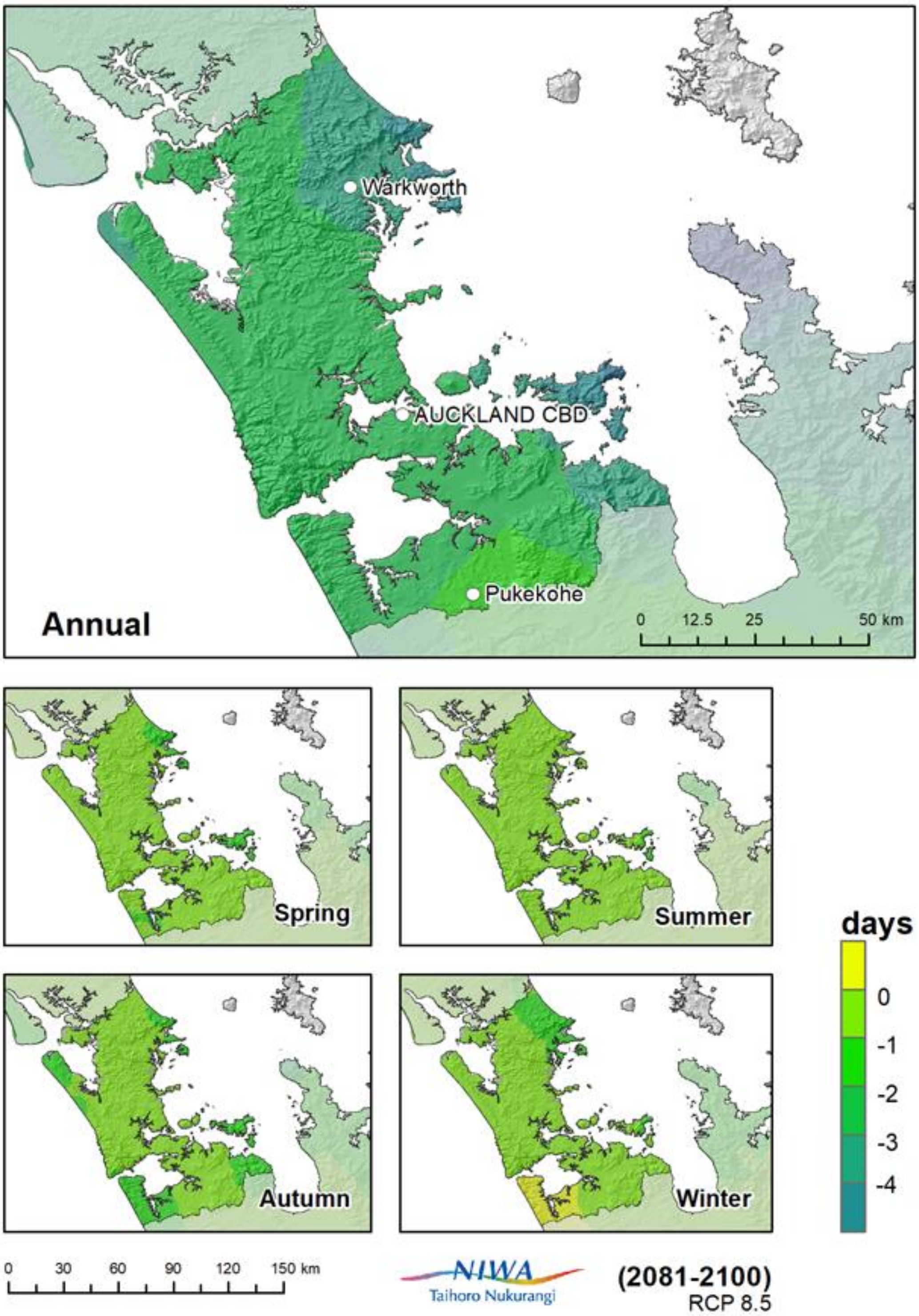

Figure 5-17: Change in the annual and seasonal number of windy days (>10m/s), for Auckland for RCP8.5 at 2090 (2081-2100). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

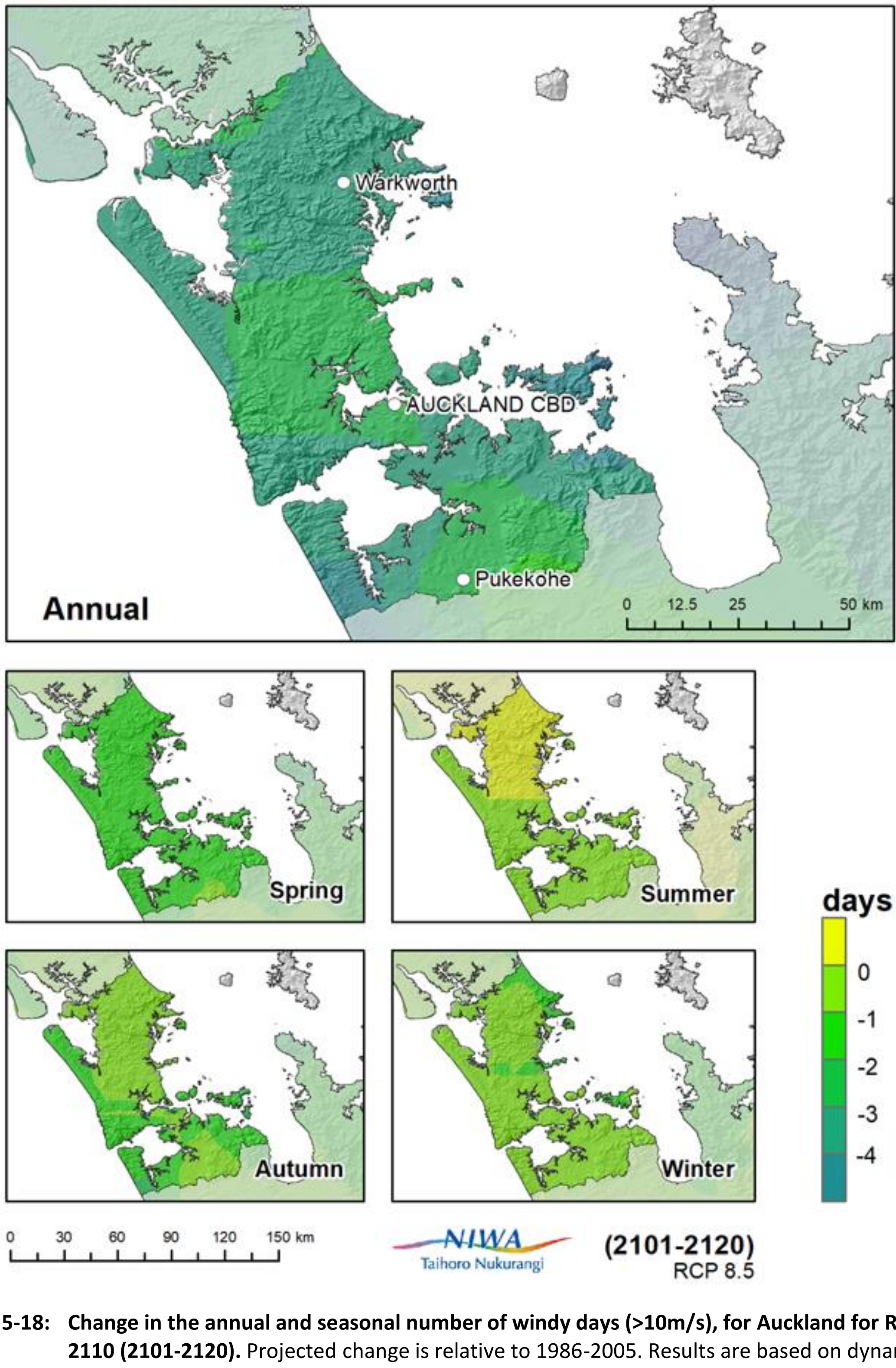

Figure 5-18: Change in the annual and seasonal number of windy days (>10m/s), for Auckland for RCP8.5 at 2110 (2101-2120). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

5.4 Extreme wind

Key messages

- The 99th percentile of daily mean wind speed equates to approximately the three windiest days of the year. The present-day 99th percentile daily mean wind speed is 44.2 km/h at Auckland Airport.
- The magnitude of 99th percentile daily mean wind speed is projected to decrease throughout the Auckland Region in the future, and the decreases are more pronounced with time and RCP forcing.
- For 2110 under RCP4.5 and RCP8.5, a decrease in the magnitude of 99th percentile daily mean wind speeds of up to 4% is projected.

5.4.1 Present

Extreme wind is considered here as the 99th percentile of daily mean wind speeds. This equates to the top 1% of daily mean winds recorded, i.e. about the top three windiest days each year. Note that this section considers wind speed in km/h rather than m/s which was used in Sections 5.2 and 5.3, because the wind speeds considered in this section are more extreme and thus it is more appropriate to use km/h.

Auckland Airport has observed a long-term decline in the 99th percentile of 9 a.m. wind speeds since 1966 (Figure 5-19). This trend is statistically significant above the 95% confidence level. The long-term average 99th percentile 9 a.m. wind speed at Auckland Airport (1981-2010) is 44.2 km/h but this ranges from 38 to 57 km/h in the historical record.

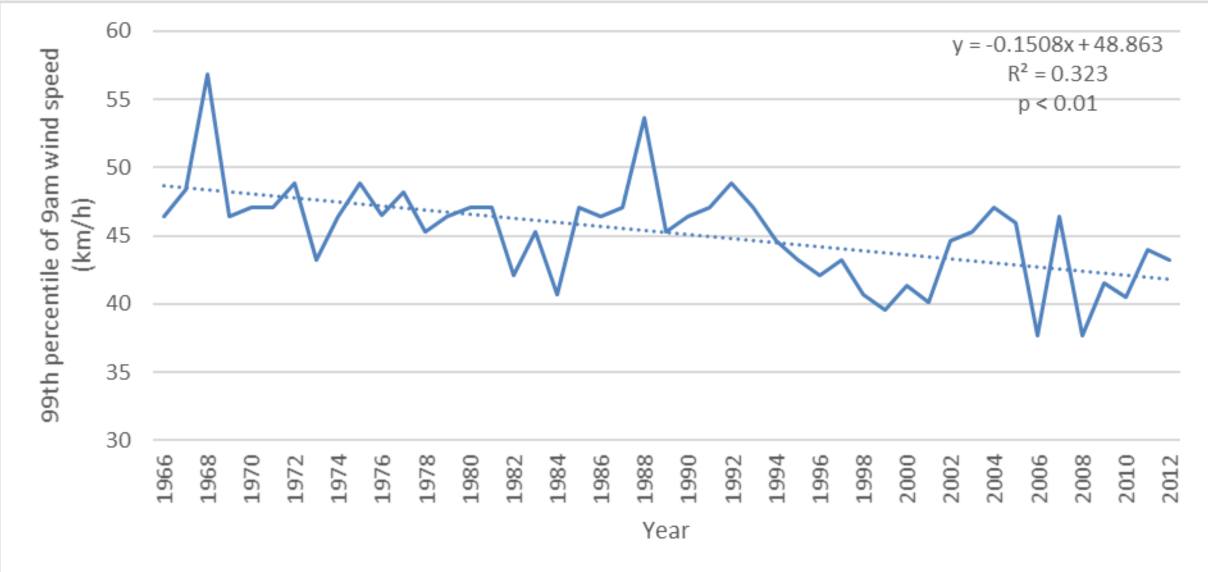

Figure 5-19: 99th percentile of 9 a.m. wind speed (km/h) for Auckland Airport, 1966-2012. Trend indicates a decrease in the 99th percentile of 9 a.m. wind speed of approximately 15 km/h per century.

5.4.2 Future

The 99th percentile of daily mean wind speed was evaluated in the downscaled (but not bias-corrected) regional model output data. The ensemble average of six dynamically downscaled models is presented. Figure 5-20 maps how the magnitude of the 99th percentile daily mean wind speed at 2040, 2090 and 2110 differs from the current climate for RCP4.5 and RCP8.5.

The magnitude of 99th percentile daily mean wind speed is projected to decrease everywhere in the Auckland Region in the future. The decreases are more pronounced with time and RCP forcing. At 2040 under both RCP4.5 and RCP8.5, decreases of 0-2% in the 99th percentile daily mean wind speeds are projected across the region. For 2090 under RCP4.5, the northeast of the region projects a 3-4% decrease in 99th percentile daily mean wind speed, and the remainder of the region projects a 1-2% decrease. For RCP8.5 at 2090, the northeast of the region projects a 4-5% decrease in 99th percentile daily mean wind speed, and the rest of the region projects a 2-4% decrease in 99th percentile daily man wind speed. For 2110 under RCP4.5, a decrease in 99th percentile daily mean wind speed of 2-4% is projected for most of the region. For 2110 under RCP8.5, a decrease of 4-5% is projected in the south and northeast of the region and 3-4% decrease in the remainder of the region.

Past observed changes in extreme wind for Auckland shows approximately a 35% decrease per century in 99th percentile daily mean annual wind speed (if the trend is extended to 100 years). Future changes in extreme wind are projected to be slower than past observed changes, like for mean wind speed in Section 5.2 (up to 5% decrease by 2110 under RCP8.5 for extreme wind). This is possibly because of a slowing of the positive trend of the Southern Annular Mode due to recovery of the ozone hole and an increase in anthropogenic greenhouse gas emissions (see Section 5.3.2 for more details).

Model agreement is good for RCP4.5 at 2110 and RCP8.5 at 2090 and 2110 because all models project a decrease in 99th percentile daily mean wind speeds.

Projections of very localised extreme winds from vigorous summer convection (i.e. tornadoes associated with thunderstorms) are not able to be projected by the regional model being used in this study, due to the spatial resolution of the model being too coarse to resolve these features.

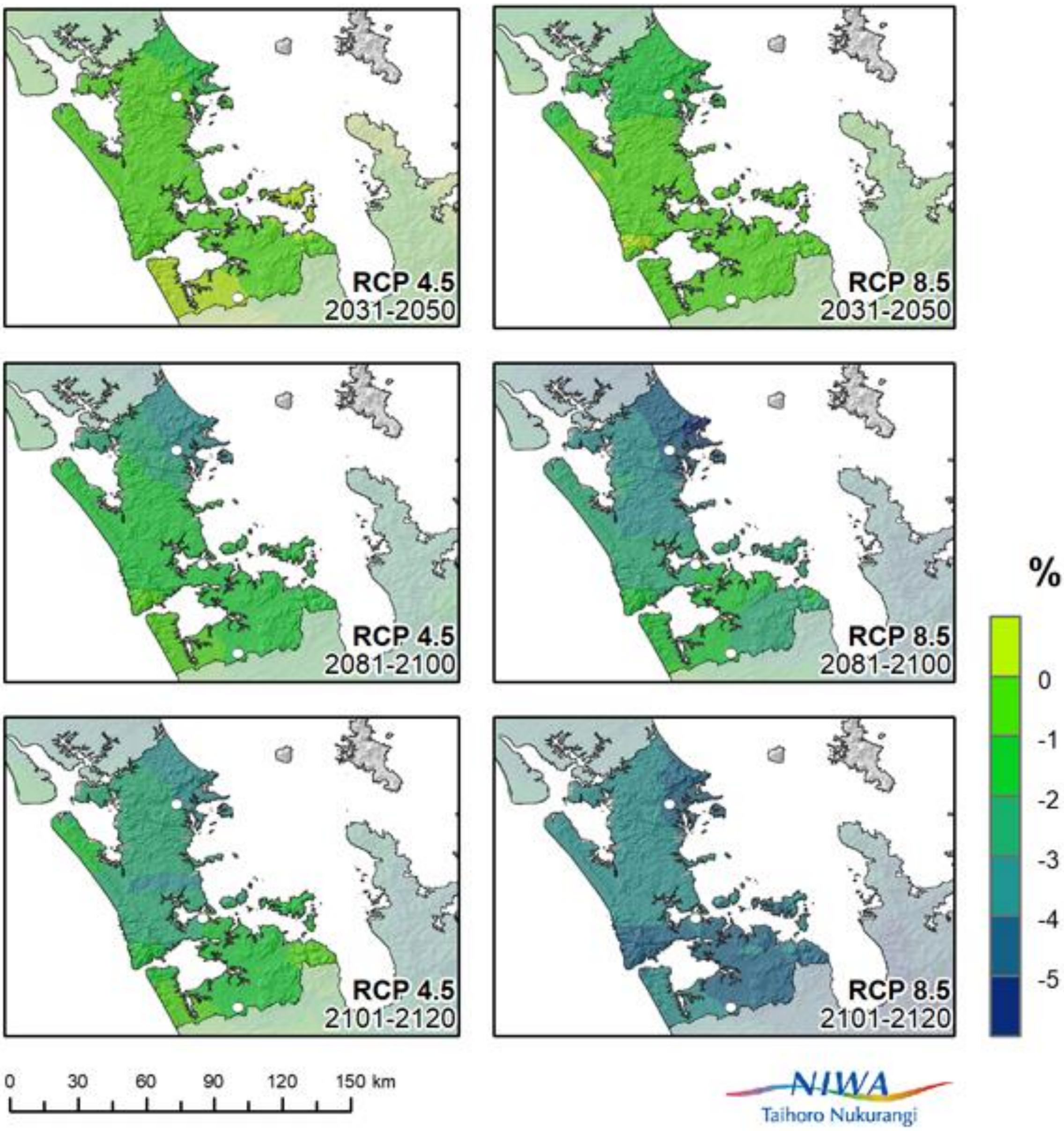

Figure 5-20: Change in the magnitude of the 99th percentile of daily mean wind speed for Auckland, for RCP4.5 (left panels) and RCP8.5 (right panels) at 2040 (2031-2050), 2090 (2081-2100) and 2110 (2101-2120). Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km. The white dots correspond to (north-south) Warkworth, Auckland CBD, Pukekohe.

5.5 Storms

Key messages

- The intensity of tropical cyclones (rain rate and wind speed) is projected to increase in the future, but the frequency of tropical cyclones is projected to remain similar to present.
- Ex-tropical cyclones that approach Auckland in the future may be stronger due to retention of tropical cyclone characteristics farther south than at present.
- The total number of mid-latitude cyclones (i.e. low pressure systems that affect New Zealand every few days) is unlikely to decline by more than a few percent.
- There is significant uncertainty about the future influence of the increasing strength of the mid-latitude jet to the south of New Zealand on the future frequency and magnitude of storms affecting the country.

5.5.1 Present

The Auckland Region is relatively often adversely affected by storms of tropical origin. These storms may or may not have originated as tropical cyclones further north in the southwest Pacific Ocean. These storms may bring heavy rain and strong winds to the Auckland Region, which can cause flooding, generate primary and secondary wind damage to vegetation and infrastructure, and higher-than-normal wave heights and coastal storm surges. Approximately nine ex-tropical cyclones come within 550 km of Auckland CBD every 10 years, and the most active months are March and February, respectively (Lorrey et al., 2014). During El Niño and La Niña periods, there is an equal chance of an ex-tropical cyclone passing east or west of the region.

New Zealand is usually affected by mid-latitude low pressure systems every few days. Some of these low pressure systems may cause heavy rain and high winds which sometimes result in significant damage to land and infrastructure. Mid-latitude cyclones are generally stronger in the winter months.

5.5.2 Future

Tropical and ex-tropical cyclones

The IPCC considers it 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, 2013b). 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 rainfall 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. Kossin et al. (2014) found that the average latitude at which tropical cyclones have achieved their lifetime-maximum intensity has migrated poleward over the past 30 years, an average of 62 km per decade for the Southern Hemisphere. This may indicate an expansion of the tropics, an expected outcome of anthropogenic climate change that has been projected by climate change theories and models (Walsh et al., 2016). This is important for New Zealand and Auckland, as the ex-tropical cyclones that approach the region in the future may be stronger due to retention of tropical cyclone characteristics farther south than at present. Characteristics include well-organised cyclonic circulation, a well-defined eye, strong interior wind speeds, and high rainfall rates.

Overall, there is significant uncertainty surrounding projections of tropical cyclones into the future. 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 a southward trajectory that may influence New Zealand. Therefore, the frequency with which ex-tropical cyclones and other tropical depressions may reach the Auckland Region in the future is uncertain and requires further research.

As mentioned above, 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 the projections presented in this report.

Mid-latitude cyclones

IPCC (2013) suggests that the global number of mid-latitude 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 percent, 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. Mid-latitude storm tracks will tend to shift poleward by several degrees (Figure 5-21), but the reduction in storm frequency is only a few percent.

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 projected 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. How this finding translates to the impact of mid-latitude storm systems is unclear for New Zealand, so further analyses that include regional consequences of this type of change is needed.

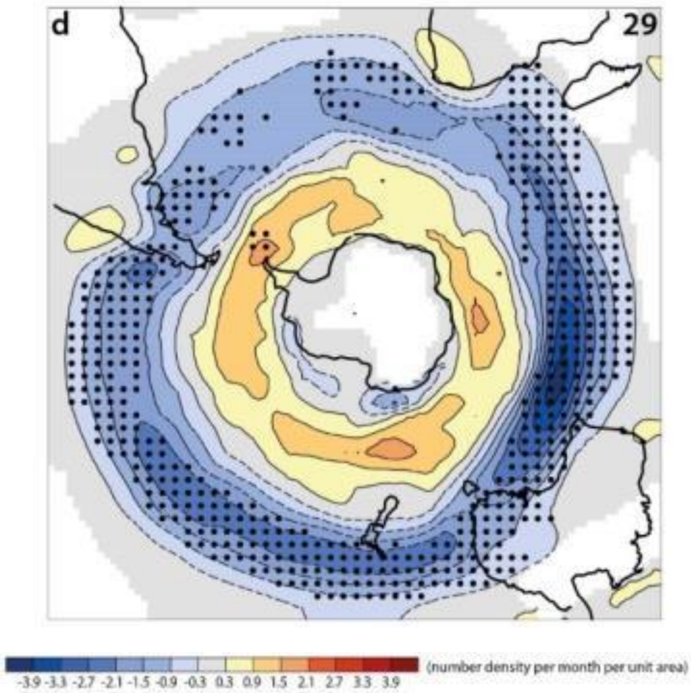

Figure 5-21: Change in winter Southern Hemisphere storm track between 1986–2005 and 2081–2100, under RCP8.5, from a 29-member CMIP5 multi-model ensemble. Blue shading indicates a decrease, and yellow-orange shading an increase in the number of storm 'centres'. Stippling is added where 90 per cent of 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 southeast 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.

6 Solar radiation

Key messages

- Present-day mean annual solar radiation is 159 W/m^2 for Mangere. Summer average solar radiation is 234 W/m^2 and winter average solar radiation is 87 W/m^2.
- There is minimal change in solar radiation projected for the Auckland Region.
- The largest increases are projected for summer and spring at 2090 and 2110, respectively, under RCP8.5, where an increase of > 5 W/m^2 is projected for the northern part of the Auckland Region.
- The largest decreases are projected in winter at 2090 and 2011 under RCP8.5 where the southern part of the region is projected to experience a decrease of more than 4 W/m^2.

Present-day solar radiation conditions in the Auckland Region are summarised in this section and future projections are presented for RCP4.5 and RCP8.5 at 2040, 2090 and 2110.

6.1 Present

Present-day median annual daily solar radiation is highest in the north of the region and on Great Barrier Island. Solar radiation is lowest along the west coast, the isthmus, and to the west of the isthmus. These spatial patterns are similar for solar radiation observed in summer and winter in the Auckland Region. Mean annual solar radiation at Mangere is 159 W/m^2, summer average solar radiation is 234 W/m^2 and winter average solar radiation is 87 W/m^2.

6.2 Future

Projections of solar radiation were calculated for the Auckland Region using NIWA's Regional Climate Model. The ensemble average of six dynamically downscaled models is presented. Figure 6-1 to Figure 6-5 show maps of changes in incident total solar radiation (direct plus diffuse) at the surface for 2040, 2090 and 2110 under RCP4.5 and RCP8.5. The changes are with respect to the model 1986–2005 climatology. Note that these data have not been bias-corrected as has been done for temperature and rainfall.

At the annual timescale, there is minimal change for RCP4.5 at 2040 (Figure 6-1), 2090 (Figure 6-2) and 2110 (Figure 6-3), and for RCP8.5 at 2040 (Figure 6-4) (± 1 W/m^2 change). For RCP8.5 at 2090 (Figure 6-5), northeast parts of the region are projected to experience up to 2 W/m^2 increase in solar radiation at the annual scale, and by 2110 (Figure 6-6) most of northern Auckland is projected to experience up to 2 W/m^2 increase in annual solar radiation. A decrease of up to 2 W/m^2 is projected for Waiheke Island and the southeast of the region at 2110 under RCP8.5.

At the seasonal scale, increases in solar radiation are generally projected for spring and summer and decreases are generally observed for autumn and winter, although this is not consistent between all time slices and RCPs. The largest increases are projected for summer at 2090 under RCP8.5 (Figure 6-5), when an increase of more than 5 W/m^2 is projected for northern Auckland, and spring at 2110 under RCP8.5 (Figure 6-6), when the northeast coast of the region is projected to receive an increase of more than 5 W/m^2. The largest decreases are projected in winter at 2090 and 2110 under RCP8.5, where the southern part of the region is projected to experience a decrease of more than 4 W/m^2.

Model agreement is good for summer at 2040, 2090 and 2110 under RCP4.5 and at 2090 and 2110 under RCP8.5 as most models project an increase in solar radiation.

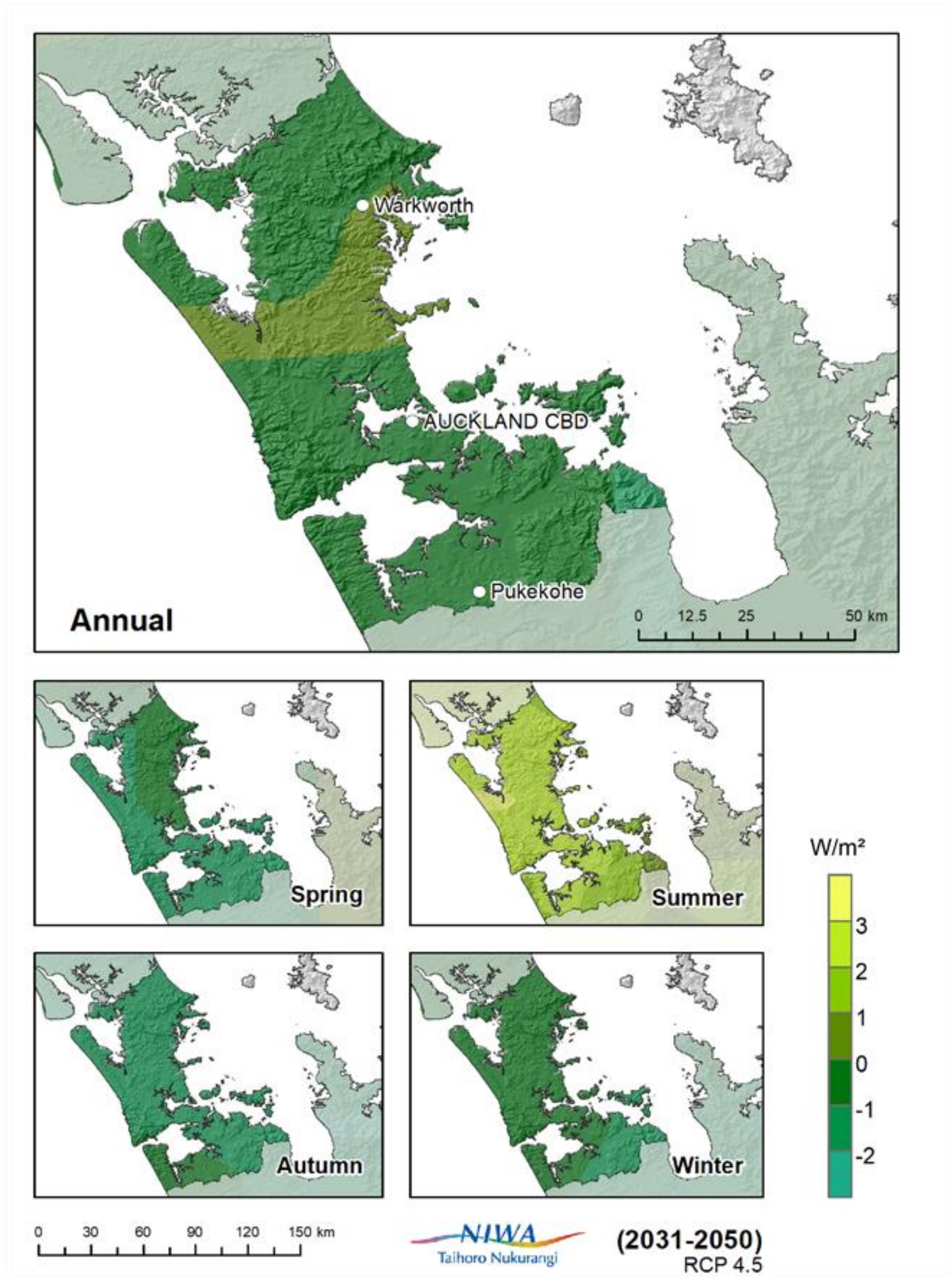

Figure 6-1: Projected change in annual and seasonal solar radiation (in W/m²) at 2040 (2031-2050) for RCP4.5, for the Auckland Region. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

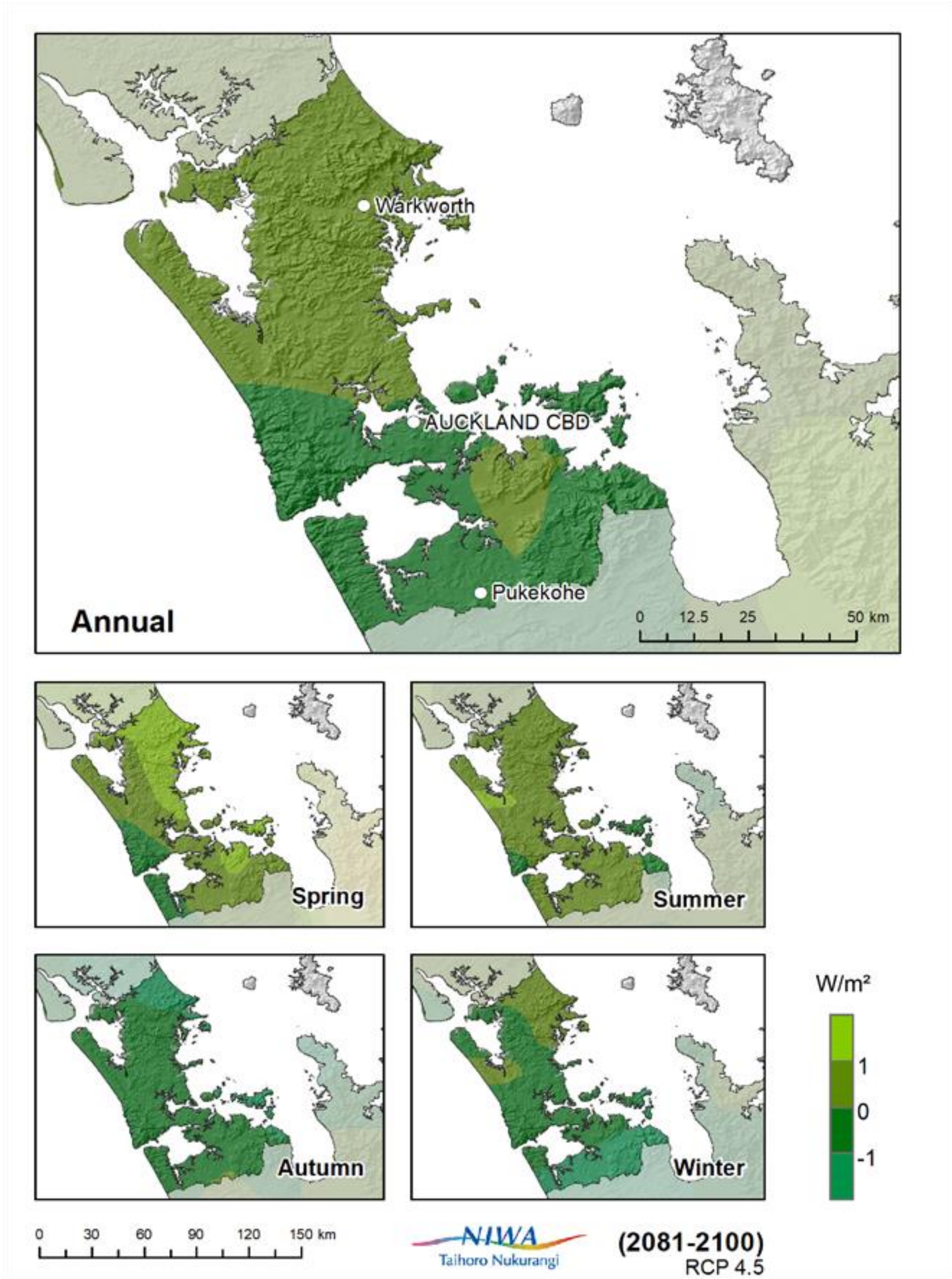

Figure 6-2: Projected change in annual and seasonal solar radiation (in W/m^2) at 2090 (2081-2100) for RCP4.5, for the Auckland Region. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

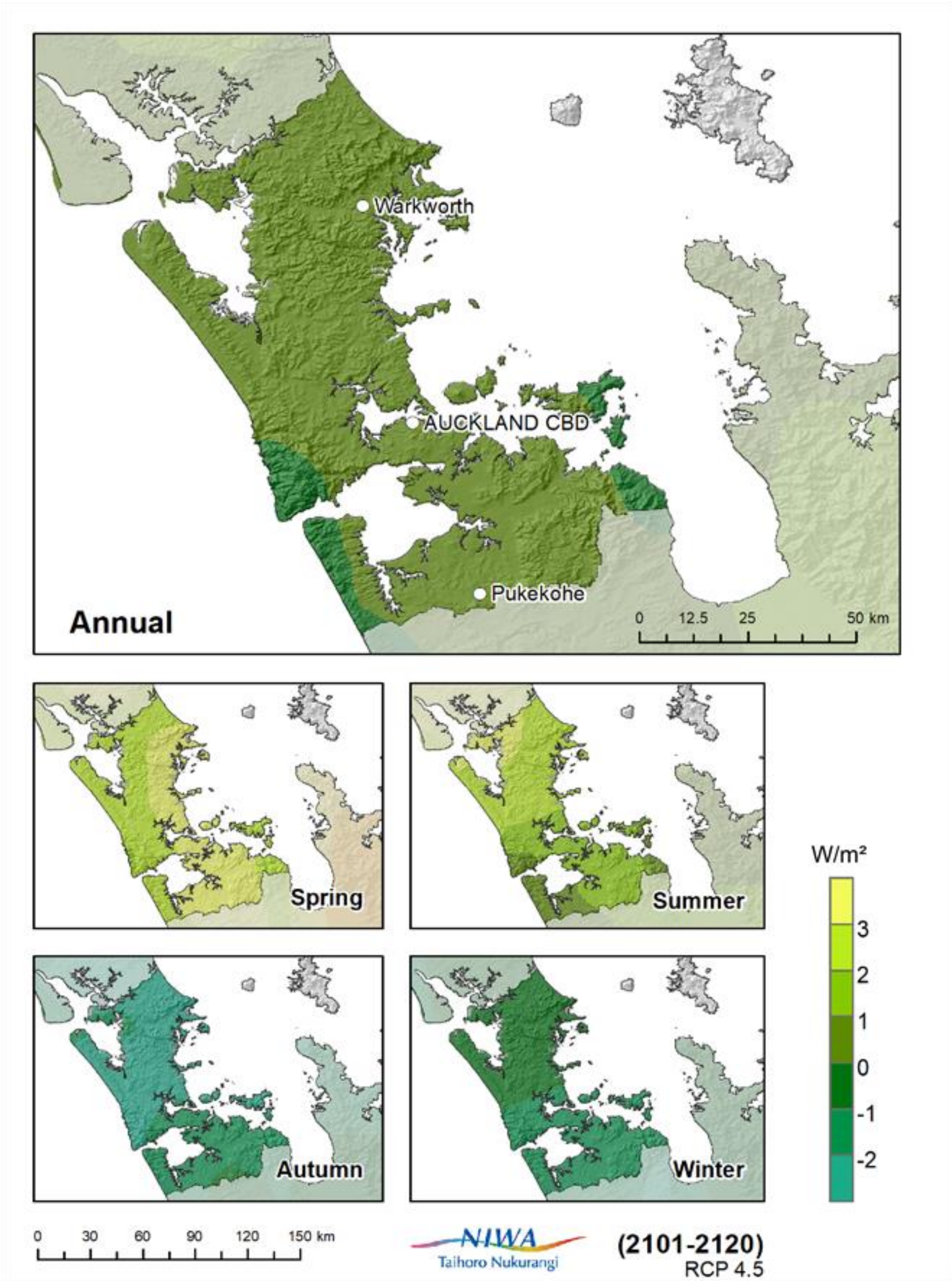

Figure 6-3: Projected change in annual and seasonal solar radiation (in W/m^2) at 2110 (2101-2120) for RCP4.5, for the Auckland Region. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

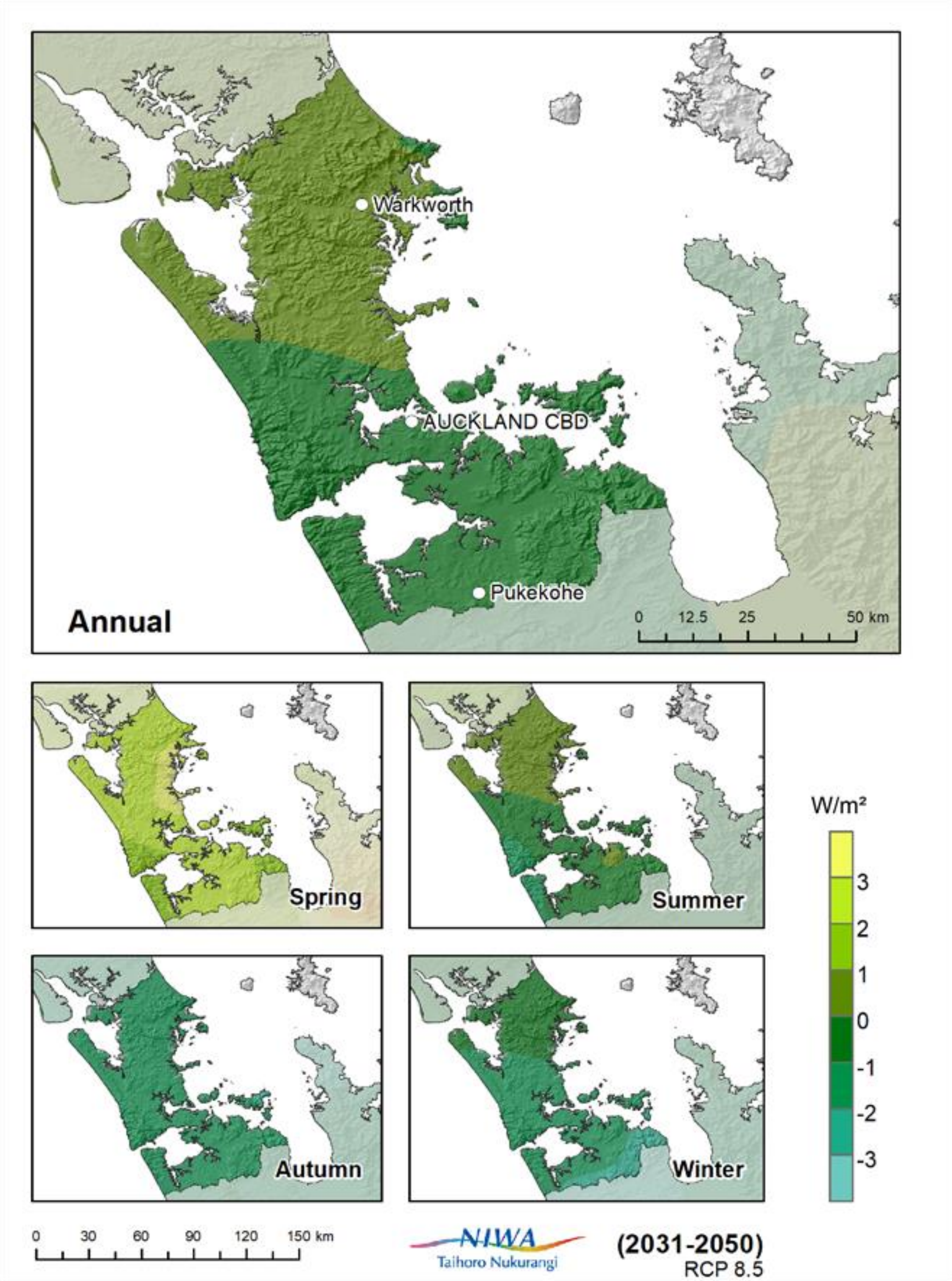

Figure 6-4: Projected change in annual and seasonal solar radiation (in W/m²) at 2040 (2031-2050) for RCP8.5, for the Auckland Region. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

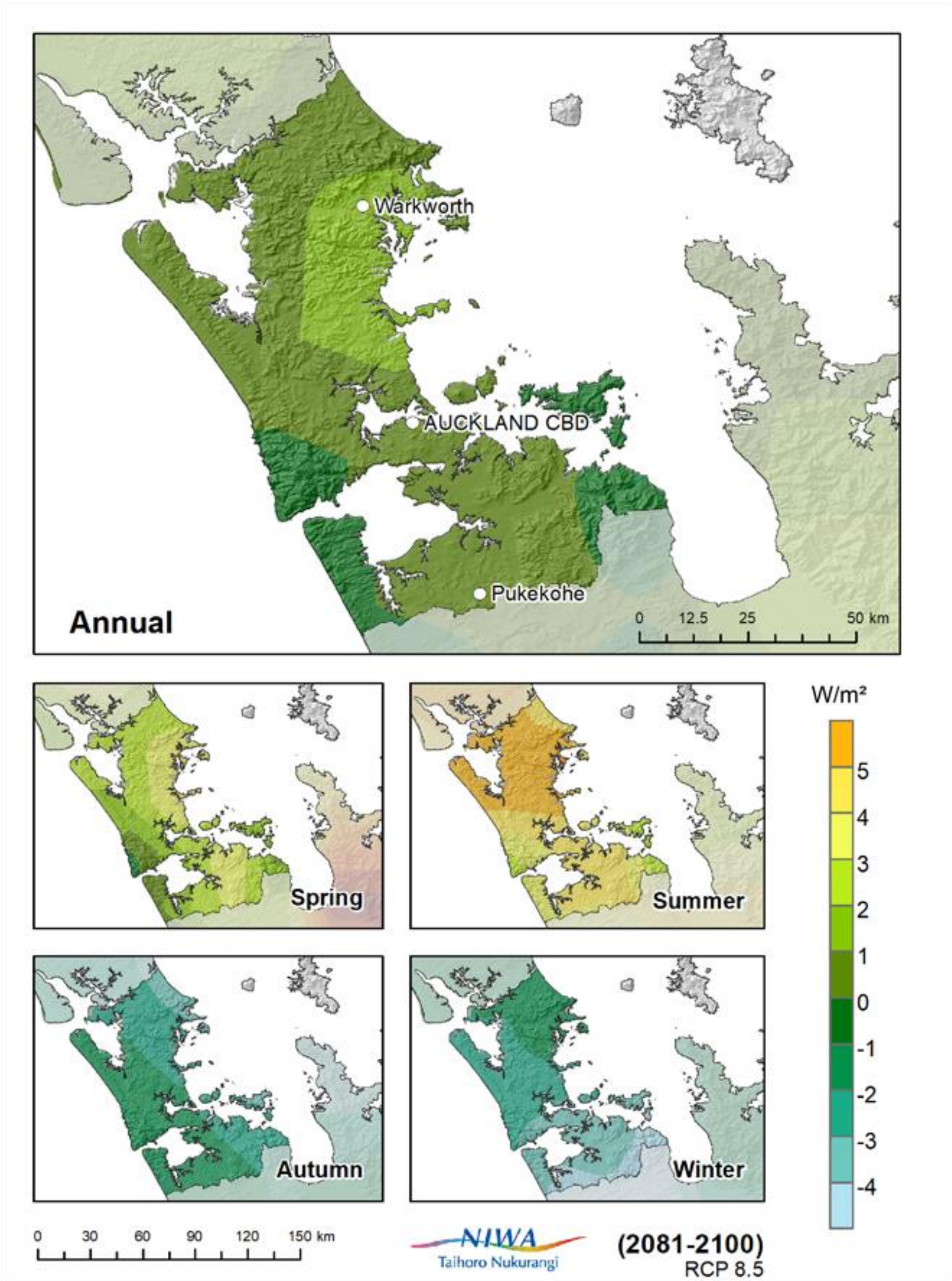

Figure 6-5: Projected change in annual and seasonal solar radiation (in W/m^2) at 2090 (2081-2100) for RCP8.5, for the Auckland Region. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

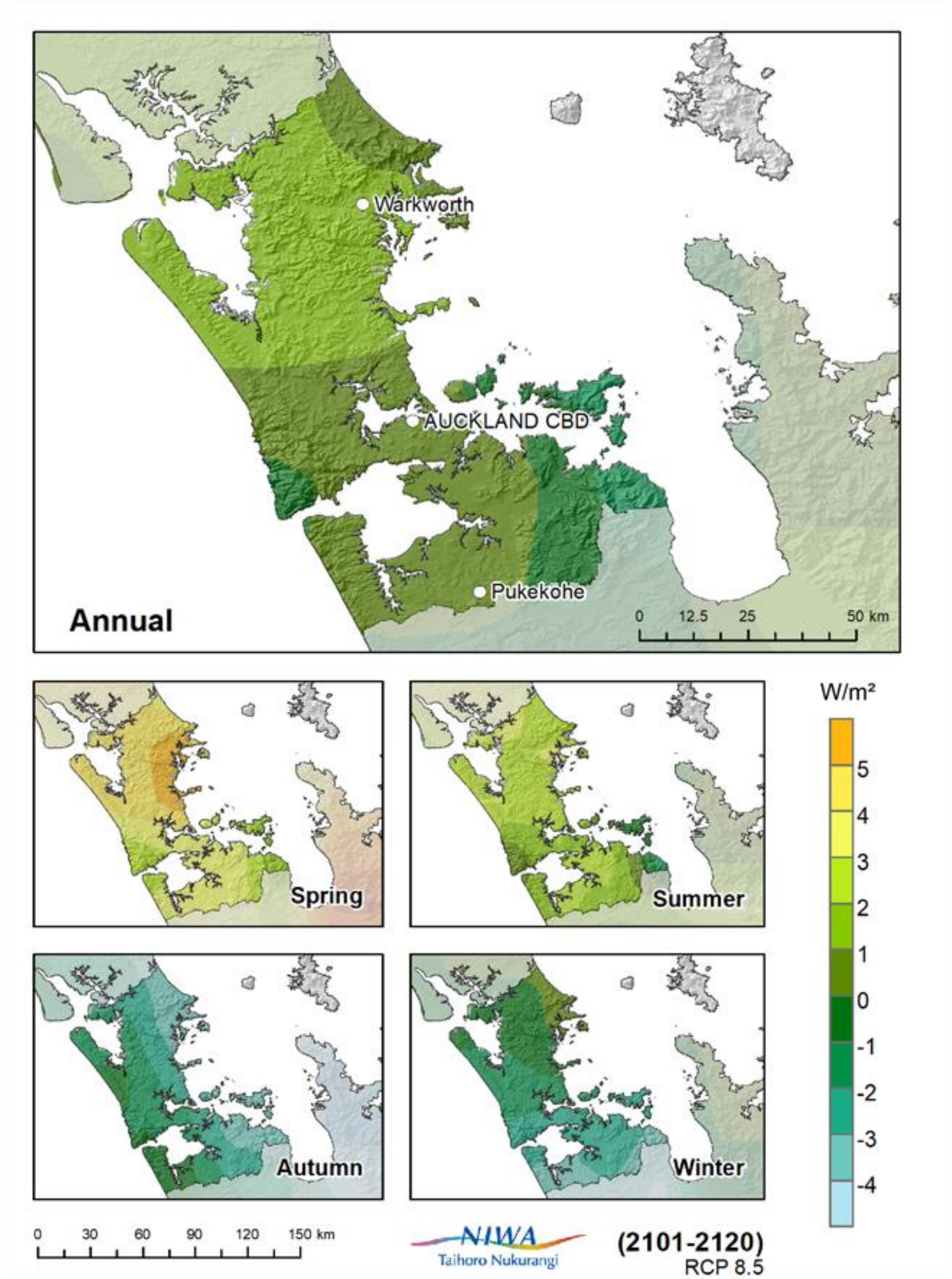

Figure 6-6: Projected change in annual and seasonal solar radiation (in W/m²) at 2110 (2101-2120) for RCP8.5, for the Auckland Region. Projected change relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

7 Relative humidity

Key messages

- Most of the Auckland Region presently experiences average annual 9 a.m. relative humidity of 80-85%. Relative humidity is higher in winter than in summer.
- For most parts of the Auckland Region, annual relative humidity is projected to slightly decrease into the future, but only by a few percent.
- Spring is the season that will experience the largest decreases in relative humidity (up to 3%). Some small increases are projected for autumn (1%).

Present-day relative humidity conditions in the Auckland Region are summarised in this section and future projections are presented for RCP4.5 and RCP8.5 at 2040, 2090 and 2110.

7.1 Present

Due to its subtropical and maritime location, Auckland experiences high year-round 9 a.m. relative humidity compared with drier, more inland parts of New Zealand. The south and west of the Auckland Region have the highest average annual 9 a.m. relative humidity (85-90%), and the urban area on the isthmus has the lowest (75-80%) (Figure 7-1). Relative humidity is higher in winter than it is in summer (Figure 7-2, Figure 7-3). Relative humidity has slightly declined on average since 1966 at Auckland Airport, but this trend is not statistically significant at or above the 95% confidence level (Figure 7-4). At Auckland Airport, diurnal relative humidity varies, on average, from a maximum of about 85% before dawn to a minimum of about 67% in the mid-afternoon.

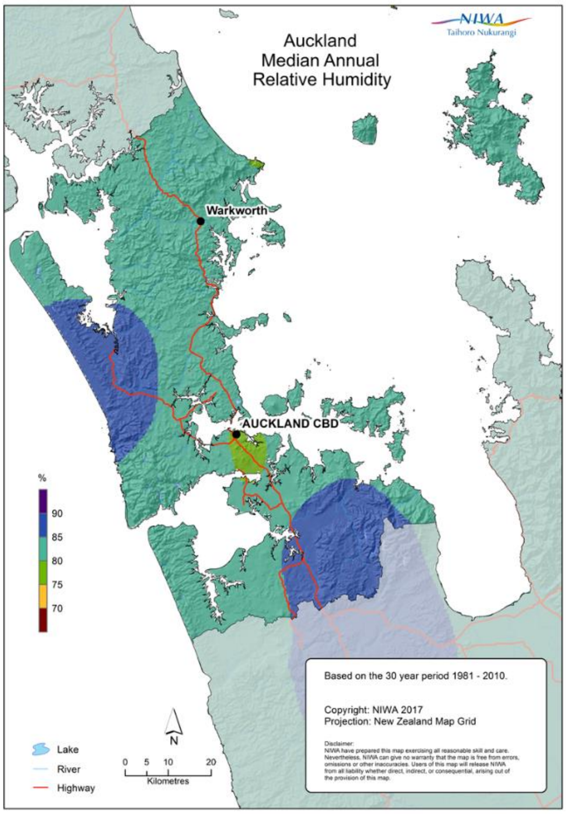

Figure 7-1: Median annual relative humidity for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

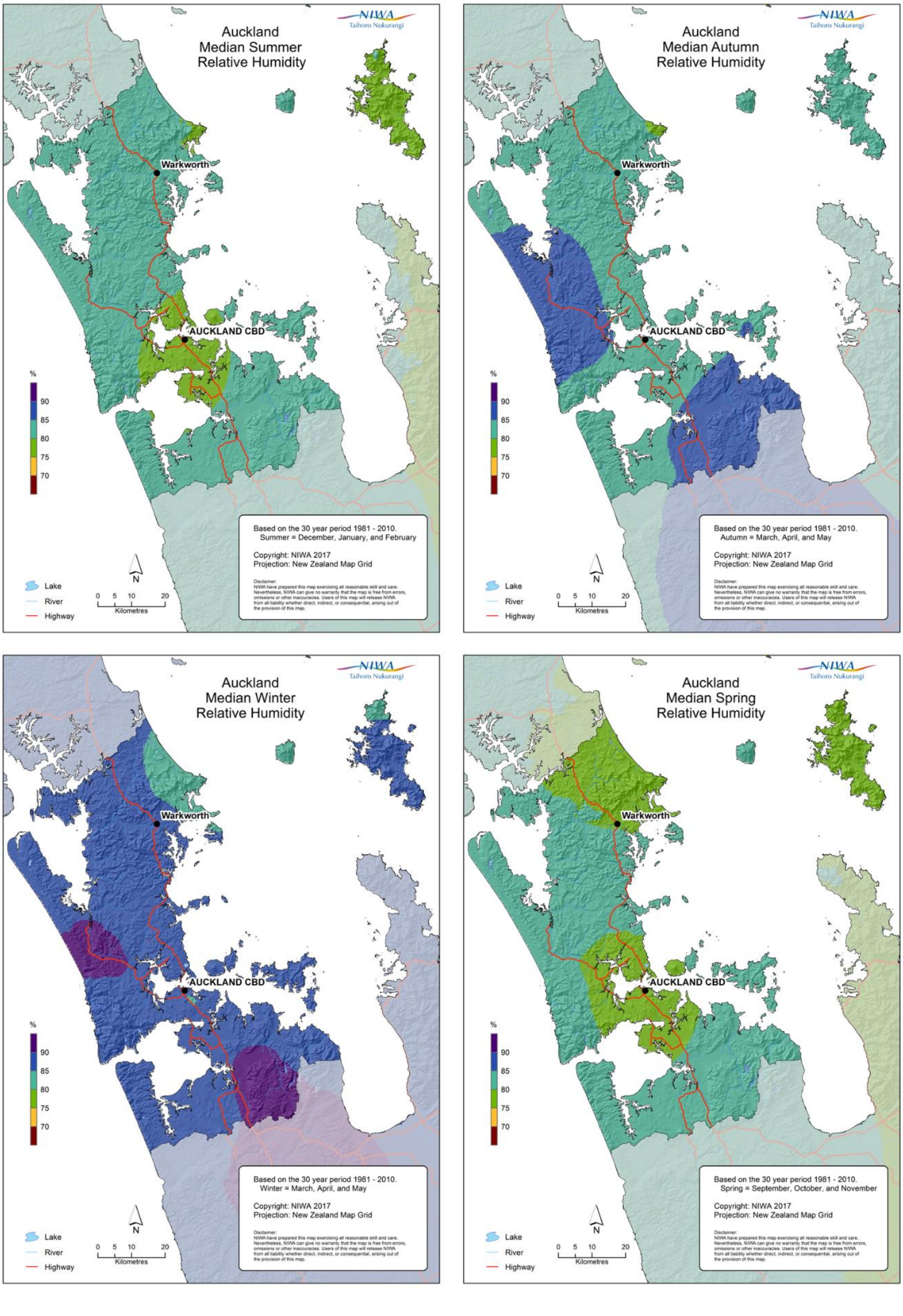

Figure 7-2: Median seasonal relative humidity for the Auckland Region (1981-2010). Based on data from NIWA's Virtual Climate Station Network.

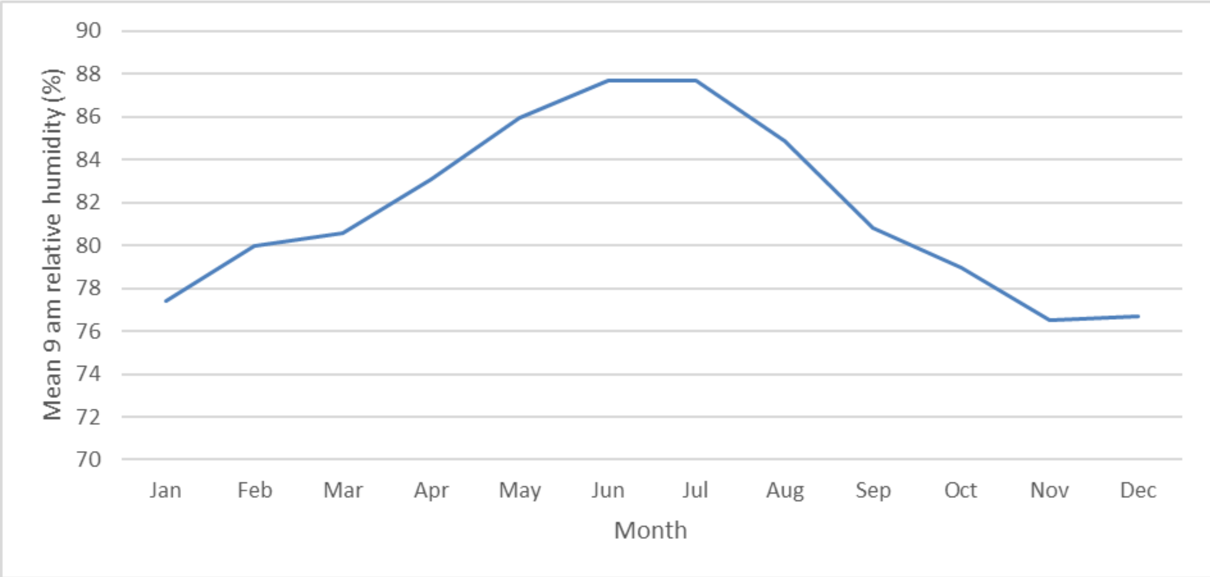

Figure 7-3: Mean monthly 9 a.m. relative humidity (%), 1981-2010, at Auckland Airport.

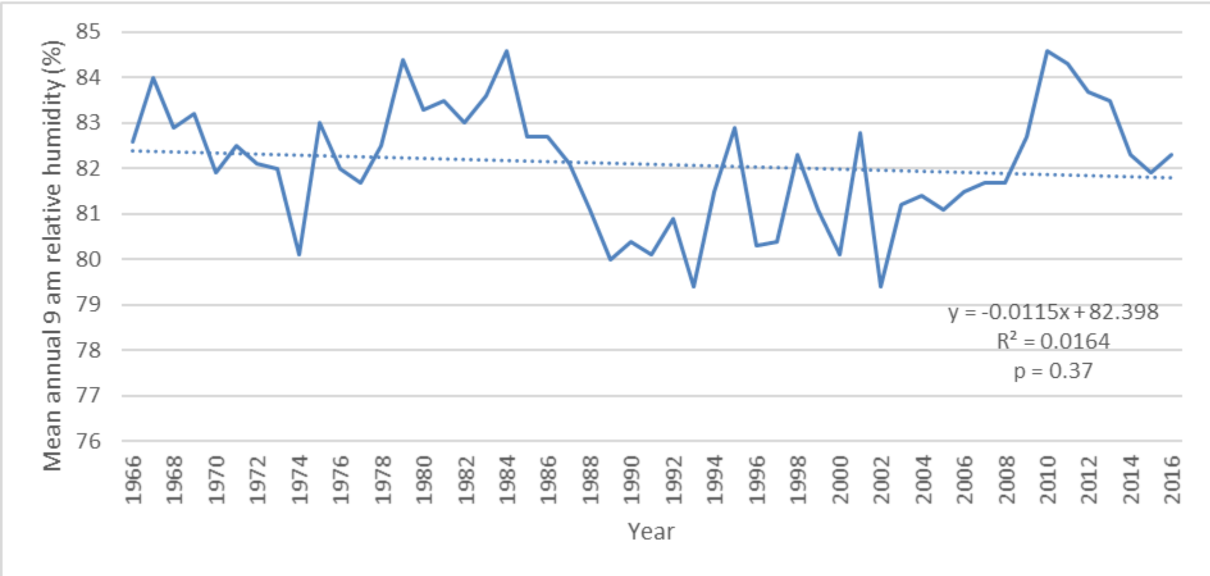

Figure 7-4: Annual mean 9 a.m. relative humidity (%) for Auckland Airport, 1966-2016.

7.2 Future

Changes to daily mean relative humidity are presented in Figure 7-5 to Figure 7-10 for RCP4.5 and RCP8.5 at 2040, 2090 and 2110. These projections have been dynamically downscaled using NIWA's Regional Climate Model, and the ensemble average of six models is presented.

For most parts of the Auckland Region, relative humidity is projected to slightly decrease.

For RCP4.5, annual relative humidity is projected to decrease by up to 1% for most of the region at all three time slices (Figure 7-5 to Figure 7-7). Relative humidity is projected to slightly increase by up to 1% in autumn at 2040 and 2110 for most of the region, and decrease by up to 2% for most of the region in spring at 2110.

For RCP8.5 at 2040 (Figure 7-8), annual relative humidity is projected to decrease by up to 1%. Spring relative humidity at 2040 is projected to decrease by 1-2% for much of the region, and autumn relative humidity is projected to increase by 1% for western parts of the region. At 2090 (Figure 7-9), annual relative humidity is projected to decrease by up to 2% and by up to 3% for central parts of the region in spring at 2090. Autumn relative humidity is projected to increase by 1% for some western and eastern areas. By 2110 (Figure 7-10), annual relative humidity is projected to decrease by up to 2% for most of the region and spring relative humidity is projected to decrease by up to 3% for most of the region. Autumn relative humidity is projected to increase by 1% for the whole region at 2110 under RCP8.5.

Model agreement is good for winter and spring at 2090 and 2110 under RCP4.5 and 2040 and 2090 under RCP8.5, as most models project a decrease in relative humidity.

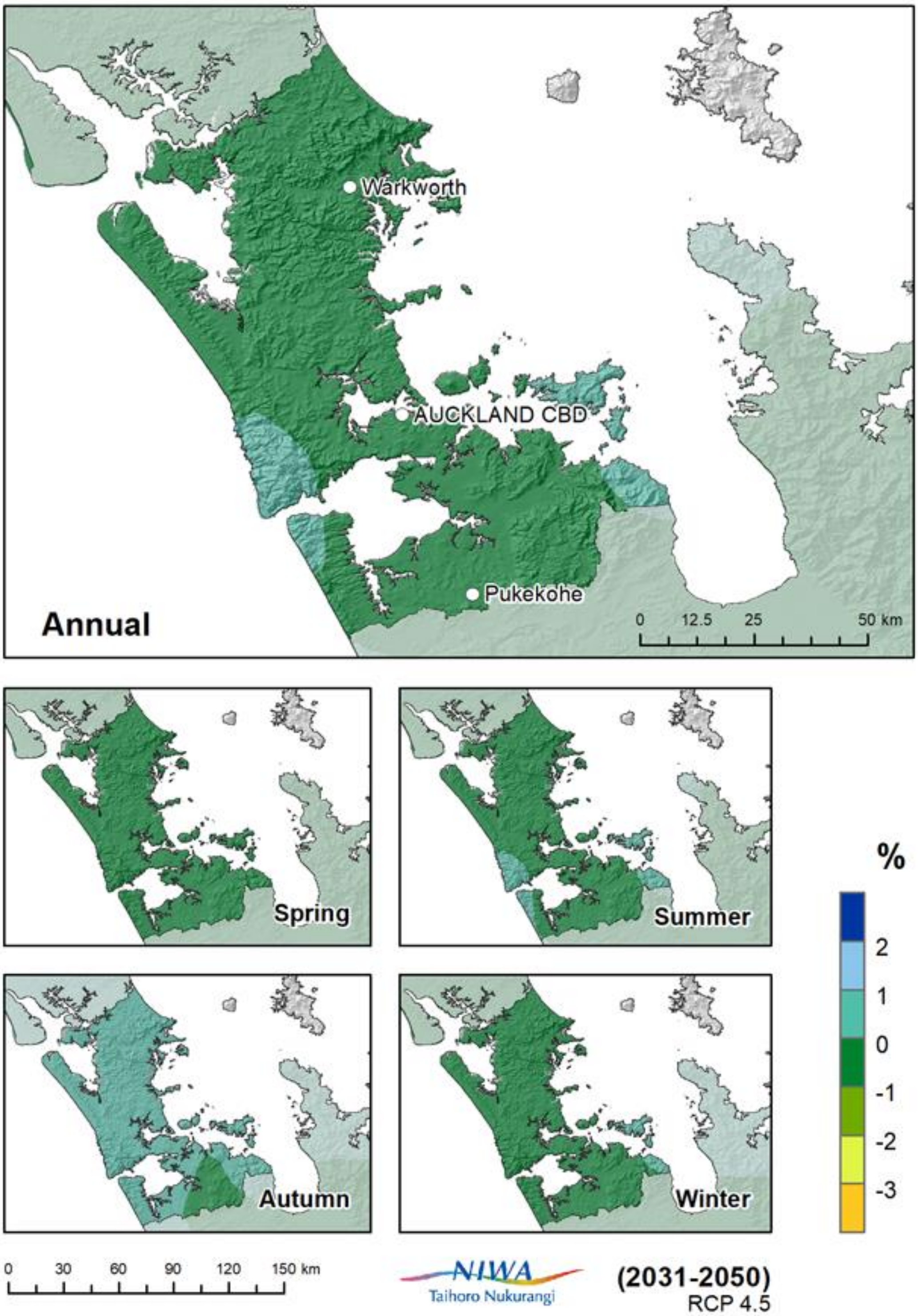

Figure 7-5: Projected change in annual and seasonal relative humidity (change in relative humidity, which is measured in %) at 2040 (2031-2050) for RCP4.5, for the Auckland Region. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

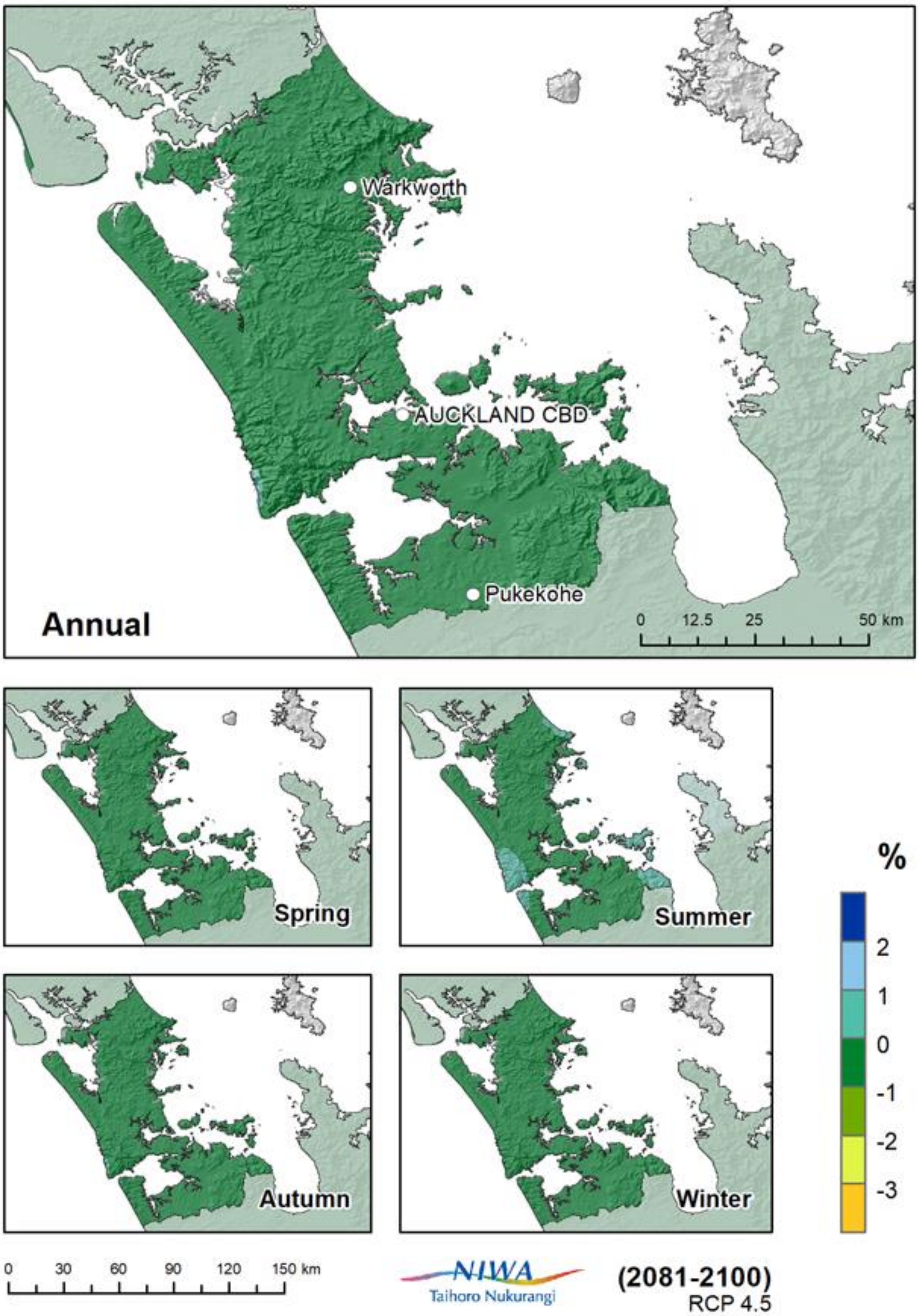

Figure 7-6: Projected change in annual and seasonal relative humidity (change in relative humidity, which is measured in %) at 2090 (2081-2100) for RCP4.5, for the Auckland Region. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

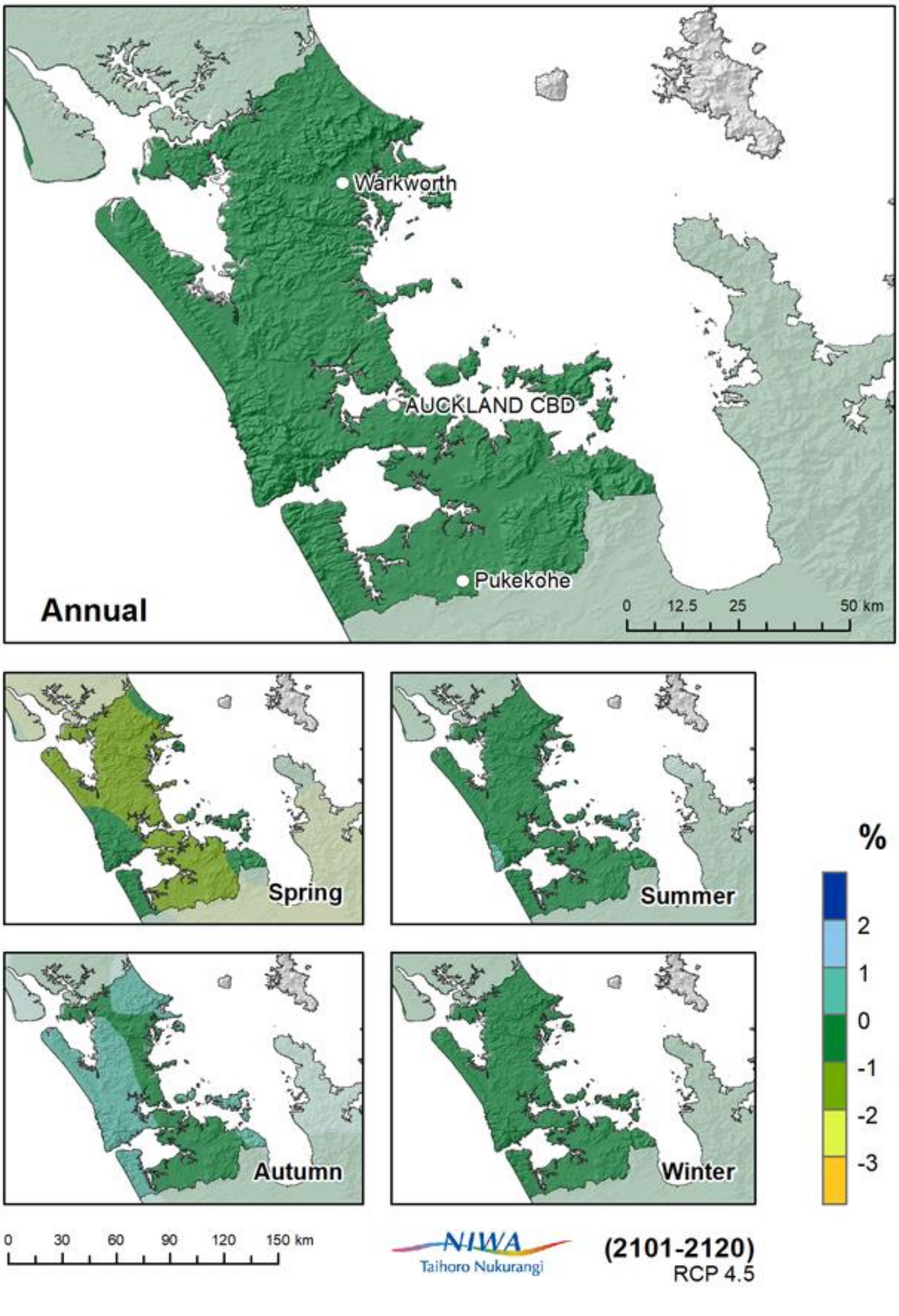

Figure 7-7: Projected change in annual and seasonal relative humidity (change in relative humidity, which is measured in %) at 2110 (2101-2120) for RCP4.5, for the Auckland Region. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

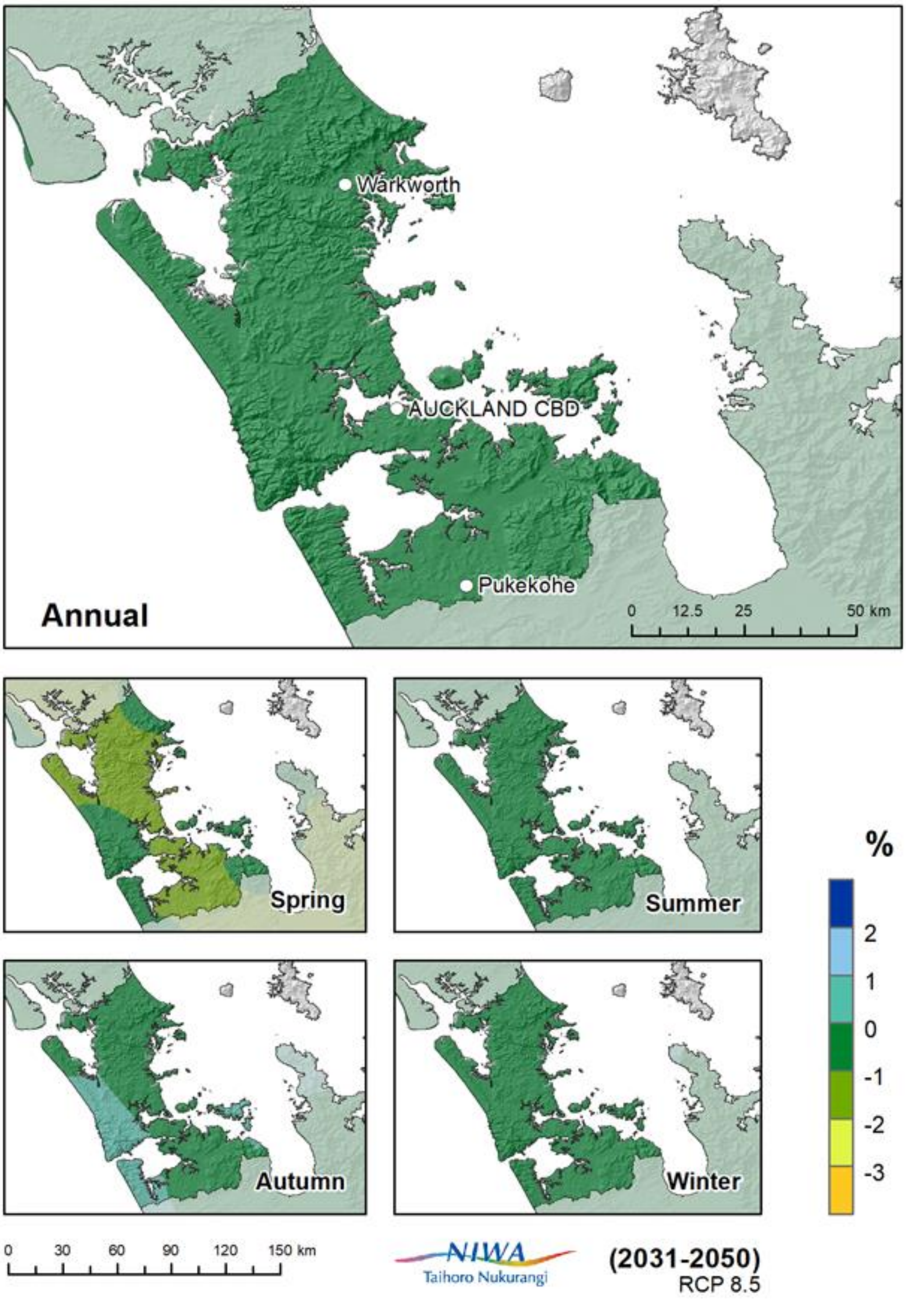

Figure 7-8: Projected change in annual and seasonal relative humidity (change in relative humidity, which is measured in %) at 2040 (2031-2050) for RCP8.5, for the Auckland Region. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

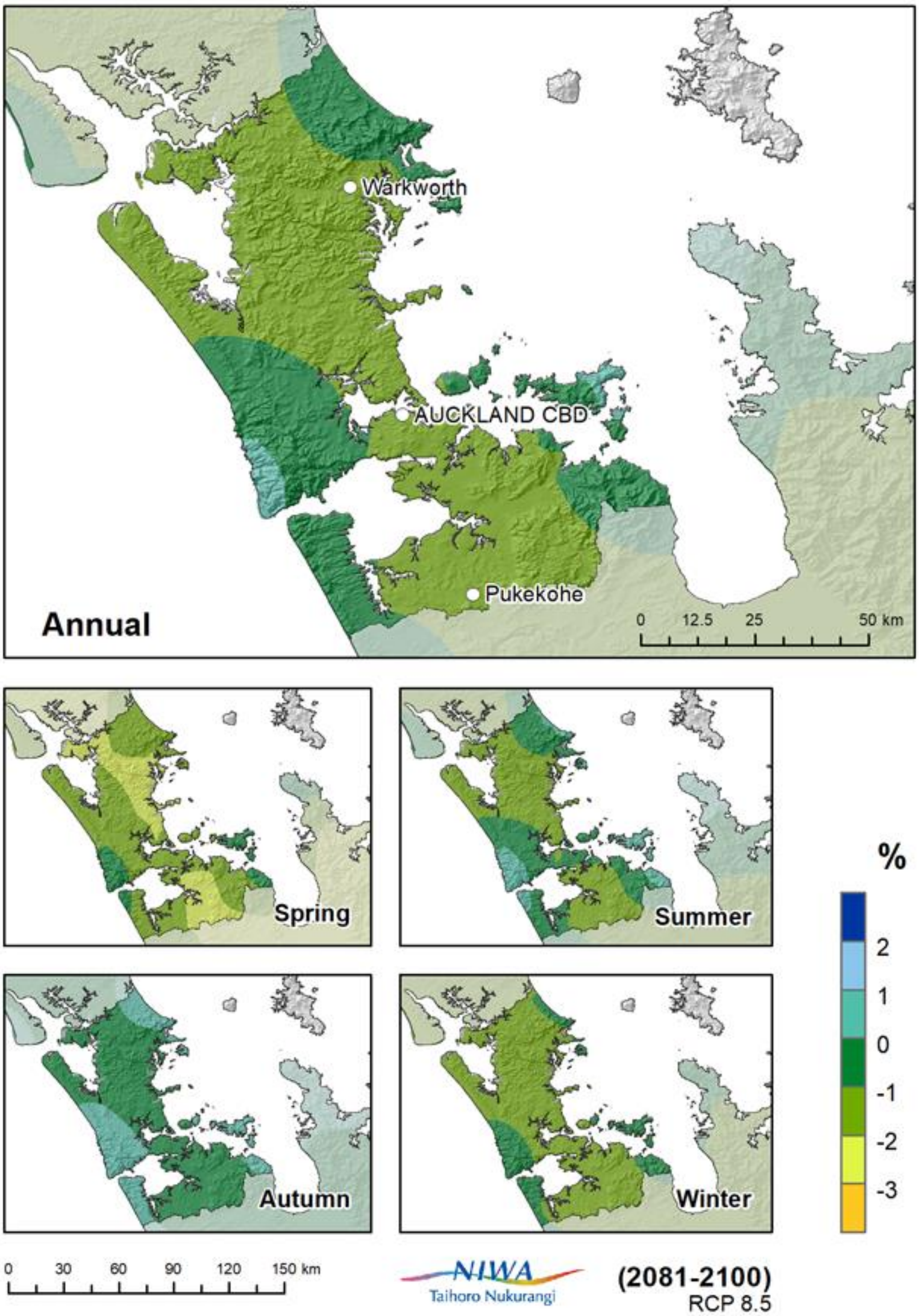

Figure 7-9: Projected change in annual and seasonal relative humidity (change in relative humidity, which is measured in %) at 2090 (2081-2100) for RCP8.5, for the Auckland Region. Projected change is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

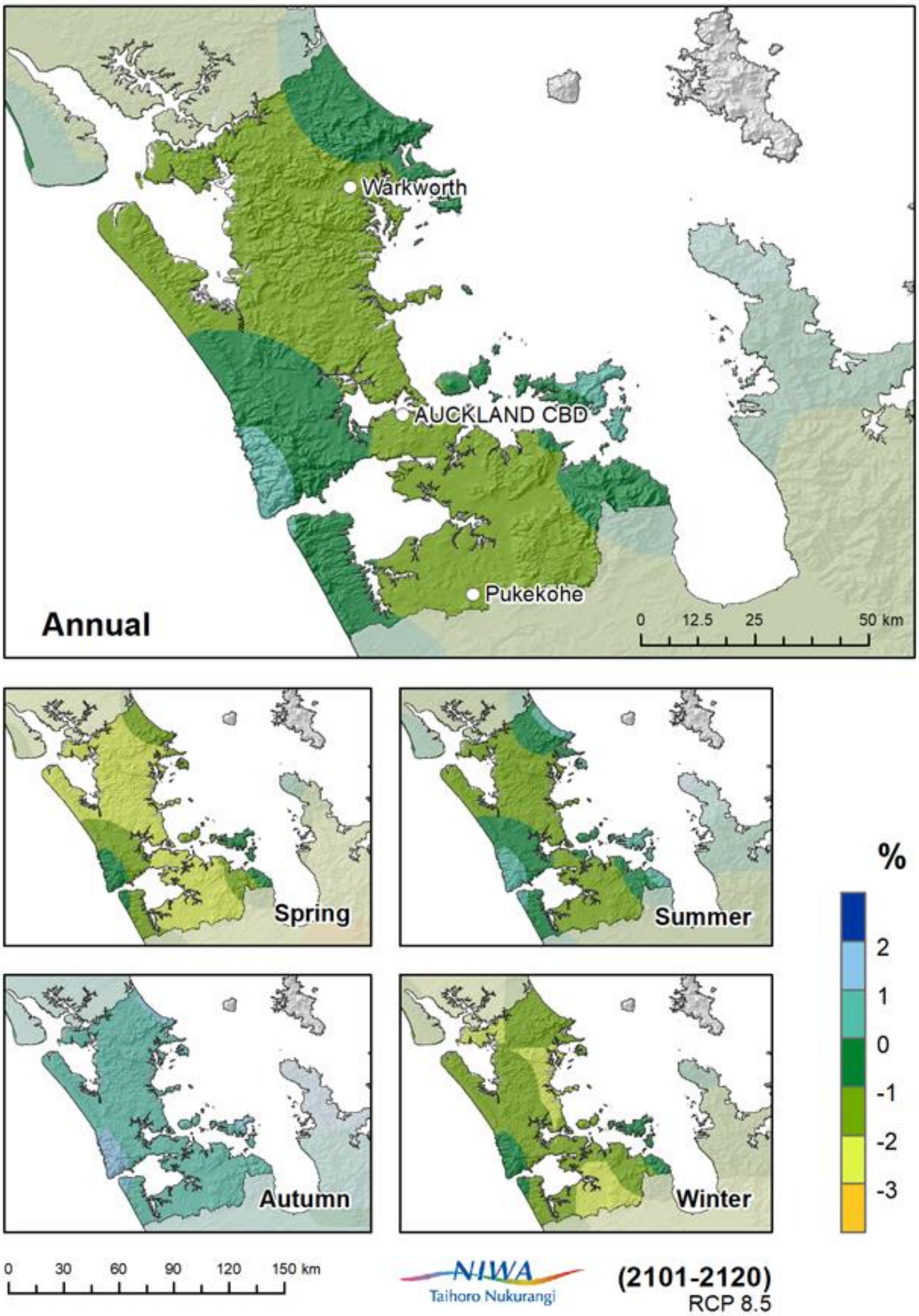

Figure 7-10: Projected change in annual and seasonal relative humidity (change in relative humidity, which is measured in %) at 2090 (2081-2100) for RCP8.5, for the Auckland Region. Projected is relative to 1986-2005. Results are based on dynamical downscaled projections and show the average of six global climate models. Resolution of projection is 5km x 5km.

8 Impacts and implications for climate change in Auckland

This section considers impacts and implications of climate change on different sectors and environments in the Auckland Region. At Auckland Council's request, we have compiled information on climate change impacts for river flows, hydrologic drought, groundwater recharge, slips and landslides, ocean temperatures, ocean acidification, nutrients, and salinity, sea level rise and coastal hazards, air quality, wildfire, biodiversity, and biosecurity.

8.1 Hydrologic impacts of climate change

Key messages

- Changes to Auckland's rainfall patterns will have an impact on the region's hydrology.
- Projections of mean discharge are variable across the region, but decreases in mean discharge are generally larger with time and RCP forcing, particularly in the northern Auckland Region. The expected mean discharge changes are consistent with projected rainfall decreases in the northern Auckland Region.
- Mean annual low flow is projected to decrease across the whole Auckland Region under both time slices and scenarios, with increasing severity under RCP8.5 at end-century.
- Mean annual flood (MAF) is projected to decrease for most of the region under RCP4.5 at both time slices. For RCP8.5, MAF is projected to increase for the whole region at late-century by up to 40-60%. These projections are consistent with increases in extreme rainfall. However, there is high uncertainty in flood projections.
- Mean seasonal soil moisture is projected to change the most in spring and summer, with both seasons projecting reductions up to 16% under RCP8.5 at end-century, and summer projecting up to 16% decrease in mean soil moisture under RCP4.5 at mid-century. These projections are consistent with spring and summer rainfall reductions and increases in PED.
- Hydrologic drought conditions are projected to be more frequent and severe in Auckland, particularly under RCP8.5. The timing of low river flows and dry soil conditions is projected to happen earlier in the hydrologic year (1 July-30 June). An increase in hydrologic drought severity and frequency is consistent with projected increases in annual PED and rainfall decreases in spring.
- Groundwater recharge may decline due to projected reductions in soil moisture and mean annual low flow, and increases in potential evapotranspiration deficit. Coastal aquifers may also be affected by sea-level rise in terms of flow velocities and salinity.
- Projected increases to extreme rainfall may increase the occurrence of slips and landslides in Auckland. The soft cliffs on Auckland's east coast have may be prone to erosion, and the intensive agricultural area around Pukekohe and urban subdivisions in Auckland have been identified as hotspots for sheet erosion.

Freshwater is important to a wide range of ecosystem goods and services of value to the Auckland Region and New Zealand. As a whole, irrigation is consented to abstract (draw upon) 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)[7]. While these freshwater issues pose challenges today, climate change and shifts in the hydrologic cycle are likely to exacerbate such impacts in the future (Collins et al., 2012, IPCC, 2014a).

Previous climate change hydrologic assessments based on the IPCC Fourth Assessment Report (IPCC, 2007) estimated that projected future 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).

Projections are presented (using the median hydrological results of the six separate RCM runs for RCP4.5 and RCP8.5) using the New Zealand TopNet hydrological model (McMillan et al., 2013, Clark et al., 2008, Bandaragoda et al., 2004) for the Auckland Region. Result for changes to the mean discharge, the mean annual low flow, the mean annual flood, mean seasonal soil moisture and several statistics related to hydrologic drought are shown. 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'). Projections for the 2110 time slice were not available for inclusion in this report. Note that the modelled river flows do not consider other climate-induced hazards such as sea level rise and storm surge.

This section includes information extracted from work 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 (Collins and Zammit, 2017). In general, the hydrologic projections presented in this section are consistent with projections in rainfall discussed in Section 4.

8.1.1 Mean discharge

Median changes of the six RCM model runs in mean discharge are presented in Figure 8-1. Mean discharge exhibits a sub-regional patchwork of increases and decreases, depending on the RCP and projection period. For RCP4.5, most of the Auckland Region is projected to experience small increases in mean discharge at 2040. The northeast of the region is projected to experience a decrease in mean discharge. By 2090 under RCP4.5, most of the Auckland Region is projected to experience decreases in mean discharge, except for the Waitakere Ranges, the Hunua Ranges and the Hauraki Gulf islands which are projected to experience a small increase in mean discharge. The remainder of the region projects no change in mean discharge.

The projections for 2040 under RCP8.5 are similar to RCP4.5, but a larger area is projected to experience a small decrease in mean discharge and covers most of the northern Auckland Region. The remainder of the region is projected to experience a small increase in mean discharge. By 2090 under RCP8.5, more of the northern part of the region projects decreases in mean discharge, and the southern and western part of the region projects a small increase in mean discharge. These

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

projections are consistent with rainfall projections, in that rainfall is projected to decline in the northern part of the region, particularly in spring, and increase in the southern part of the region, particularly in autumn.

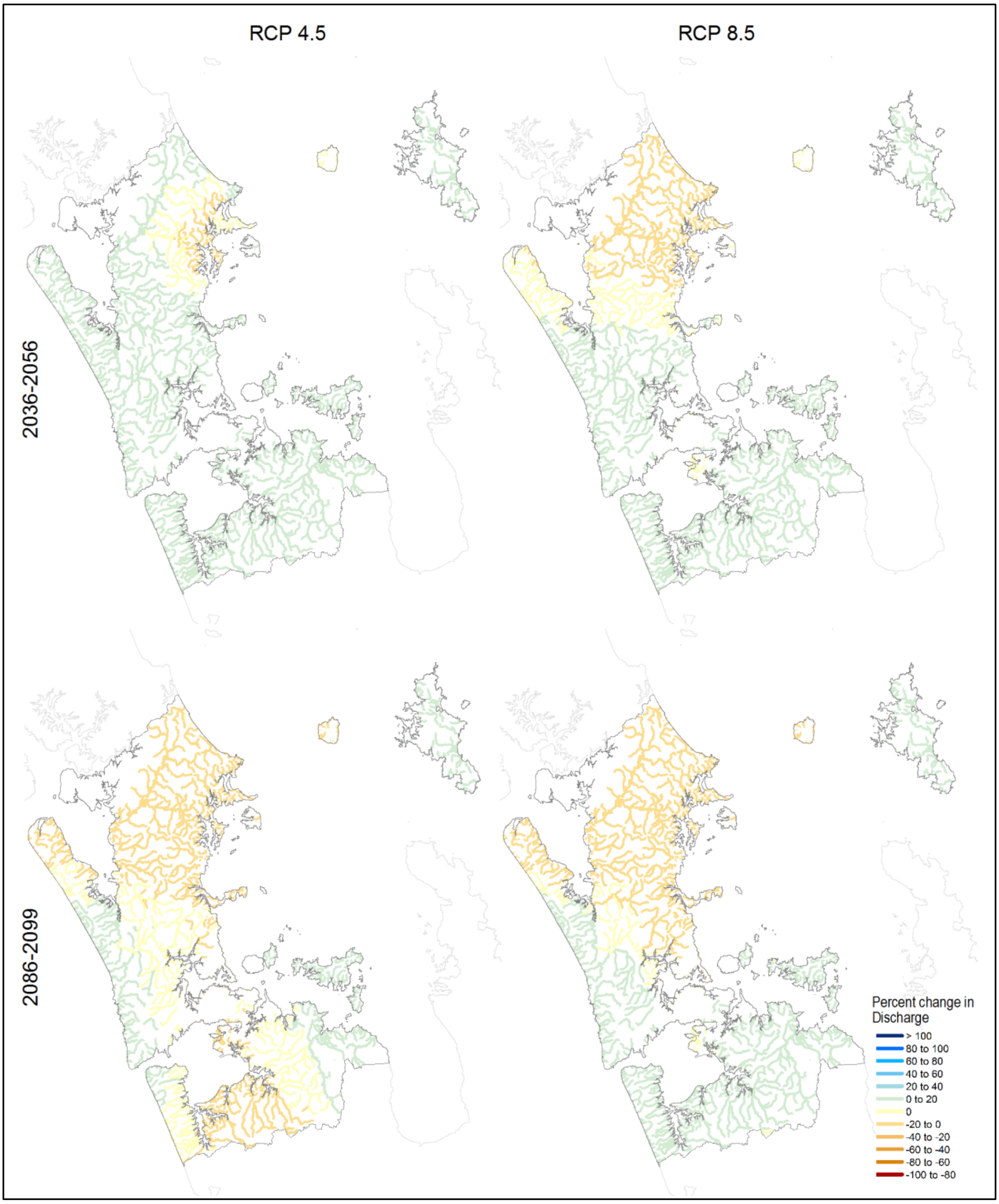

Figure 8-1: Multi-model median changes in mean discharge (%) for RCP4.5 and RCP8.5, for mid- and end-century. Projected change in discharge is relative to 1986-2005. Results are the median of projections based on hydrological modelling based on dynamical downscaled projections using NIWA's Regional Climate Model, drawing from six global climate models. Resolution of projection is Strahler order 3 river reach. © NIWA.

8.1.2 Mean annual low flow (MALF)

MALF is defined as the mean of the lowest seven-day average flows in each year of a projection period. Median changes in the MALF are presented in Figure 8-2. 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 Auckland Region, with some small exceptions in the southwest of the region and the isthmus which show small increases in MALF at 2040 under RCP8.5. These projections are consistent with projected decreases in spring rainfall and increases in potential evapotranspiration deficit.

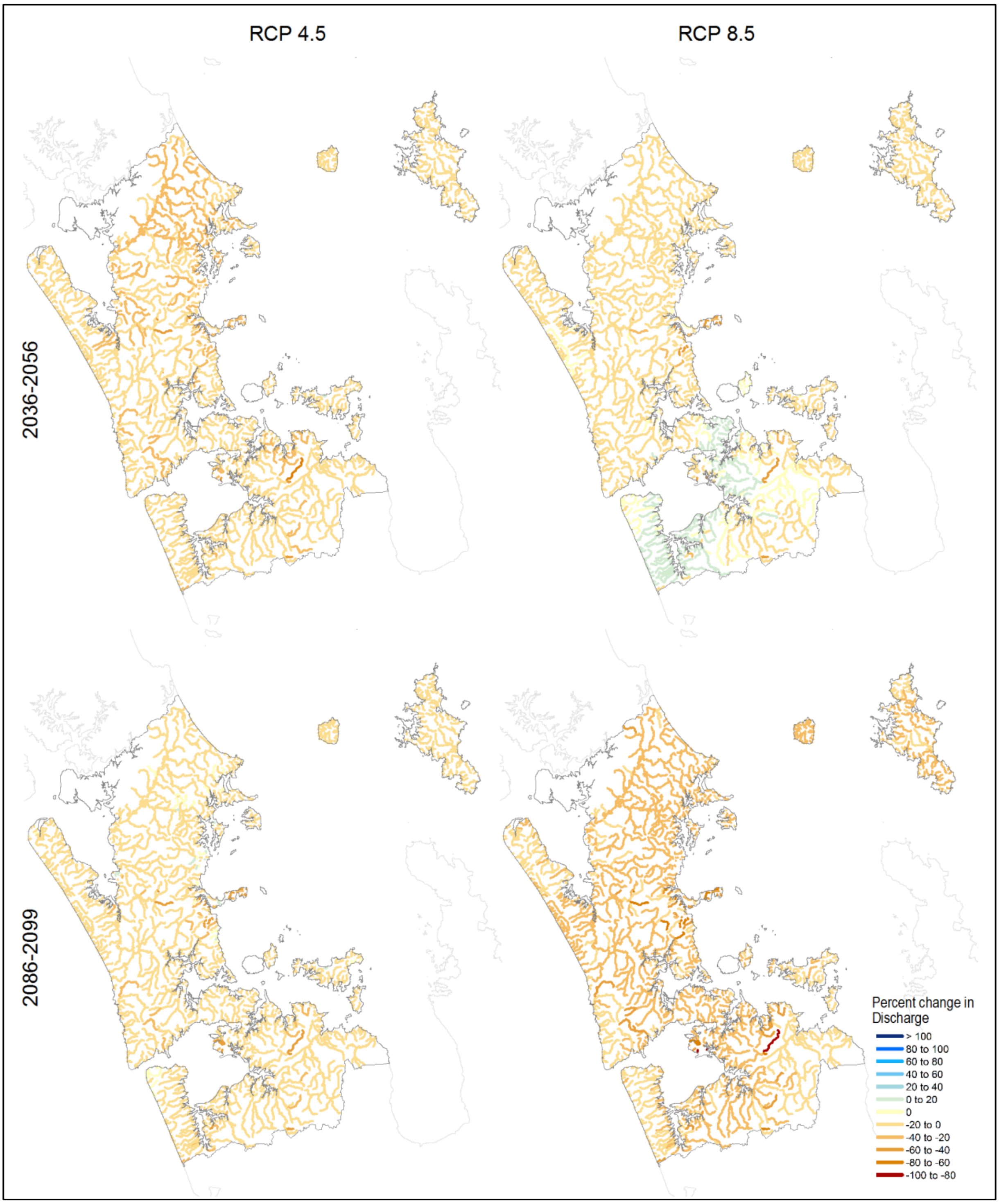

Figure 8-2: Multi-model median changes in mean annual low flow, MALF (%) for RCP4.5 and RCP8.5, for mid- and end-century. Projected change in low flow is relative to 1986-2005. Results are the median of projections based on hydrological modelling based on dynamical downscaled projections using NIWA's Regional Climate Model, drawing from six global climate models. Resolution of projection is Strahler order 3 river reach. © NIWA.

8.1.3 Mean annual flood (MAF)

MAF is the average of the maximum flood discharges experienced in a river over a time slice, which should have a recurrence interval of once every 2.33 years. Note that mean annual flood is a relatively low threshold for engineering purposes. Upcoming projects at NIWA will focus on projections for more extreme, rare flood events.

Median changes in MAF are presented in Figure 8-3. Under RCP4.5, most of the region projects decreases in mean annual flood at 2040. At 2090 for RCP4.5, about half the region projects decreases in MAF and half the region projects increases. Under RCP8.5 at 2040, northern Auckland is projected to experience small decreases in MAF, and the central and southern part of the region is projected to experience increases in MAF. The largest increases are projected for the Waitakere Ranges and the far south of the region. By 2090 under RCP8.5, the entire Auckland Region is projected to experience increases in MAF, with some areas projecting a 40-60% increase in MAF. Increases in MAF are consistent with projected increases to extreme rainfall.

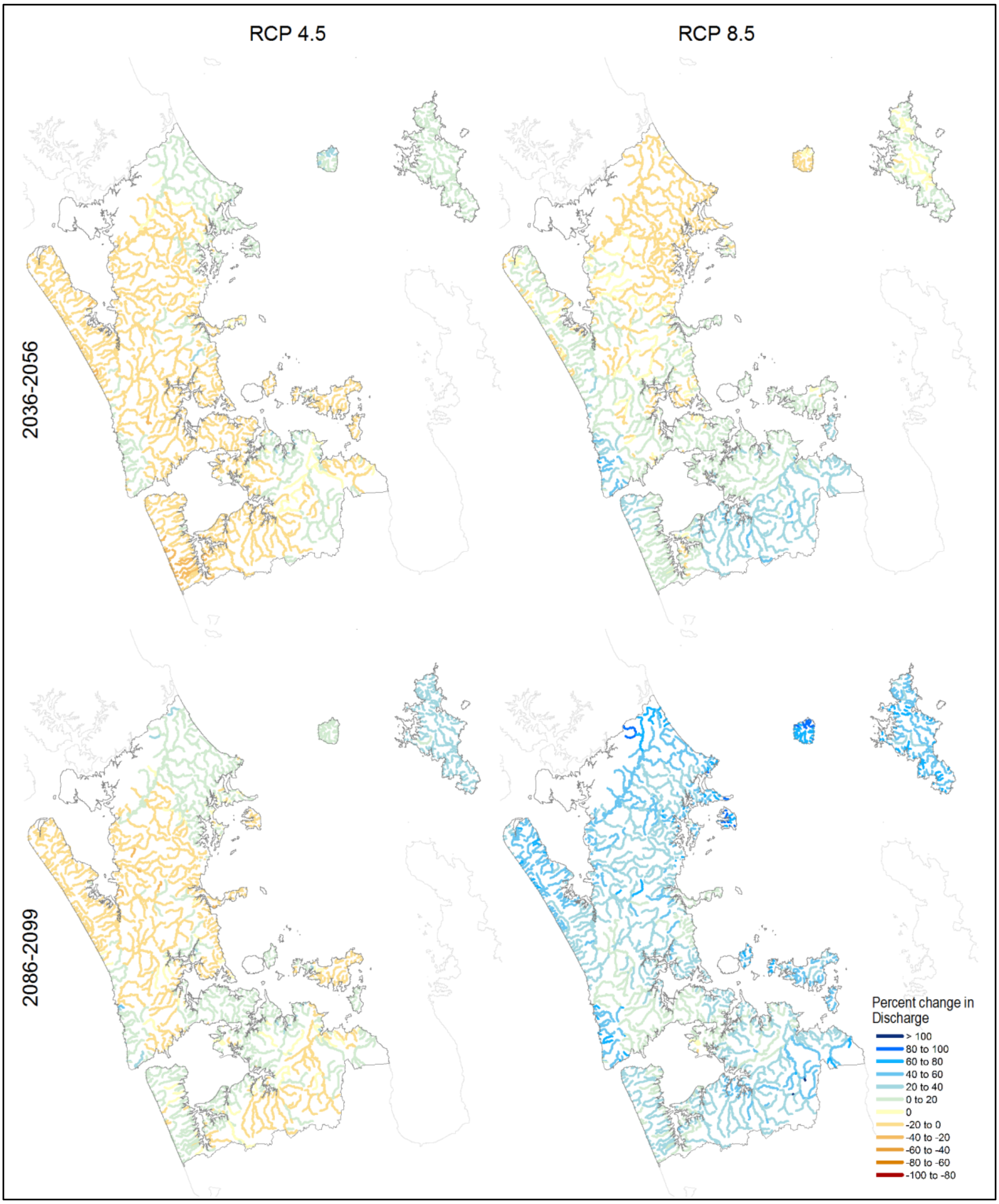

Figure 8-3: Multi-model median changes in mean annual flood, MAF (%) for RCP4.5 and RCP8.5, for mid- and end-century. Projected change in mean annual flood is relative to 1986-2005. Results are the median of projections based on hydrological modelling based on dynamical downscaled projections using NIWA's Regional Climate Model, drawing from six global climate models. Resolution of projection is Strahler order 3 river reach. © NIWA.

8.1.4 Mean seasonal soil moisture

The seasonal projections for mean soil moisture are discussed in line with each of the seasonal figures for ease of interpretation. Mean autumn soil moisture shows little change under any averaged climate change projections, with most of the region falling within -4 to 4% change (Figure 8-4). Based on the maps, we can see more extensive coverage of soil moisture decreases under RCP 8.5, but the changes are almost all smaller than -4%.

For winter, changes in mean soil moisture are also very small, again largely falling within -4 to 4% (Figure 8-5). There is no compelling difference between the RCPs, but there is a tendency for the slight decreases in moisture levels to be more extensive late-century.

In contrast with autumn and winter, mean spring soil moisture shows more pronounced effects of climate change (Figure 8-6). While there is little change and not a consistent direction of change for RCP4.5 mid-century, late-century RCP4.5 and mid-century RCP8.5 both show changes in soil moisture from 0 to -12%. It worth noting that the changes by late-century under the mid-range RCP4.5 are similar to changes mid-century under the business as usual RCP8.5. For RCP8.5 late-century, the climate change-related drying continues, leaving some parts of the region up to 16% drier when compared with the baseline results.

Mean summer soil moisture changes show the most prominent results of all the seasons (Figure 8-7). Looking at late-century RCP8.5, substantial and widespread reductions in soil moisture exceed 16% in some places. These are the largest changes seen for any season, time slice, and RCP. Late-century RCP4.5 also tends to produce drier soils, but mostly within 0-8% decrease in soil moisture compared to the historical period. Mid-century RCP8.5, on the other hand, shows very little change, with most locations falling within -4 to +4% difference from the baseline period. For the mid-century RCP4.5, universal coverage of soil moisture decreases almost to the magnitude of what is observed for late-century RCP8.5. While all other maps for every season show intuitive progressions of change under climate change, this result stands out as an apparent anomaly. The likely cause of this can be seen in the climate projections: summer rainfall projections for mid-century RCP4.5 (Figure 4-4) are drier than late-century RCP4.5 (Figure 4-5). This highlights the importance of not always assuming linear or even consistent effects of climate change as we look further ahead in time or across different RCPs.

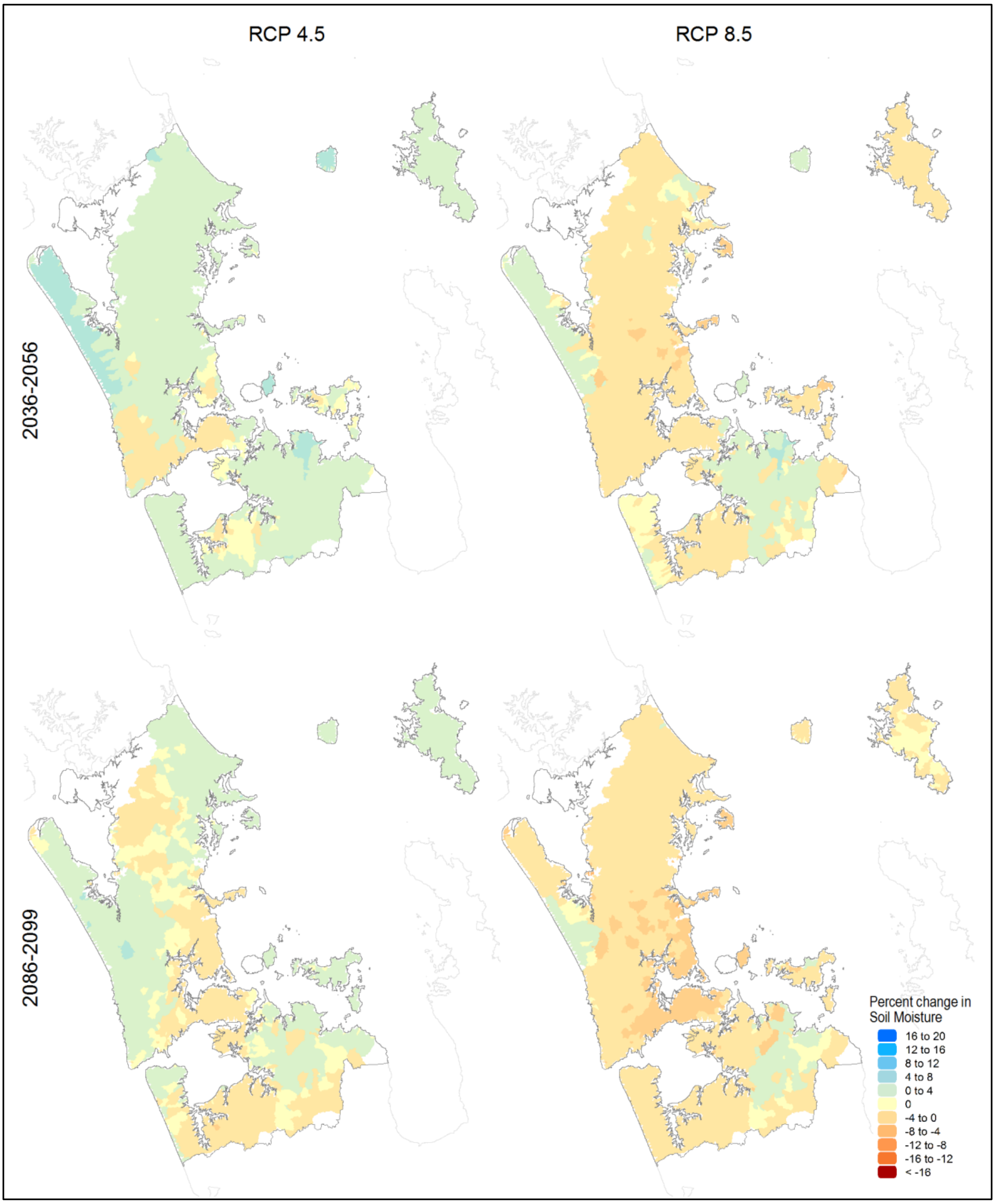

Figure 8-4: Multi-model median changes in mean autumn soil moisture (%) for RCP4.5 and RCP8.5, for mid- and end-century. Projected change in soil moisture is relative to 1986-2005. Results are the median of projections based on hydrological modelling based on dynamical downscaled projections using NIWA's Regional Climate Model, drawing from six global climate models. Resolution of projection is the area associated with the Strahler order 3 river reach. © NIWA.

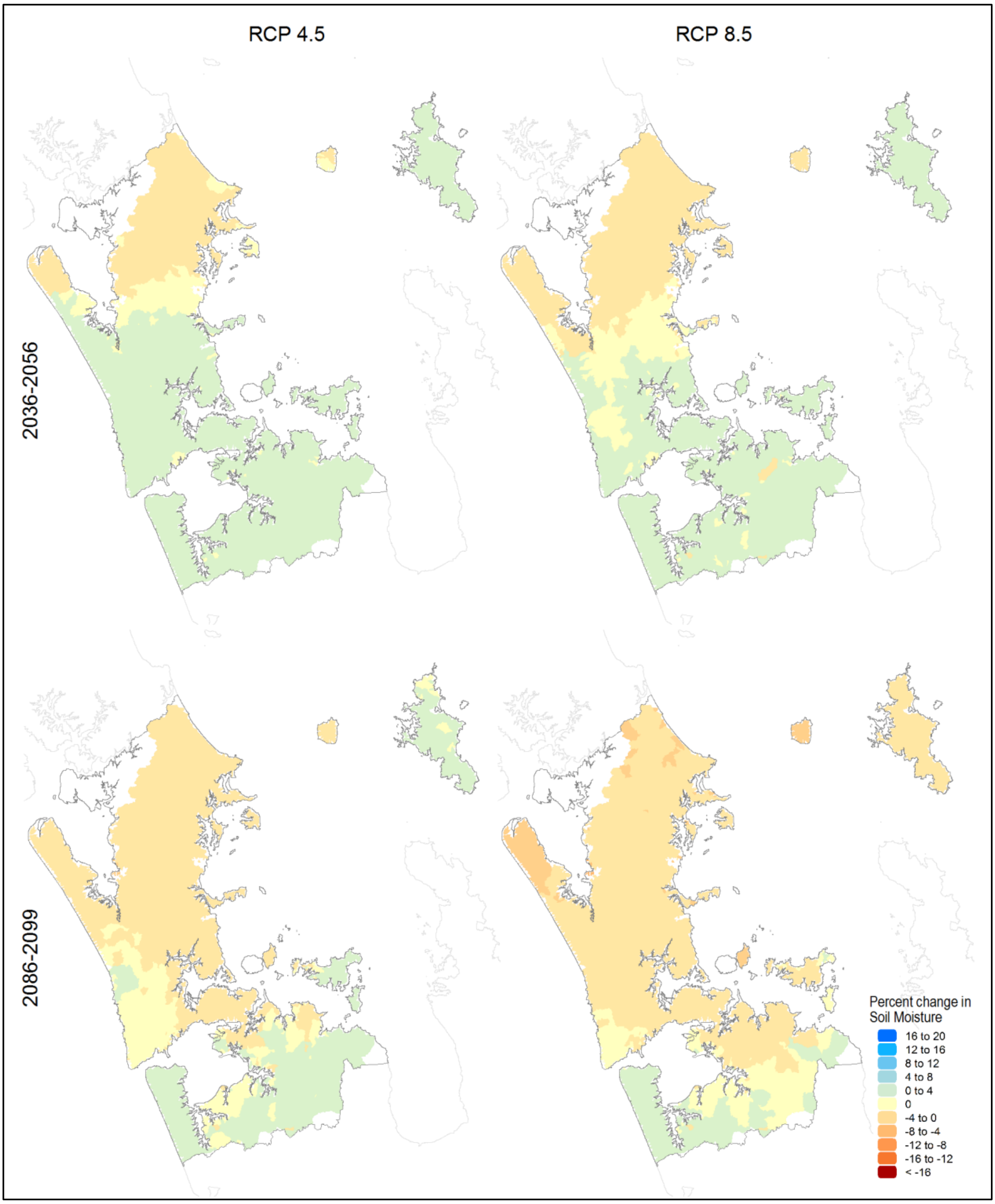

Figure 8-5: Multi-model median changes in mean winter soil moisture (%) for RCP4.5 and RCP8.5, for mid- and end-century. Projected change in soil moisture is relative to 1986-2005. Results are the median of projections based on hydrological modelling based on dynamical downscaled projections using NIWA's Regional Climate Model, drawing from six global climate models. Resolution of projection is the area associated with the Strahler order 3 river reach. © NIWA.

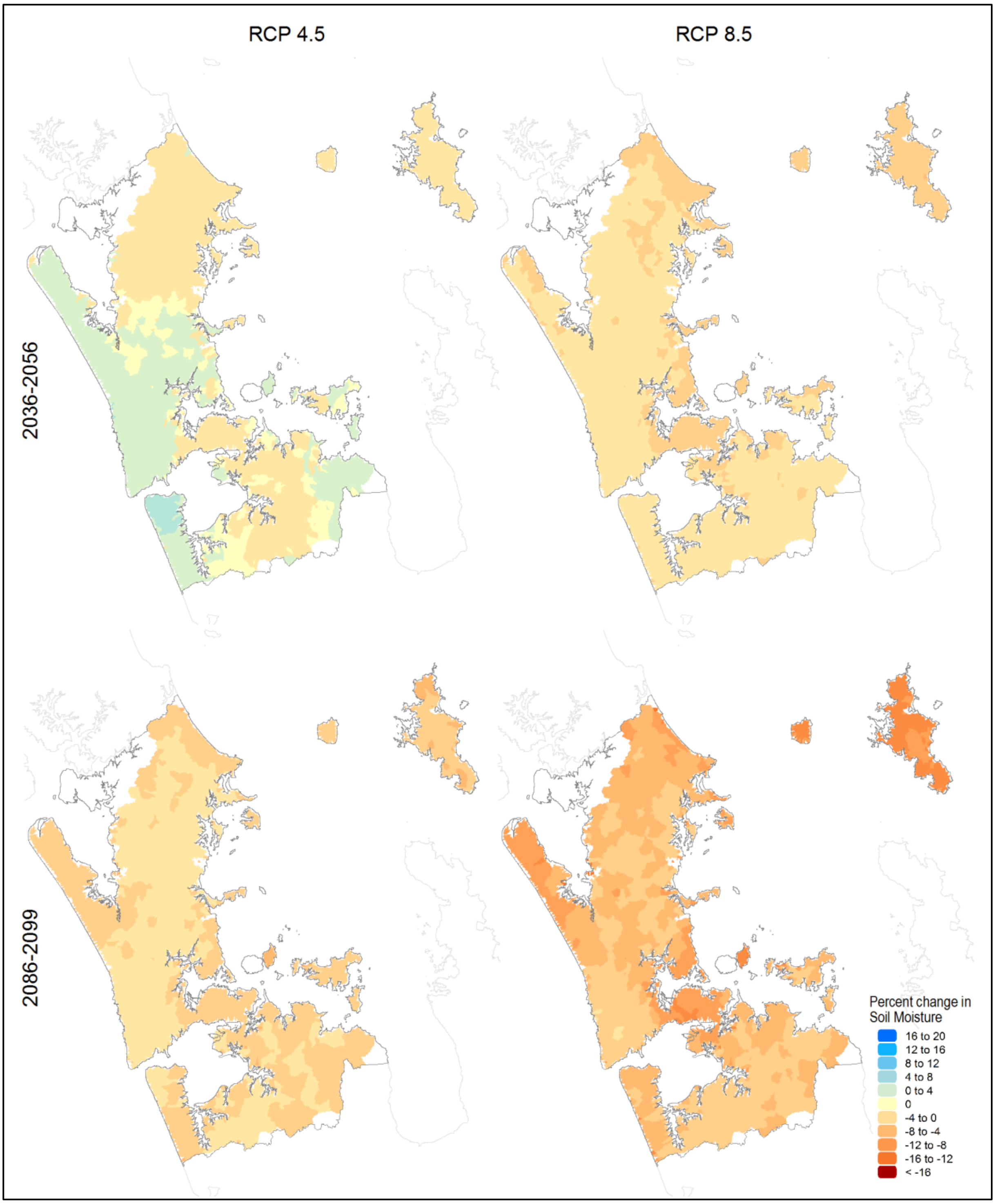

Figure 8-6: Multi-model median changes in mean spring soil moisture (%) for RCP4.5 and RCP8.5, for mid- and end-century. Projected change in soil moisture is relative to 1986-2005. Results are the median of projections based on hydrological modelling based on dynamical downscaled projections using NIWA's Regional Climate Model, drawing from six global climate models. Resolution of projection is the area associated with the Strahler order 3 river reach. © NIWA.

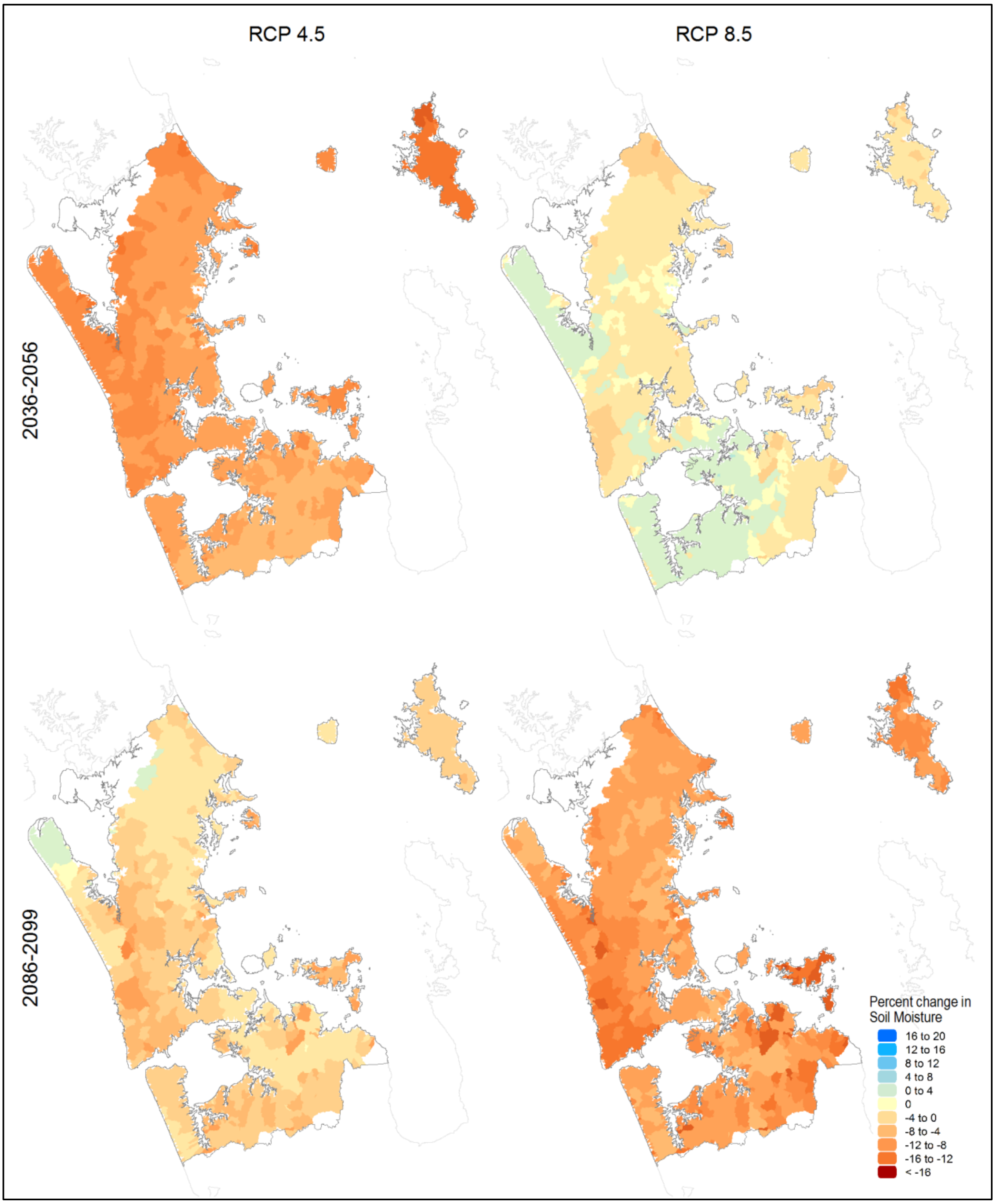

Figure 8-7: Multi-model median changes in mean summer soil moisture (%) for RCP4.5 and RCP8.5, for mid- and end-century. Projected change in soil moisture is relative to 1986-2005. Results are the median of projections based on hydrological modelling based on dynamical downscaled projections using NIWA's Regional Climate Model, drawing from six global climate models. Resolution of projection is the area associated with the Strahler order 3 river reach. © NIWA.

8.1.5 Hydrologic drought

In contrast with meteorological drought (Section 4.8), which focuses on rainfall and evaporation deficits, hydrologic drought relates to deficits in soil moisture stores, river flows, or other land-based liquid water stores and fluxes (Figure 8-8). Modelled statistics that can be used to shed light on hydrological drought conditions under climate change include mean annual seven-day low flow (MALF) and mean seasonal soil moisture that are discussed above. In addition, flow reliability, the timing of low flow conditions, soil moisture reliability, and the timing of dry soil conditions can also be used. Low flow timing is the mean number of days into the water year (i.e. after July 1, until June 30 the following year) before stream discharge first drops to a minimum flow threshold related to water abstraction (removal from the source). This threshold is based on the Proposed National Environmental Standard for Ecological Flows[8]. Flow reliability is the fraction of time the river flow is above this threshold, and reflects the frequency of drought conditions. The timing of dry conditions in this situation refers to the first day during the year the dry condition is reached. The dry condition threshold is designated as above wilting point by 25% of the difference between wilting point and field capacity. This is an indication of how quickly water deficits or droughts are reached after winter. Soil moisture reliability is the fraction of time that unirrigated soil moisture is at or above the soil moisture threshold used for the low soil moisture timing. This is a measure of time spent under water-short or drought conditions.

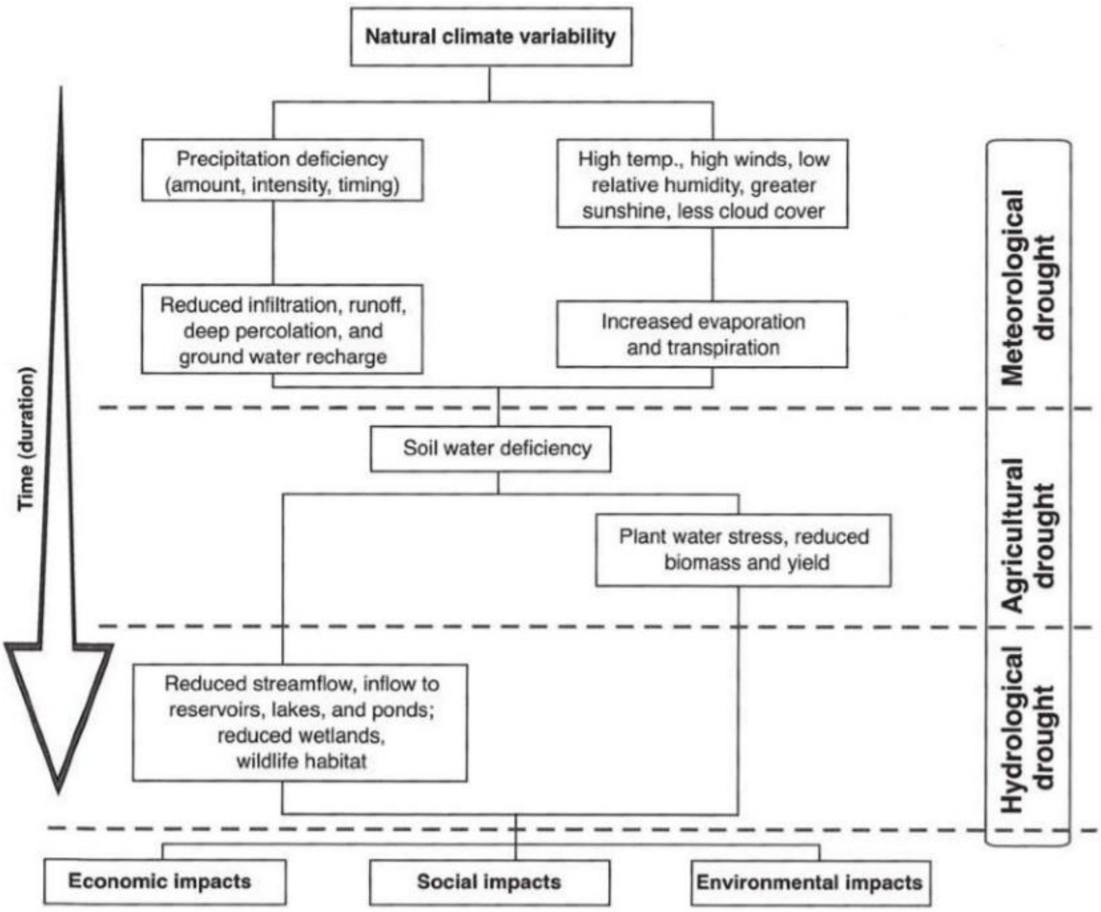

Figure 8-8: Relationship between various types of drought and duration of drought events. From Wilhite (2000).

[8] http://www.mfe.govt.nz/publications/rma-fresh-water/proposed-national-environmental-standard-ecological-flows-and-water

For the Auckland Region, flow reliability is generally projected to decline, particularly for RCP8.5 late-century where an additional 2-4% of the time is spent under low flow conditions (Figure 8-9). The patterns of change for this scenario largely resemble those for MALF (Figure 8-2). Low flow conditions are generally reached earlier in the year for RCP8.5, particularly towards the end of the century with many rivers reaching the low flow threshold over 40 days earlier than at present (Figure 8-10). This pattern of the low flow threshold being reached earlier in the year is also true for RCP4.5 mid-century, but directions of change are very mixed late-century.

Changes in soil moisture reliability (Figure 8-11) are more mixed and less severe than for flow reliability, with both RCPs and time points showing both increases and decreases. Late-century RCP8.5 is projected to have the largest and most extensive declines, with many watersheds experiencing an additional 2-4% of time in dry conditions. These results are consistent with the projections of annual PED related to meteorological drought (Section 4.8). Dry soil conditions are projected to be reached around the same time or earlier in the year (Figure 8-12), generally up to 20 days earlier, although the dependence of this result for future time slices and RCPs is not as pronounced as for the other hydrological variables. Taken together, these river flow and soil moisture projections suggest drought conditions will become more frequent under climate change, particularly for RCP8.5.

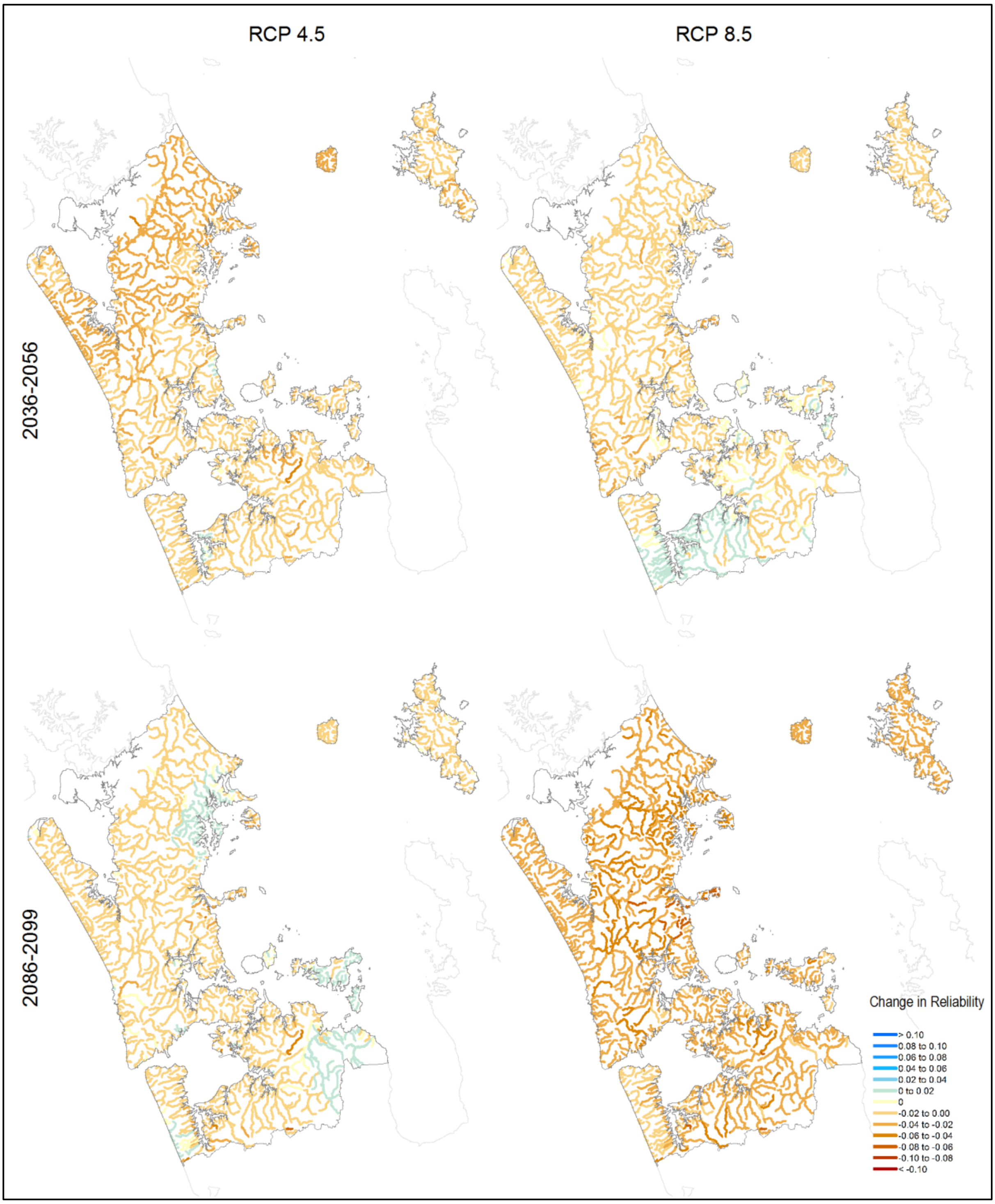

Figure 8-9: Projected change in river flow reliability (fraction of time flows are above a low flow threshold) for the Auckland Region, for RCP4.5 and RCP8.5, at mid-century and end-century. Projected change in flow reliability is relative to 1986-2005. Results are the median of projections based on hydrological modelling based on dynamical downscaled projections using NIWA's Regional Climate Model, drawing from six global climate models. Resolution of projection is Strahler order 3 river reach. © NIWA.

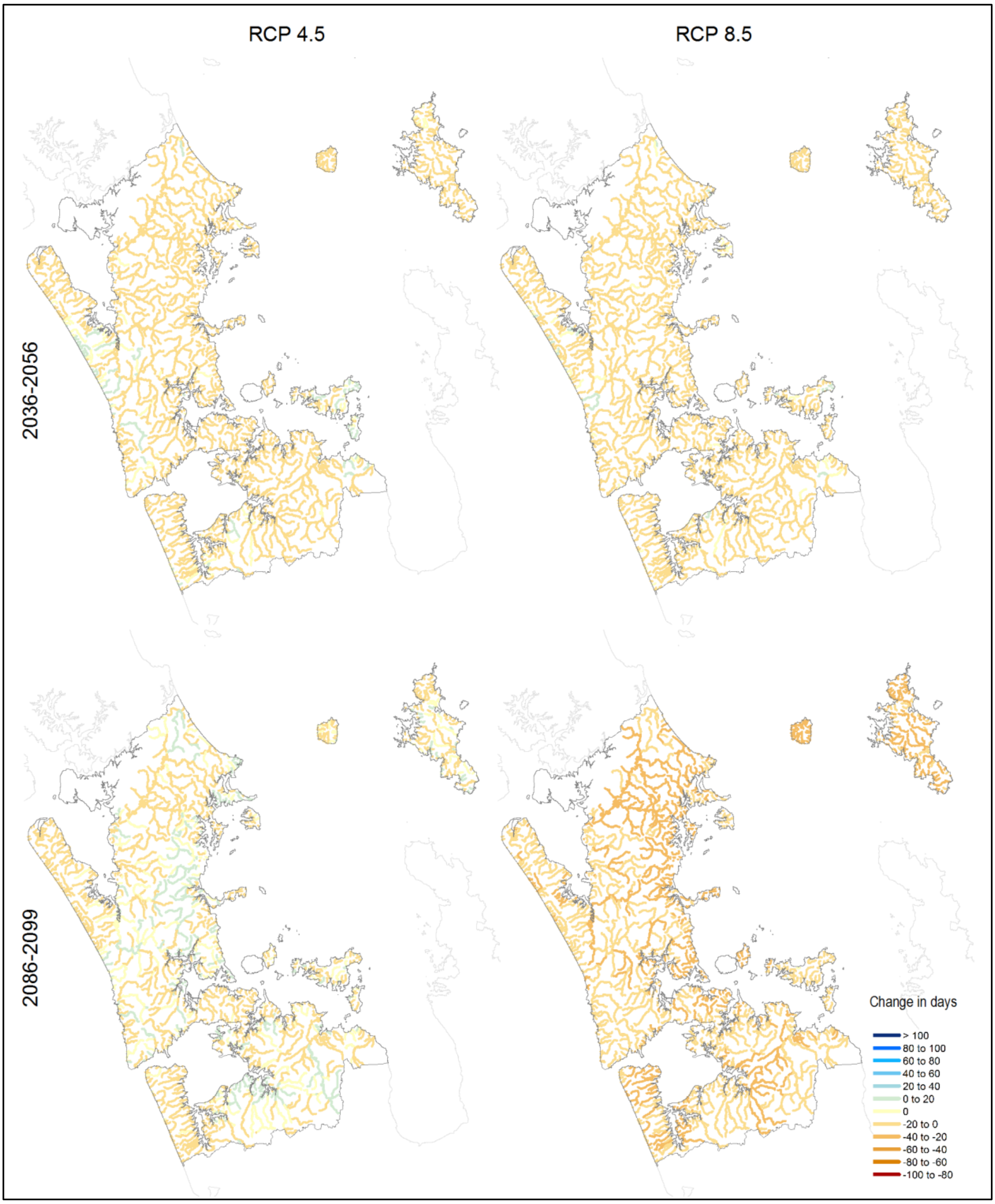

Figure 8-10: Projected change in timing of the onset of low flow conditions for the Auckland Region, for RCP4.5 and RCP8.5, at mid-century and end-century. Projected change in timing is relative to 1986-2005. Results are the median of projections based on hydrological modelling based on dynamical downscaled projections using NIWA's Regional Climate Model, drawing from six global climate models. Resolution of projection is Strahler order 3 river reach. © NIWA.

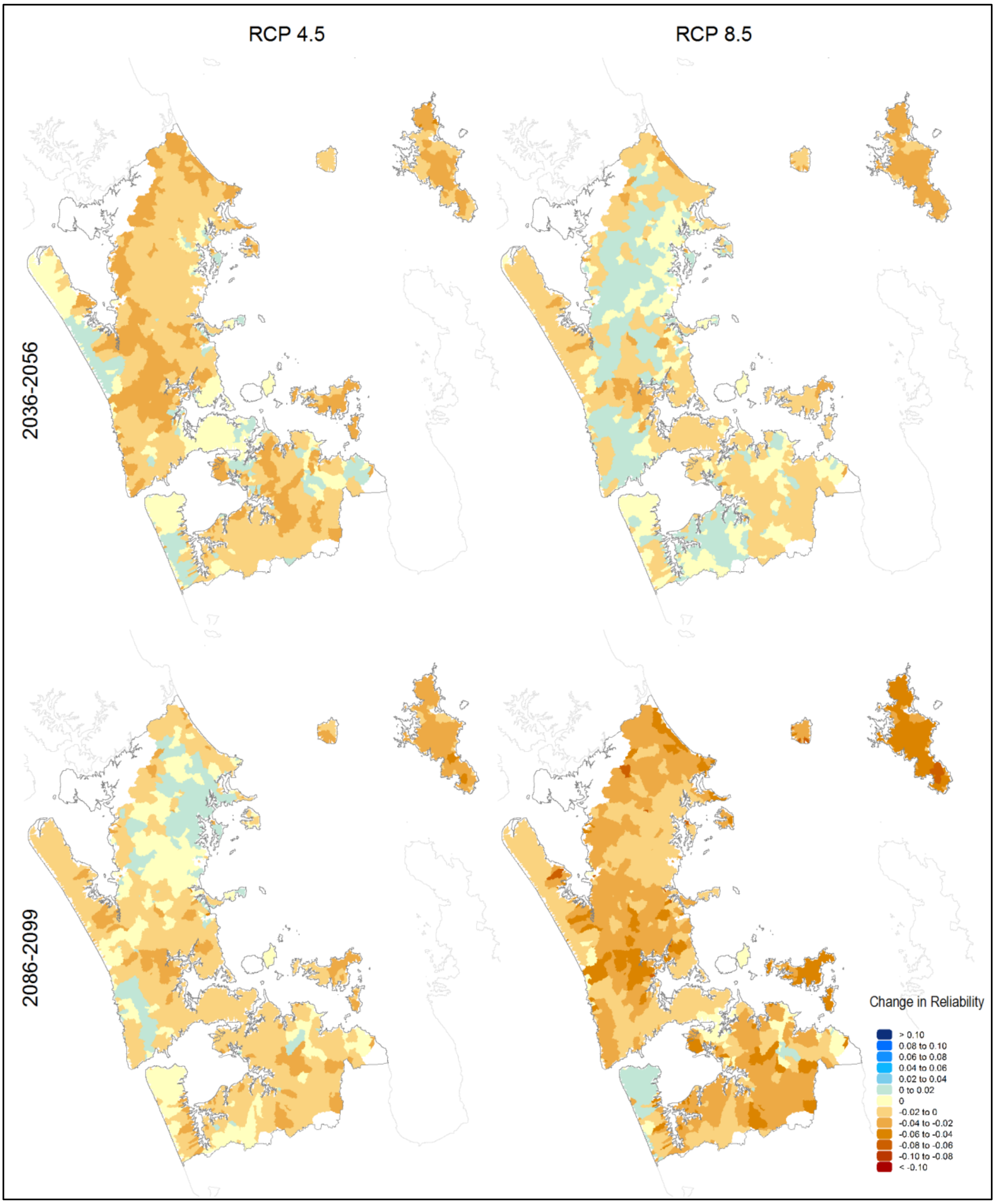

Figure 8-11: Projected change in soil moisture reliability (fraction of time soil moisture is above a low threshold) for the Auckland Region, for RCP4.5 and RCP8.5. Projected change in reliability is relative to 1986-2005. Results are the median of projections based on hydrological modelling based on dynamical downscaled projections using NIWA's Regional Climate Model, drawing from six global climate models. Resolution of projection is Strahler order 3 river sub-catchments. © NIWA.

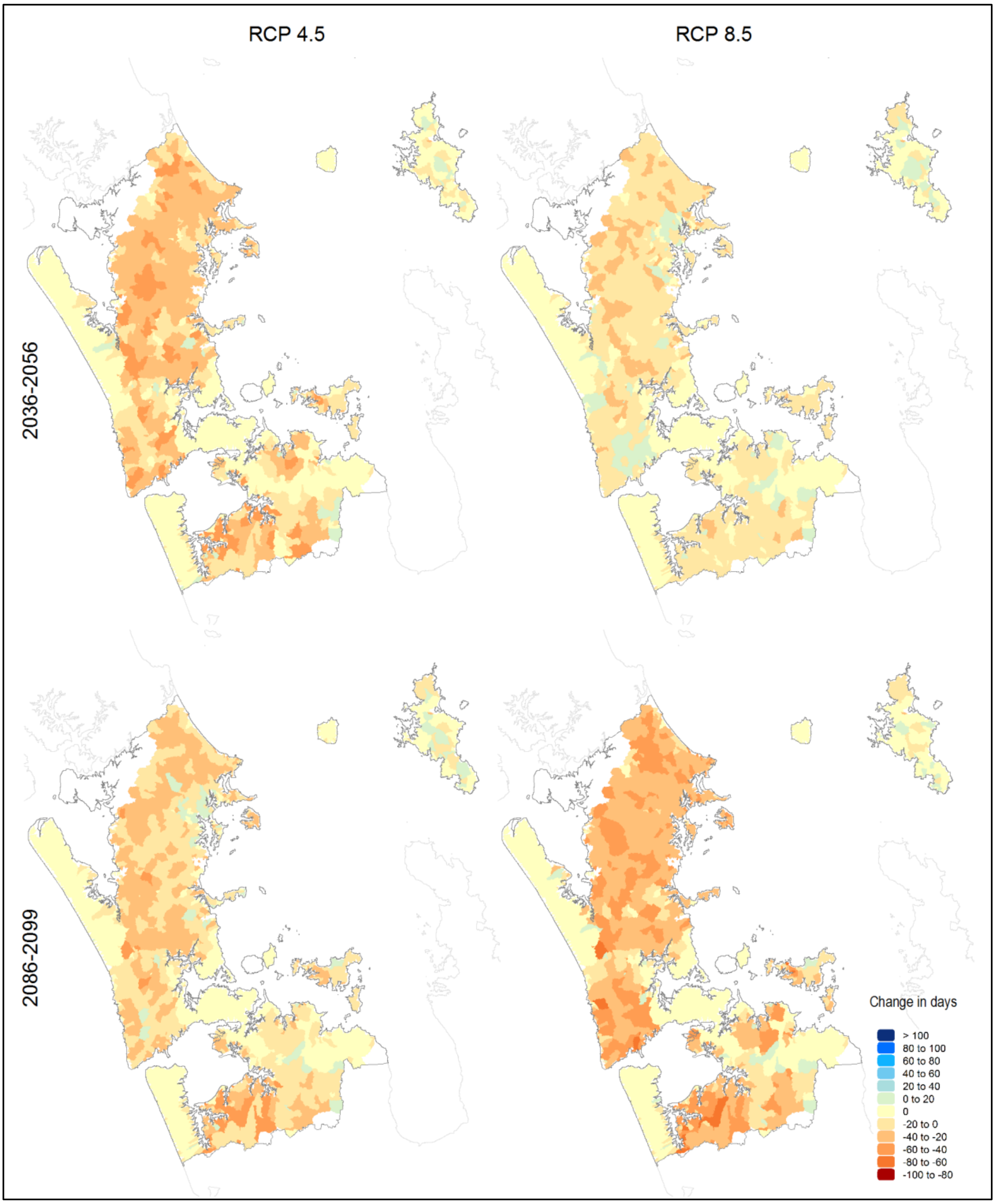

Figure 8-12: Projected change in low soil moisture timing for the Auckland Region, for RCP4.5 and RCP8.5, at mid-century and end-century. Projected change in timing is relative to 1986-2005. Results are the median of projections based on hydrological modelling based on dynamical downscaled projections using NIWA's Regional Climate Model, drawing from six global climate models. Resolution of projection is Strahler order 3 river sub-catchments. © NIWA.

8.1.6 Groundwater

The effects of climate change on Auckland's aquifers and groundwater resource have not been modelled, however basic inferences may be drawn from the river and soil moisture results discussed in Sections 8.1.1 to 8.1.5.

Groundwater recharge essentially occurs when the ground is near saturation - specifically, above field capacity in terms of soil properties - but recharge may also occur beneath rivers or through fractured rock (Taylor et al., 2012b). Increases are projected for potential evaporation deficit (PED) and soil moisture deficit (Section 4.8 and 4.9), and decreases are projected for mean seasonal soil moisture, particularly in spring and summer (Section 8.1.5). Therefore, it can be inferred that the soil moisture conditions necessary to allow drainage of water below the root zone and towards the underlying aquifer will become less frequent, leading to less recharge. This is further reflected in declines in the mean annual low flow, which is a strong reflection of groundwater contributions to baseflow (Taylor et al., 2012b). Figure 8-13 shows a conceptual representation of groundwater-climate interactions (however, note that the influence of snow and ice is not important for Auckland). A quantitative estimate of any reduction in recharge cannot be made without a more process-based model of the recharge process, although groundwater modelling per se would not be necessary.

For groundwater sources in proximity to the coast, groundwater levels are influenced by sea level because it sets the gradient for downhill flow. This is most relevant for the Waitemata aquifer and the Kaawa formation, both of which extend to the coast (Vilijevac et al., 2002). As the global mean sea level rises - projected to range from 0.26-0.98 m by 2100 relative to 1986-2005 conditions (IPCC, 2013b), coastal groundwater levels would need to increase to match sea level at the coast. This would not mean an increase in groundwater yield from the aquifer, however this would result in a reduction in groundwater flow velocities. How far this effect would extend from the coast could depend on aquifer properties, flow velocities, and the amount of sea-level rise. This process would also increase the potential for salinisation of coastal aquifers.

Potential future changes to land use, water supply, and irrigation in the Auckland Region, which may happen in response to climate change, may have ramifications for Auckland's groundwater sources in terms of water demand and recharge rates.

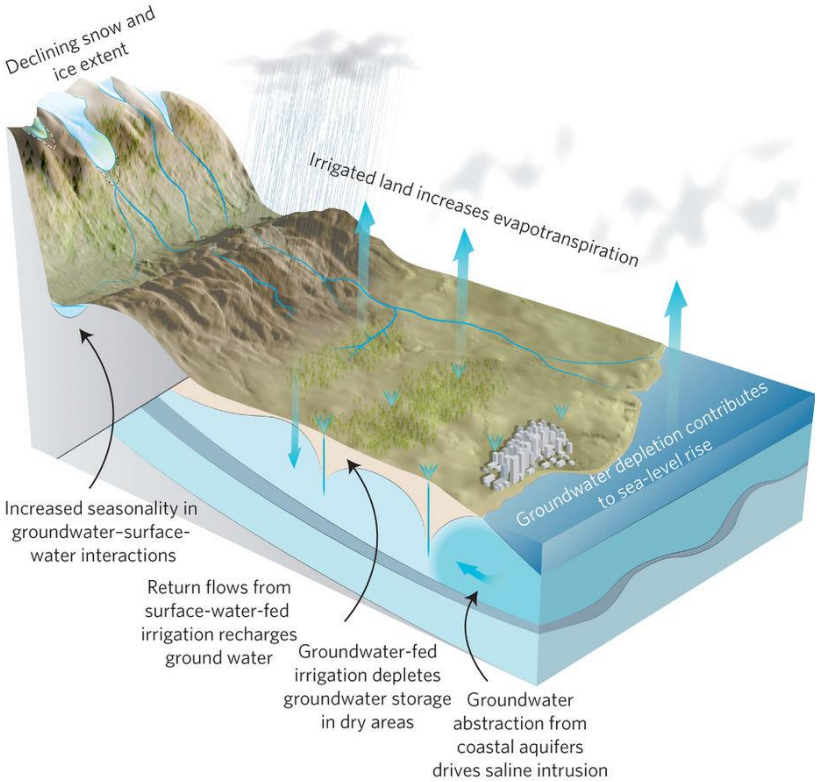

Figure 8-13: Conceptual representation of key interactions between groundwater and climate. From Taylor et al. (2012b).

8.1.7 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 in Sections 8.1.1 to 8.1.3 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 events can be very complex and is an on-going area of research investigation.

There is no direct relationship between increases in extreme rainfall 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 in New Zealand has produced results that vary significantly, depending on the climate model, scenario used and time slice considered (Collins and Zammit, 2017). 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 is that the differences in hydrological metrics between the time slices may not be attributable to climate change alone, or even predominantly for that matter. Natural multidecadal variability (e.g. IPO) also has an influence on flood magnitude (McKerchar and Henderson, 2003) and may counter or enhance climate change effects, but this element has not been analysed for this report.

Despite a lack of clear signal, the risk of significant change to flood flows is high (Section 8.1.3). On-going research and model refinement is needed to reduce this uncertainty.

8.1.8 Climate change impacts on slips and landslides

It is clear that climate change will affect the stability of natural and engineered slopes and have consequences for landslides (Gariano and Guzzetti, 2016). Less clear is the type, extent, magnitude and direction of the changes in the stability conditions, and on the location, abundance, activity and frequency of landslides in response to projected climate changes. Landslide frequency and magnitude will be affected directly by changes in rainfall regimes (that influence the amount of rainfall that can result in landslides) and indirectly by changes to rainfall regimes that may alter land cover types and land use, which have consequences for slope stability (Gariano and Guzzetti, 2016). It is uncertain how humans will impact landslides and slips in the future, with changes to land use in response to climate change and other socio-economic factors (e.g. urban spread, deforestation).

Land erosion (including landslides and slips) is a significant issue for parts of the Auckland Region, particularly those areas used for primary industries such as agriculture, horticulture and forestry. Land erosion has downstream effects including river sedimentation which can have impacts on flooding magnitude and frequency, water quality, and aquatic habitats. Major erosion events already cause and will continue to cause significant economic stress for people and businesses within the Auckland 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)
- Increases in temperature affecting plant water use and soil water balance
- Increased windiness and incidence of drought

Climate and erosion are clearly linked through water movement into and through the soil, the soil water balance, and slope hydrology. Hillslope erosion processes (e.g. shallow landslides, earthflows, gully, and sheet erosion) are likely to be influenced by future changes to extreme rainfall patterns, seasonal rainfall distribution, as well as changes to soil moisture deficits.

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 Auckland Region was identified by Basher et al. (2012) as having high potential for landslide erosion, and the intensive cropping area around Pukekohe and urban subdivisions in Auckland were identified as having high potential for sheet erosion. Section 4 shows that the Auckland Region is projected to experience increases in extreme daily rainfall, particularly in the south for 99th percentile of daily rainfall, which may exacerbate sheet erosion and landslides.

Assuming increasing CO_2 concentrations in the atmosphere throughout the 21st century, the productivity of forestry (e.g. *Pinus radiata*) and pasture is projected to increase throughout most of New Zealand (Rutledge et al., 2017). The increase in productivity may help to offset land erosion in the Auckland Region.

8.2 Oceanic changes

Key messages

- Changes to global oceans as a response to climate change will have impacts on the distribution, species composition, and health of marine life in the Auckland Region.
- Sea surface temperatures are increasing globally and a further increase of around 2.5°C is projected for the Southwest Pacific by 2100 under RCP8.5.
- Ocean pH is declining (becoming more acidic) and this is projected to continue around New Zealand. Ocean acidification will have impacts on marine food webs and ocean carbon uptake.
- The availability of some nutrients in the oceans is projected to decline by the end of the 21st century under RCP4.5 and RCP8.5. This will impact phytoplankton growth and ocean productivity. Nitrogen levels in the Firth of Thames have increased in the past, predominantly due to increased fertiliser use on land.
- Future changes to coastal salinity in Auckland will depend on changes to rainfall and runoff patterns. It is possible that increased air temperature may cause increases in evaporation and therefore slightly increased sea surface salinities in the East Auckland Current.

This section includes information extracted from a report on climate changes, impacts and implications for New Zealand's Exclusive Economic Zone (Law et al., 2016), undertaken during the CCII project (Climate Change Impacts and Implications for New Zealand, funded by the Ministry for Business, Innovation and Employment from 2012-2016). That report contains 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 biological 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.

8.2.1 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 RCP8.5.

Figure 8-14 shows the spatial variation of change in SST for end-century under RCP8.5, with surface warming across the entire Southwest Pacific. The most striking feature is the strong warming of +4°C in the western Tasman Sea (in region 2 on Figure 8-14) associated with the southerly penetration of the East Australian Current off southeast Australia in region 2 (Ridgway, 2007). The western Tasman Sea region is warming at a rate four times that of the global average as a result of the climate-driven spin-up of the South Pacific gyre (Roemmich et al., 2016). This warming propagates across the northern Tasman Sea (region 3) along 35°S in association with the Tasman Front, causing the most significant regional SST increase in the New Zealand Exclusive Economic Zone. Although no temperature change was observed during the 1990s, surface warming in the Tasman Sea has been observed more recently (P. Sutton, pers. comm.).

Sea surface temperatures at Leigh coastal marine laboratories on the northeast coast of Auckland have been measured for over 50 years, but show no clear evidence of any general trends in SST (Bowen et al., 2017), this is in contrast to the SST at Portobello (Dunedin) and Maria Island (Tasmania; Bowen et al., in review) which have a warming trend. The difference is due to the wind forcing, which has an increasing trend in the higher latitudes and less of a trend further north near Leigh. These wind forcing trends are projected to continue with future warming, so it is suggested that the southern sites will see more warming than at the Leigh marine laboratories.

The Leigh SST record shows seasonal variation and vary inter-annually, with a strong correlation to New Zealand air temperatures and the Southern Oscillation Index (SOI – the El Niño Southern Oscillation index; Bowen et al., 2017). Typically negative SOI drives cooler southwest winds which lead to cooler SST, while positive SOI drives warmer northeast winds and warmer SST (Salinger and Mullan, 1999). This suggests that the Leigh coastal SST is strongly controlled by atmosphere-ocean heat exchange, but ocean dynamics also contributes to the changes in temperature (Bowen et al., 2017). We would expect temperatures to continue with this level of inter-annual variation and with a continued correlation with the winds and SOI (Bowen et al., 2017).

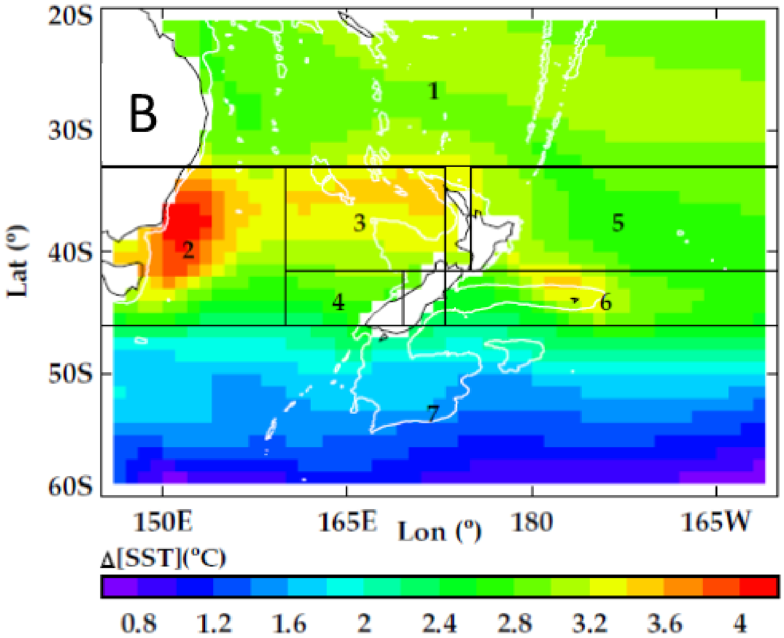

Figure 8-14: Regional variation of the projected change in SST for the End-Century (2081-2100) compared with present-day (1976-2005) under RCP8.5 (Rickard et al., 2016).

Increasing ocean temperatures will have an impact on the distribution of marine species around the Auckland Region, particularly regarding tropical and sub-tropical species and pests that will be able to survive further south for longer than at present. This is further addressed in Sections 8.6.3 and 8.7.2.

8.2.2 Ocean acidification

The transfer of anthropogenic CO_2 into the ocean is altering the ocean's carbonate buffering system, lowering pH (i.e. increasing acidity) and carbonate ion availability whilst increasing dissolved CO_2. As pH and dissolved inorganic carbon species play critical roles in many physiological processes and also influence nutrient availability, changes in these properties will have a fundamental impact upon marine biogeochemistry and ecosystems (Law et al., 2017).

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%.

As pH is primarily determined by atmospheric CO_2 exchanging with the surface waters and there is no upwelling of low pH water in the Southwest Pacific, surface pH is relatively uniform. The decline in surface pH at mid- and end-century is clearly apparent in Figure 8-15, 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 gradient 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.

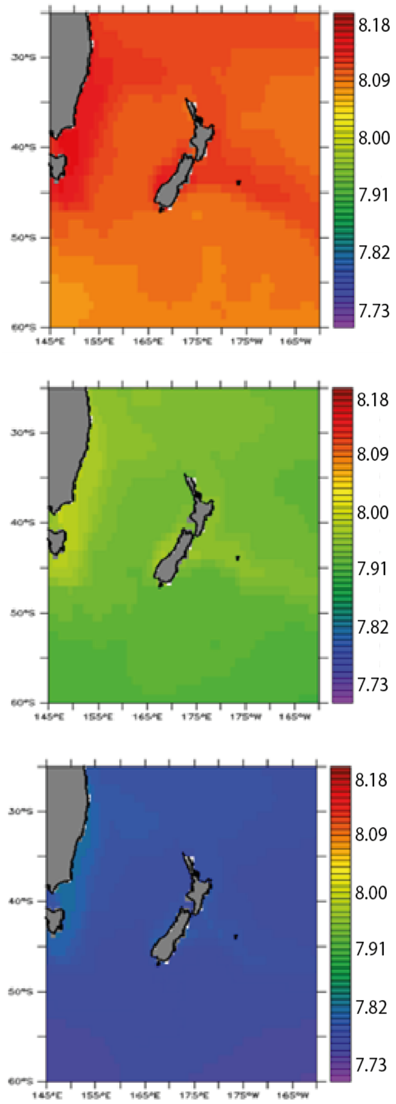

Figure 8-15: The spatial variation in mean surface pH in the Southwest Pacific. For the present-day (1976-2005, left panel), and projected for Mid-Century (2036-2055, central panel) and End-Century (2081-2100, right panel) using the GFDL-ESM2G model under RCP8.5. The legend shows pH.

Figure 8-16 illustrates how the projected pH, averaged across the New Zealand EEZ, 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).

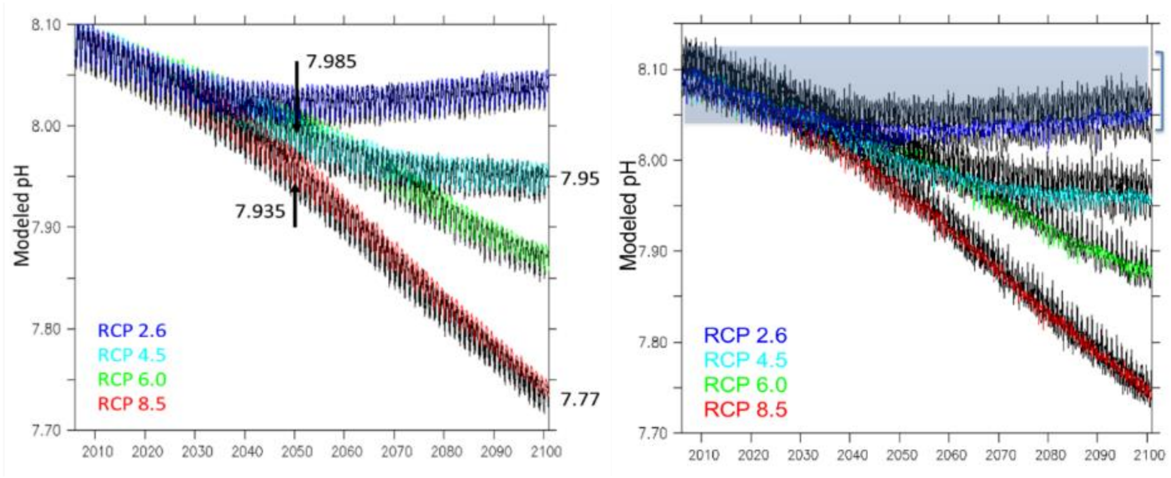

Figure 8-16: Projected surface pH for the New Zealand Exclusive Economic Zone. under each RCP, with the Mid and End-Century mean pH identified for RCP4.5 and 8.5 (left panel). For each RCP, the black line indicates the mean of the six climate models, and the coloured line the best model. The right panel 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).

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 food webs and ocean carbon uptake. The abundance and distribution of planktonic organisms with carbonate shells, and the food webs 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.

While the pH in the open ocean may be directly affected by the changing atmospheric CO_2, with some draw-down by biological productivity, the pH in the coastal regions is influenced by both rising CO_2 in the atmosphere and local conditions in Auckland. The pH (and other carbonate parameters) were measured in the Hauraki Gulf and Firth of Thames on a series of voyages in 2010-2013 (e.g. Figure 8-17). There is a decreasing gradient in pH from the outer Hauraki Gulf to the inner Firth of Thames (Zeldis and et al., 2015). These results show that there is a significant seasonal variation in the pH of the Firth of Thames. In spring, the pH values are similar to the open ocean values of pH 8.05-8.1, these start to drop in summer in the inner Firth of Thames and reach a minimum value of pH 7.92 in autumn, before increasing in winter back to open ocean values of pH 8.1. The pH was lower during the autumn 2010 voyage (pH 7.88) compared to 2013 (pH 7.92; Zeldis et al., 2015). The changes in pH are linked to the changes in oxygen in the Firth of Thames, which are reduced in autumn due to the breakdown of biological productivity, which uses up the oxygen. pH has been measured in the Firth of Thames only for a few years so it is unclear if the pH is changing inter-annually (Zeldis et al., 2015).

There is currently a pH sensor (SeaFET) on the mooring at the monitoring site (36° 45.6 S, 175° 18.0 E; 40 m depth) in the Firth of Thames and one other location in the Hauraki Gulf to monitor the pH hourly for the next few years as part of the Coastal Acidification: Rates, and Mitigation (CARIM) project funded by MBIE. One of these sensors is owned by NIWA and the other is owned by the University of Auckland.

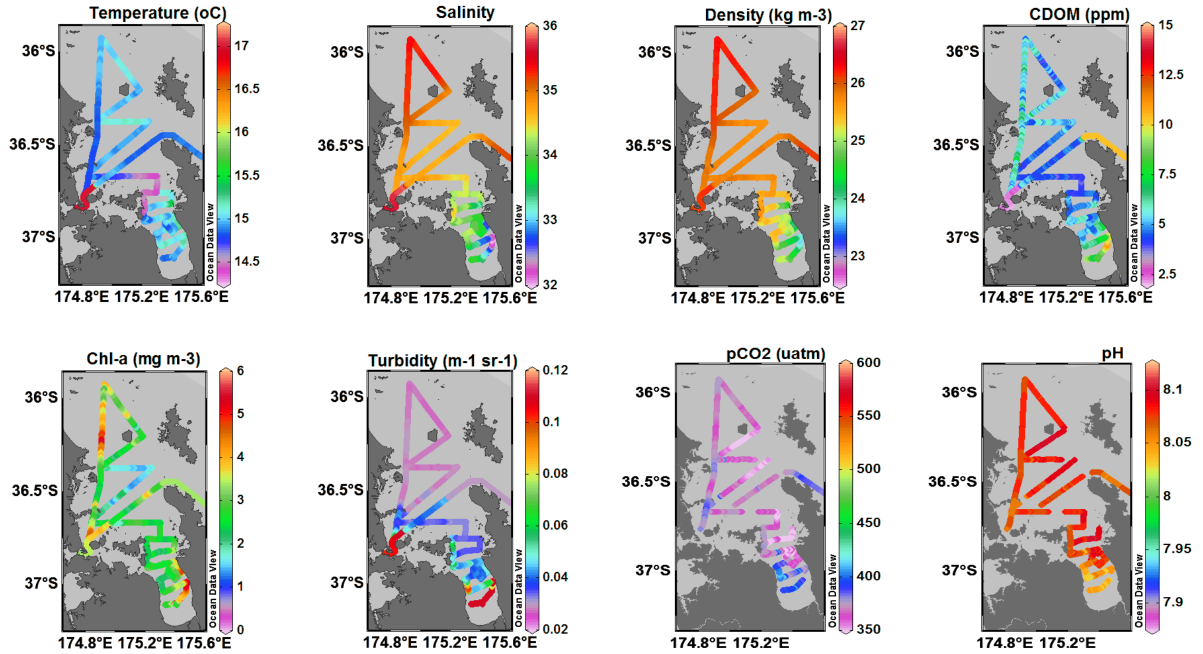

Figure 8-17: Spring (KAH1209) underwater sampling results. Ribbon plots of surface water properties for temperature, salinity, water density, coloured dissolved organic matter (CDOM), chlorophyll *a*, turbidity (backscatter), partial pressure of CO_2 and pH. From Zeldis et al., 2015.

Potential impacts of ocean acidification on Auckland's marine life is discussed in Section 8.6.3.

8.2.3 Changes to nutrients

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 and RCP8.5 (the assessment was not performed for RCP2.6 and RCP6.0) (Figure 8-18). 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.

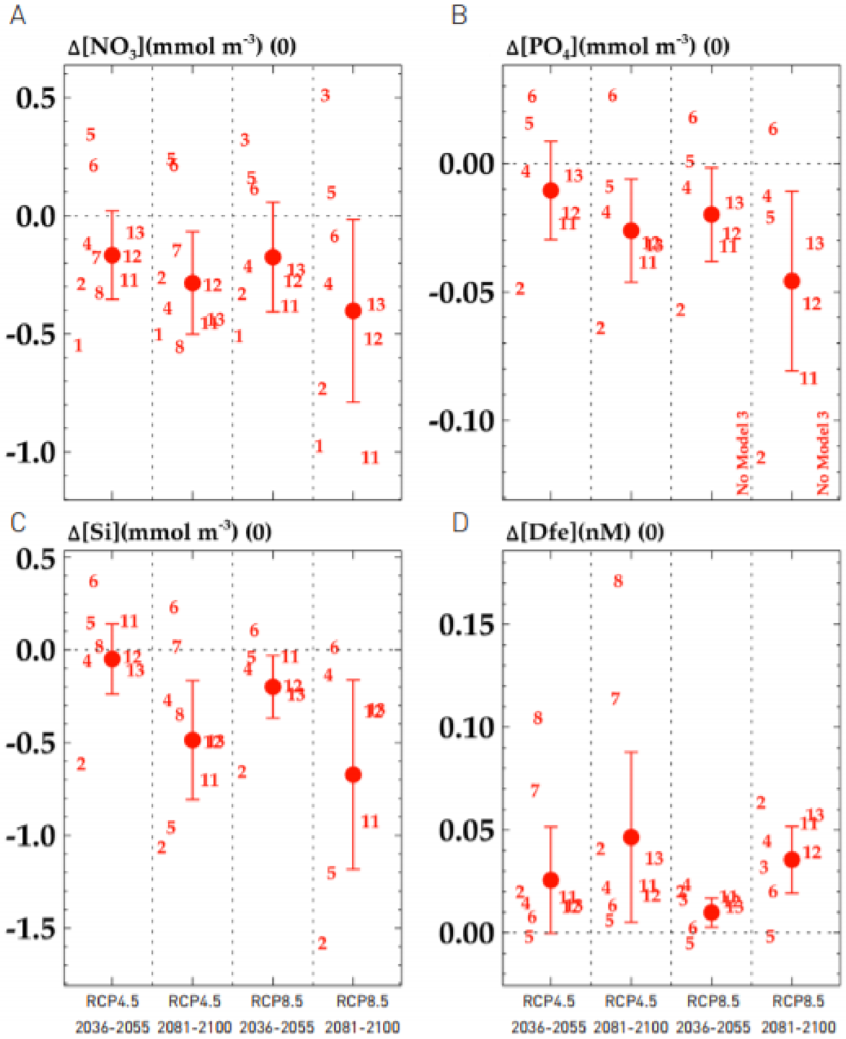

Figure 8-18: Projections of change in dissolved surface nutrient concentrations for A: nitrate, B: phosphate, C: silicate, and D: iron. Model values are indicated by numbers, which is explained in more detail by Law et al. (2016). The filled circles are the ensemble mean for each RCP. Negative values indicate a decrease in concentration, and positive values an increase in concentration. Vertical dashed lines separate the different projections for mid- and end-century under RCP4.5 and RCP8.5, and the horizontal dashed line indicates zero change in concentration. From Law et al. (2016).

The projected changes in pH, SST and nutrient availability may alter regional productivity and food webs. 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.

Measurements of nutrients in the Hauraki Gulf over the last 15 years at the Firth of Thames monitoring site (36° 45.6 S, 175° 18.0 E; 40 m depth) shows large increases in dissolved inorganic and organic nitrogen over this time (Zeldis et al., 2015). This is not the result of increased nitrogen from offshore as the offshore waters are low in nitrogen. Much of this increase comes from the increased nitrogen loads in the rivers flowing into the Firth of Thames, but these loads are still insufficient to explain the increases, which are likely also affected by changes in denitrification (which is a bacterially-driven process at low oxygen levels). Nitrogen levels in the Firth of Thames are likely to continue to rise in the future with increased use of fertilisers on farmland in the Waikato Region. The Firth of Thames is especially sensitive to nutrient loading due to its low flushing rate. These increases in nitrogen are likely to influence aquaculture and fisheries in the Firth. Other coastal regions that have a greater influence of open ocean waters will be less affected.

8.2.4 Changes to salinity

Salinity was not examined during the Climate Change Impacts and Implications (CCII) project. The following paragraph is a brief report on what we currently know and do not know about the changes in salinity in the past and future in the Auckland region.

The waters offshore from the Auckland Region in the East Auckland Current (EAUC) are subtropical surface waters (STW) with a typical salinity of 35.4 Practical Salinity Units (PSU) (Stanton et al., 1997, Zeldis et al., 2004). Despite several oceanographic studies on the EAUC, few have reported on the salinity within the current. One study has shown that the salinity of the continental shelf waters is significantly influenced by intrusions of high salinity EAUC onto the shelf caused by wind events (Sharples, 1997, Sharples and Greig, 1998). The salinity values in the coastal Auckland Region also vary significantly with proximity to rivers (especially in the estuaries and harbours). There is a general salinity increase away from the inner Firth of Thames (<33 PSU) towards the Hauraki shelf (35.25 PSU; Zeldis et al., 2004; Figure 8-17).

Salinity data from the monitoring site (36° 45.6 S, 175° 18.0 E; 40 m depth; Figure 8-19) in the Firth of Thames display a seasonal salinity cycle with lowest salinity measurements in spring (Sept-Nov) and highest salinities during autumn (March-May) with a median salinity value of 34.89 PSU (Zeldis et al., 2004). However, there is no trend in salinity over 15 years at this site (Zeldis and et al., 2015).

It is unclear how salinity will vary with future climate change. Coastal salinity variability will depend on whether there is increased rainfall in the Auckland region and thus increased freshwater run off. Changes in the wind strength or direction will also affect the amount of upwelling/downwelling and intrusions of EAUC onto the shelf (Sharples and Greig, 1998, Zeldis et al., 2004, Sharples, 1997) and flow of offshore waters into the Hauraki Gulf and Firth of Thames (Zeldis and et al., 2015). Further offshore the salinity of the EAUC will depend on upstream changes in the East Australian Current and Tasman Front as well as the winter mixed layer depth due to wind mixing. It is possible that along with an increase in air temperature there may be increased evaporation and thus slightly increased sea surface salinities in the EAUC under future climate conditions.

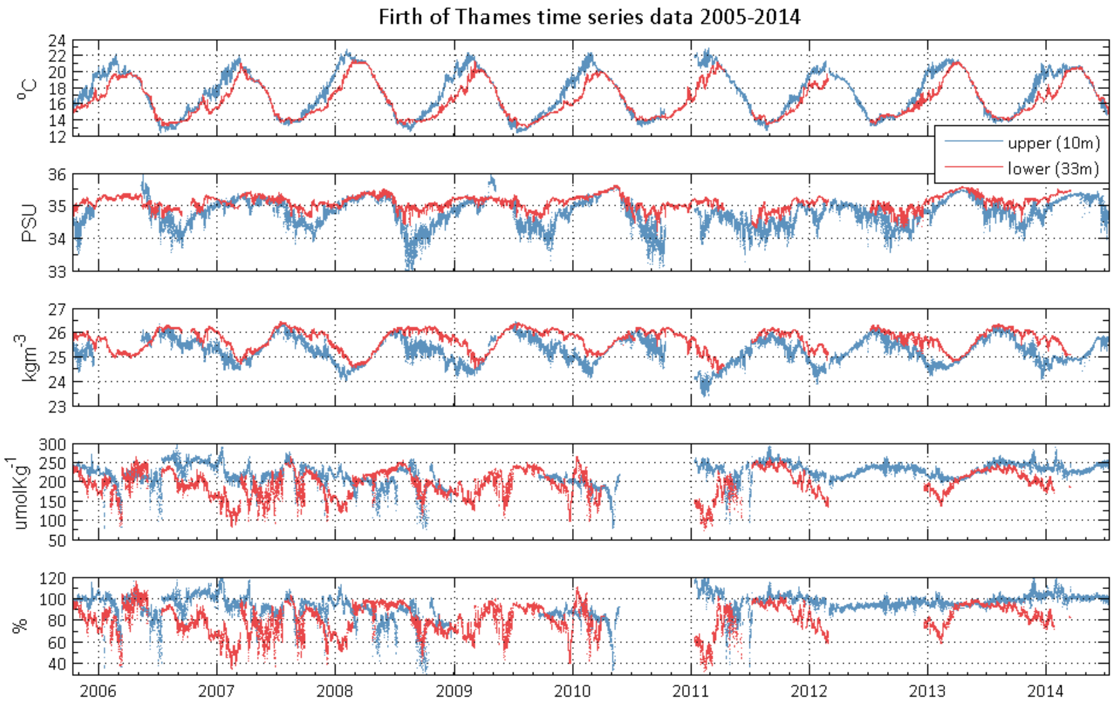

Figure 8-19: Time series of marine observations from the Firth of Thames monitoring site mooring, 2005–2014. The blue data are from the upper water column at 10 m depth and the red data are from the lower water column at 33 m depth. Shown are data for temperature, salinity, seawater density, oxygen concentration and oxygen saturation. From Zeldis et al., 2015.

8.3 Climate change and sea level

Key messages

- Future sea-level rise (SLR) is a significant issue for Auckland as much of the region's communities and infrastructure are near the coast.
- Sea level at the Port of Auckland has risen by 1.60 ± 0.08 mm per year since the early 20th century, with an acceleration of SLR in recent years.
- Cumulative global greenhouse gas emissions to date have already committed the Earth to an eventual 1.6-1.7 m of global SLR relative to the present level. However, this could take 1-2 centuries depending on future emission trends.
- By 2100, global SLR will likely be in the range 0.28-0.98 m (IPCC). Collapse of marine-based components of Antarctic ice sheets could cause global mean sea level to rise substantially higher, but the potential timing of this is highly uncertain.
- 0.5 m of SLR is projected for New Zealand between 2060 and 2110, and 1 m of SLR is projected for New Zealand between 2100 and after 2200, depending on the climate change scenario.
- SLR will cause present-day high tide levels to be exceeded more frequently in Auckland.
- Low-lying coastal areas in the Auckland Region are the most vulnerable to inundation from SLR, including parts of the Central Business District, eastern bays (e.g. Mission Bay), Onehunga, Mangere Bridge, Devonport, and Helensville.
- The east coast of Auckland is more sensitive to climate change-related erosion and inundation than the open west coast, due to different exposure, geology, landforms, tidal ranges, and changes to wave heights and storm surge.
- SLR and changes to extreme rainfall events is likely to increase erosion rates of the soft cliffs on Auckland's eastern coastline.
- Residential buildings will be the building category most affected by SLR in Auckland, with 4500 buildings affected during a 1-in-100-year storm tide event with 1 m of SLR which have a replacement cost of over $2.2 billion 2016 NZD. This will affect a usually resident population of about 12,000 people.
- Significant amounts of road, rail and Three-Waters infrastructure (stormwater, potable water, wastewater) will be affected by SLR in Auckland.

One of the major and most certain (and hence foreseeable) consequences of increasing atmospheric concentrations of carbon dioxide[9] and associated warming, is the rising sea level (Parliamentary Commissioner for the Environment, 2015c). This section covers global and New Zealand sea-level rise projections as well as Auckland-specific coastal exposure and potential impacts from sea-level rise.

8.3.1 Impacts of sea-level rise (SLR)

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 of climate change – given more than 90% of the energy that is stored in the climate system ends up in the oceans (Rhein et al., 2013). Present observed SLR, however, needs to be interpreted against the backdrop of substantial lags (decades to millennia) in the ongoing response to warming of the oceans and melting of glaciers and ice sheets (IPCC, 2013b, 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 (which has been evident in several low-lying coastal margins of Auckland)
- exacerbated erosion of sand/gravel shorelines and unconsolidated cliffs (unless sediment supply increases)
- increased incursion of saltwater in lowland rivers and nearby groundwater aquifers, raising water tables in tidally-influenced groundwater systems.

These impacts will have increasing implications for 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 and performance issues with stormwater and overland drainage systems (particularly gravity-driven networks). Public transportation infrastructure and roads will also be affected, both by nuisance shallow flooding of saltwater (e.g. vehicle corrosion) and more disruptive flooding and damage from elevated storm-tides and wave overtopping.

There are three types of 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).

[9] Global average now above 400 ppm.

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

The first two types of SLR are measured directly by satellites, using radar altimeters, or by combining many tide-gauge records globally (after adjusting for local vertical land movement and ongoing re-adjustments in the Earth's crust following ice loading during the last Ice Age[10]).

RSLR is measured by tide gauges. One advantage of knowing the RSLR from these gauge measurements is that this directly tracks the SLR 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 RSLR will be larger than the absolute rise in the adjacent ocean level acting alone (Figure 8-20). Across the Auckland Region, the landmass is relatively stable.

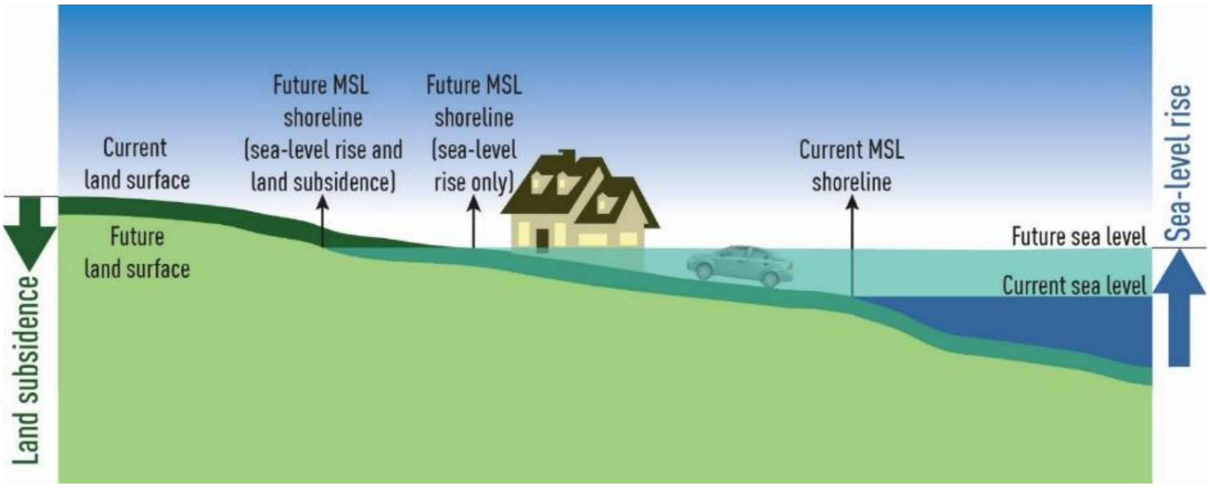

Figure 8-20: The difference in mean sea level (MSL) shoreline between absolute SLR (SLR only) and relative (local) SLR where land subsidence occurs (SLR + land level changes).

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, compared with those sections of the coast where the tide range is relatively large. Problems will be exacerbated for coastlines with smaller tidal ranges in proportion to SLR, where high tides will more often exceed current upper-tide levels, thus allowing more opportunity to coincide with storms or large swell. RSLR 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). This is discussed further for the Auckland Region in Section 8.3.5.

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

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. This is discussed further for the Auckland Region in Section 8.3.5.

Coastal dune systems are particularly vulnerable to RSLR due to the lower erosion threshold of sand compared with unconsolidated cliffs. With RSLR, 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, 2008b). 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.

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

After a period of relative local stability over the past 2000–3000 years (Kopp et al., 2016, Clement et al., 2016), sea level began to rise on a global scale from the late 1800s (Figure 8-21). The trend over this entire period is around 1.7-1.8 mm/year (Church et al., 2013b), although recent global studies using more definitive information on vertical land movement at each of the many tide gauge sites indicate the trend in absolute SLR over the last century may have been as low as 1.1–1.4 mm/year (e.g., Hay et al. (2015)).

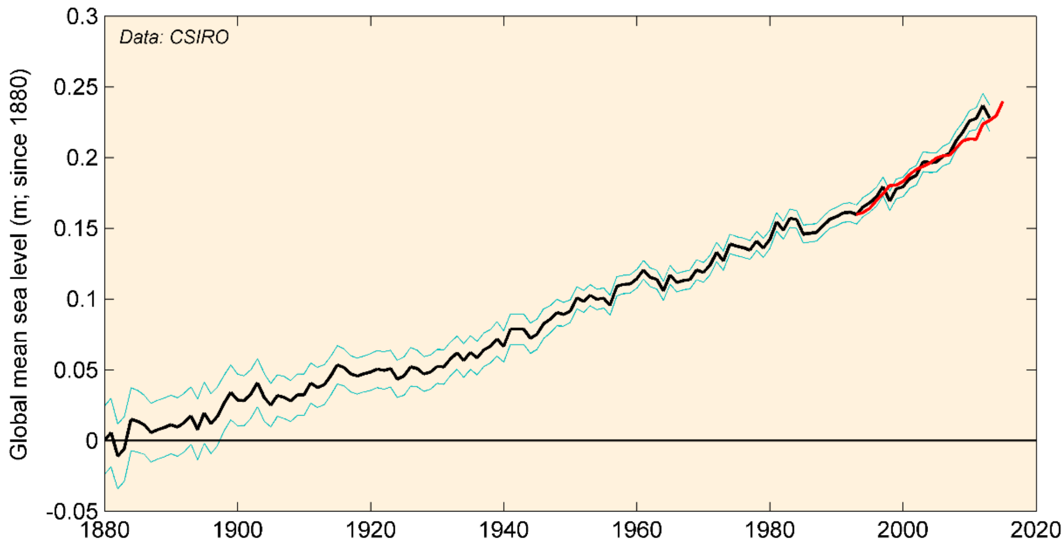

Figure 8-21: Cumulative changes in global mean sea level (MSL) since 1880, based on a reconstruction of long-term tide gauge measurements to end of 2013 (black) and recent satellite measurements to end 2015 (red). Lighter lines are the upper and lower bounds of the likely range (± 1 standard deviation) of the MSL from available tide gauges, which is a function of the number of measurements collected and the precision of the methods. 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 SLR in the 20th century has been around 45–50% (Kopp et al., 2016, Dangendorf et al., 2015). The other 50-55% of observed global SLR is likely to be from tectonic movement, natural sediment compaction, glacial isostatic adjustment (the ongoing movement of land once burdened by ice age glaciers), and natural variability in ocean-atmospheric dynamics. The anthropogenic 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 8-22), the recent trend in global-average MSL to July 2017, based on the CSIRO analysis of satellite altimeter data[11], is 3.4 ± 0.1 mm/year. This rate of increase, averaged over the past 24 years, is nearly double the global-average rate over the historic rate over the entire 20th century of 1.7-1.8 mm/year (Church et al., 2013b, Church and White, 2011) or up to three times higher if the historic rate was indeed 1.1–1.4 mm/year (Hay et al., 2015). Natural climate variability from inter-annual to decadal climate cycles, especially the 20–30 year Interdecadal Pacific Oscillation (IPO) (which changed phase around 1999, partway into the satellite era) in combination with the shorter 3-7 year El Niño-Southern Oscillation (ENSO), are evident in the

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

variability shown in Figure 8-22 (e.g., peak at end of 2015 coincided with an El Niño and the dip in 2011, with a La Niña). These climate cycles 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 SLR (Slangen et al., 2016).

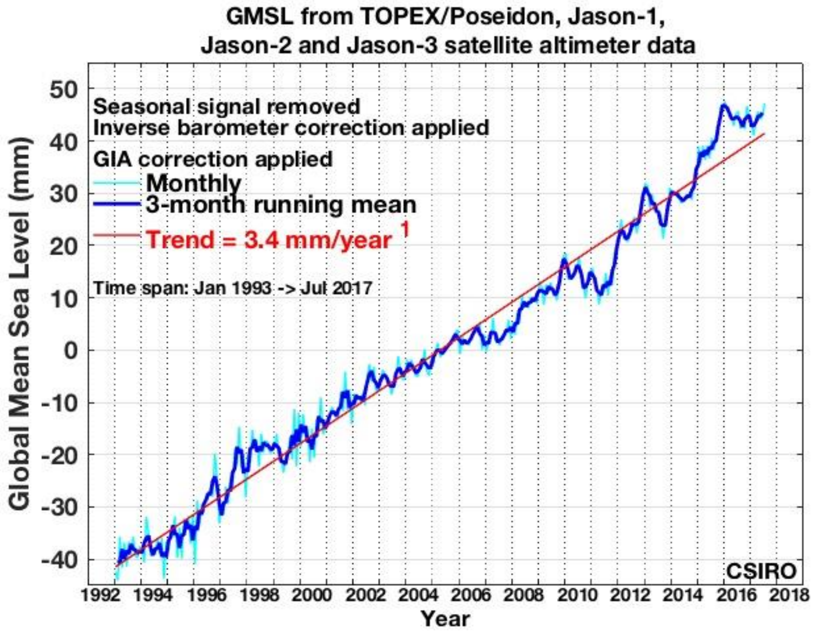

Figure 8-22: Time series and trend in global average sea level over the satellite era from January 1993 to July 2017. Adjustments for glacial isostatic adjustment (GIA), following crustal response to the last Ice Age, and inverted barometer (annual air pressure differences) have been made. Retrieved 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 from 1900 to 2015 are shown in Figure 8-23. Annual MSL is plotted relative to the average annual MSL 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 the bracketing RCP8.5 and RCP2.6 scenarios are also shown for a general comparison with New Zealand observations to end of 2015 on how sea level is tracking here. 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, which makes it difficult to isolate how the underlying rate of rise is tracking relative to the projections (Figure 8-23). For example, the annual MSL for all 4 ports is currently above the RCP projection lines, but in part this is due to the IPO shift to the negative phase in 1999–2000 (Figure 8-23), associated with a rapid rise in mean sea level throughout the western Pacific including New Zealand.

This masking effect of natural climate variability on SLR trends requires long records to extract robust historic trends, and may require one or two decades more monitoring to confirm which SLR RCP scenario is being followed (because there is little difference at present between the SLR projections – see dashed lines in Figure 8-23). Also, when the IPO shifts back to the positive phase, annual MSL around New Zealand may dip at times below the SLR projection lines, but still with a rising trend.

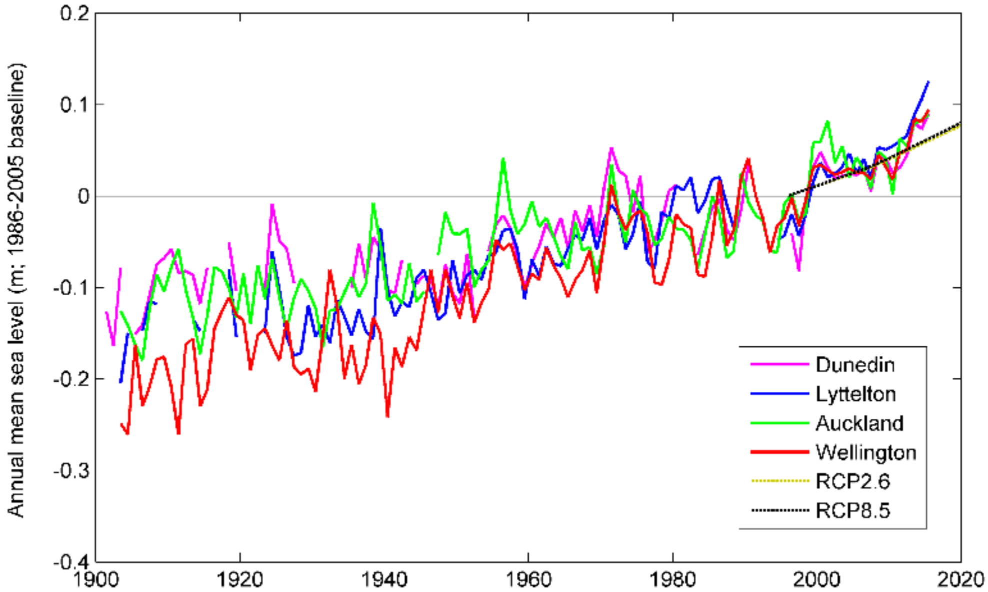

Figure 8-23: Change in annual local MSL for the four main ports from 1900–2015, and initial global-mean SLR projections for RCP2.6 and RCP8.5 to 2020 (dashed lines). Relative to the average MSL over the baseline period 1986–2005 (used for IPCC AR5 projections of SLR, with mid-point at 1996). (Source data: Hannah and Bell (2012), updated to 2015; Church et al. (2013a)).

Local sea-level or RSLR 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 were updated to 2015 (except for Whangarei), as shown in Figure 8-24, with the national average rate now closer to 1.8 mm/year.

Port of Auckland (Waitematā Harbour) mean sea level has risen by 1.60 ± 0.08 mm/year since 1899 up to 2015 (Figure 8-24). The rate of rise over the more recent 55-year period (1961–2015) for the Port of Auckland was higher at 2.34 ± 0.26 mm/year (Emeritus Professor J. Hannah, formerly University of Otago, pers. com., 2016).

Over the satellite era since 1993, the Southwest Pacific has also experienced increased rates of rise, with the seas around New Zealand rising since 1993 to mid-2016 at an average of 4.4 ± 0.9 mm/year, which is considerably higher than the global average from the satellite record of 3.4 mm/year (Figure 8-22). This difference is largely due to the IPO shift in 1999–2000, when annual sea level around New Zealand rose rapidly by around 5–6 centimetres (Figure 8-23).

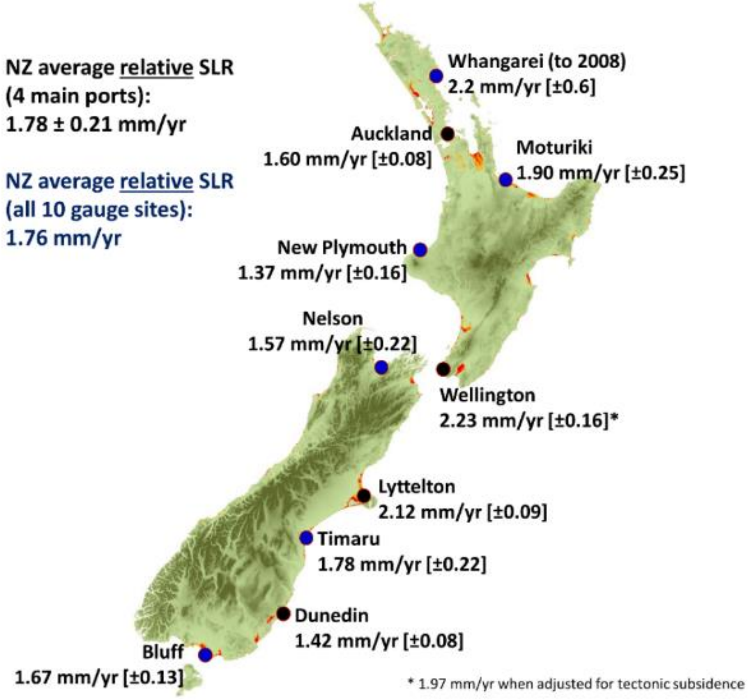

Figure 8-24: Historic long-term RSLR rates for the 20th century up to and including 2015 (excluding Whangarei), determined from longer sea-level gauge records at the four main ports. Note: Standard deviations of the trend are listed in the brackets. Sources: analysis up to end of 2008 from Hannah and Bell (2012) updated with seven years of MSL data to end of 2015 (J Hannah, pers. comm., 2016); sea-level data from various port companies is acknowledged.

Adaptation to SLR requires knowledge on why and how *local* RSLR around New Zealand is affected by ongoing vertical land movement. Of most concern is the presence of any significant ongoing *subsidence* of the landmass, which will exacerbate the absolute ocean SLR (Figure 8-20).

Future projections of SLR at some locations or regions in New Zealand will need to factor in estimates of ongoing vertical land movement. Measurements of vertical (and horizontal) land movement have been undertaken by continuous GPS (cGPS) stations around New Zealand over the past decade or more. The cGPS gauge co-located with the Port of Auckland tide gauge in 2002, has exhibited negligible vertical land movement, compared with other, more tectonically active, parts of New Zealand such as Wellington, which is subsiding (Beavan and Litchfield, 2012). Therefore, there is no need at present to factor in vertical land movement to SLR projections for Auckland City.

8.3.3 Projections for sea-level rise

The primary climate driver for SLR 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 SLR, because of the inertia in warming the deep oceans and 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 one to two 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).[12]

Headline projections by IPCC in the AR5 are summarised in the IPCC 'Summary for Policymakers' from Working Group I (IPCC, 2013b) and Synthesis Report (IPCC, 2014a). The range of global-average SLR projections derived by IPCC, based on process-based models, is shown in Figure 8-25, 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 8-23).

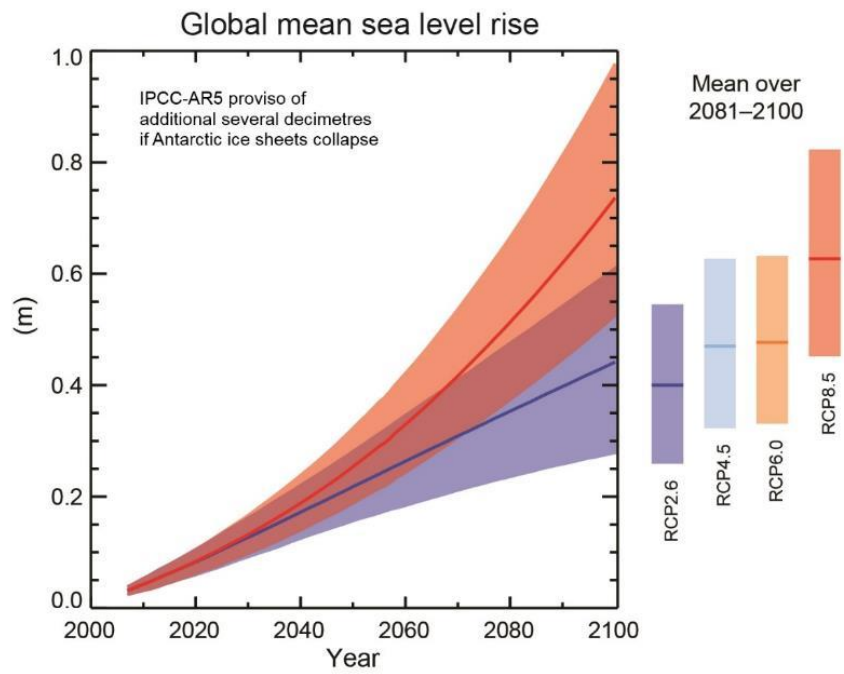

Figure 8-25: IPCC AR5 projections of global-average MSL rise (metres, relative to a base MSL of 1986-2005) covering the range of scenarios from RCP2.6 to RCP8.5. The heavy line shows the median estimate for that RCP, while the shaded area covers the "likely range" projections for the RCP, with a 33% 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. (From IPCC (2013)).

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

- Global mean SLR will continue during the 21st century, *very likely* at a faster rate than observed from 1971 to 2010.
- By 2100, global-average SLR 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 marine components of the Antarctic ice sheets (most of West Antarctica and some parts grounded below sea level for East Antarctica) could

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

cause global MSL to rise substantially above the *likely* range (Figure 8-25) during this century. While the contribution cannot be precisely quantified, there is *medium confidence* that it would not exceed several tenths of a metre[13] of SLR by 2100.

- It is *virtually certain* that global mean SLR 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 SLR 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 contributed from Antarctica 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). The present shelves, however, are not what contributes to the SLR as they are already in the water. Their loss will reduce buttressing of connected ice streams, which then move more rapidly and drain off parts of the ice sheet at higher elevation. The mechanism of loss is rapidly commuted and positively fed back into by tabular calving from the renewal of ice shelves, which can be broken off in chunks by increased SLR and warming of waters underneath the shelves (e.g. Wise et al., 2017). This is the same for Greenland where glaciers drain into the sea via ice streams (e.g. Jakobshavn Glacier).

A set of all four RCP projections for New Zealand is shown in Figure 8-26, based on the median projections from IPCC (Church et al., 2013b). An additional scenario is presented here, which is the 83rd percentile of RCP8.5 (i.e., upper end of the “likely range”). This more extreme scenario is presented to cover the possibility of polar ice sheet instabilities not factored into the IPCC projections (Stephens et al., 2017). Small offsets have been added to the global average SLR projections to account for a slightly higher (5-10%) increase in SLR in seas around New Zealand compared to the global average projections (Ackerley et al., 2013).

[13] Or decimetres (one-tenth of a metre).

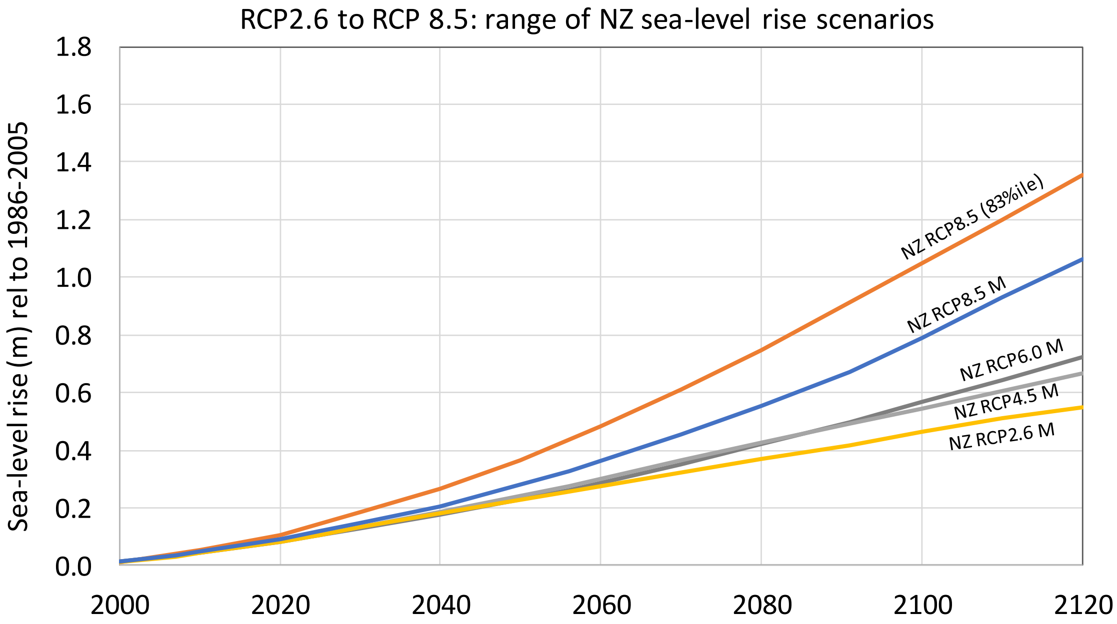

Figure 8-26: SLR scenarios for New Zealand seas, based on a set of median projections for all four RCPs (based on Church et al., 2013b) plus a higher 83rd percentile RCP8.5 projection (based on (Kopp et al., 2014)). The M next to the RCP on the plot stands for median. Note: for New Zealand seas, SLR projections will be around 5-10% higher than the global mean SLR published by IPCC, so between 2.5 to 5 cm by 2100 has been added to the median global average projections, and 7.5 cm to the higher scenario.

To assist with adaptive approaches to planning, the bracketed time window (approximate earliest to latest) when various SLR increments will be reached is shown in for all scenarios in Table 8-1 (except for NZ RCP6.0 which is similar to NZ RCP4.5). For example, 0.5 m of SLR for New Zealand is projected to occur by 2060 at the earliest (assuming a RCP8.5 83rd percentile scenario described above) and 2110 at the latest (under the low-emission RCP2.6 scenario). Even earlier exceedance of the specific SLR increment cannot be entirely ruled out (depending on the future emission controls and possible runaway polar ice sheet responses). Exceedance of a 1 m SLR is projected by 2100 for a possible earliest (based on the RCP8.5 83rd percentile scenario) and after 2200 at the latest.

Table 8-1: Approximate years, from possible earliest to latest, when specific SLR increments (metres above 1986-2005 baseline) could be reached for various projection scenarios of SLR for the wider New Zealand region. From Stephens et al. (2017)

SLR (metres)	Year achieved for RCP8.5 (83%ile)	Year achieved for RCP8.5 (median)	Year achieved for RCP4.5 (median)	Year achieved for RCP2.6 (median)
0.3	2045	2050	2060	2070
0.4	2055	2065	2075	2090
0.5	2060	2075	2090	2110
0.6	2070	2085	2110	2130
0.7	2075	2090	2125	2155
0.8	2085	2100	2140	2175
0.9	2090	2110	2155	2200
1.0	2100	2115	2170	>2200
1.2	2110	2130	2200	>2200
1.5	2130	2160	>2200	>2200
1.8	2145	2180	>2200	>2200
1.9	2150	2195	>2200	>2200

8.3.4 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, 2013b). 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 can 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 (Section 5.5).

In addition, the projections of storm surges (increase in sea level caused by inverse barometer and wind-stress effects 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, 2013a). 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 because 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, 2013a).

A previous assessment by NIWA of possible changes in storm surge and waves around New Zealand, based on Regional Climate Model simulations, showed a mix of small decreases or increases in different areas and for different emission scenarios, with mostly no more than a 5% change or around 5 cm (unpublished NIWA data). This implies that changes in waves and storm surge (and their lower uncertainties) will be secondary (minor) to the dominating influence and uncertainty of future

SLR in determining coastal impacts such as flooding – a result also shown to apply in a European case study by Le Cozannet et al. (2015).

8.3.5 Auckland's coastal exposure and sensitivity to sea-level rise

This section contains information about impacts of RSLR, coastal sensitivity, and risk to coastal assets from RSLR in the Auckland Region, including relevant past research that has been completed by NIWA scientists and others.

Effect of sea-level rise on high tide exceedance frequency

As discussed in Section 8.3.1, SLR will have an impact on high tides exceeding current mean sea levels. An example of the effect that future SLR has on the frequency of high tides exceeding certain points at Waitematā Harbour (east coast at Port of Auckland) and Anawhata (open west coast north of Piha) in the Auckland Region is shown in Figure 8-27 and Figure 8-28, respectively.

The black line in these figures show the distribution of all high tides (excluding weather effects) for the present-day mean sea level and the upper curves are for two different SLR (+0.4 m and +0.8 m). At present, 10% of high tides exceed MHWS-10 level (Mean High Water Spring level that 10% of high tides exceed, excluding weather and climate effects). With 0.4 m of SLR, approximately 65% of all high tides will exceed this level for the Waitematā Harbour (an increase of 55%) and 56% at Anawhata (an increase of 46%). With 0.8 m of SLR, 100% of high tides will exceed the level that 10% of present-day high tides exceed in Waitematā Harbour and approximately 97% of high tides will exceed this level at Anawhata. These statistics are for tides only and exclude weather and climate effects such as storm surge and ENSO.

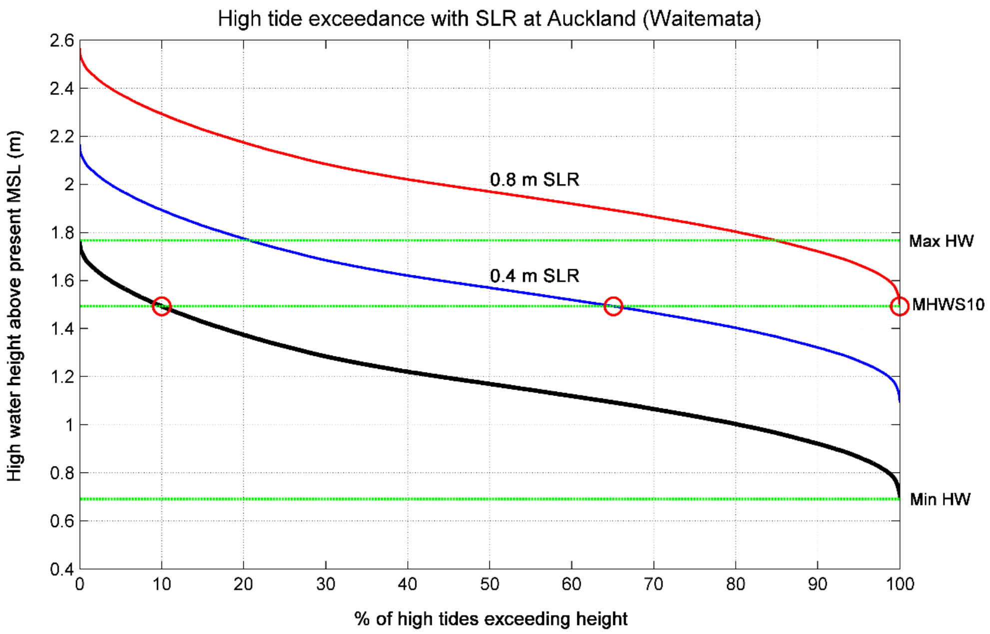

Figure 8-27: The frequency of occurrence of high tides exceeding different present-day tide marks at Waitemata Harbour (east coast). The tide marks for the present is shown by the heavy black line, 0.4 m of SLR (blue line) and 0.8 m of SLR (red line). ©NIWA.

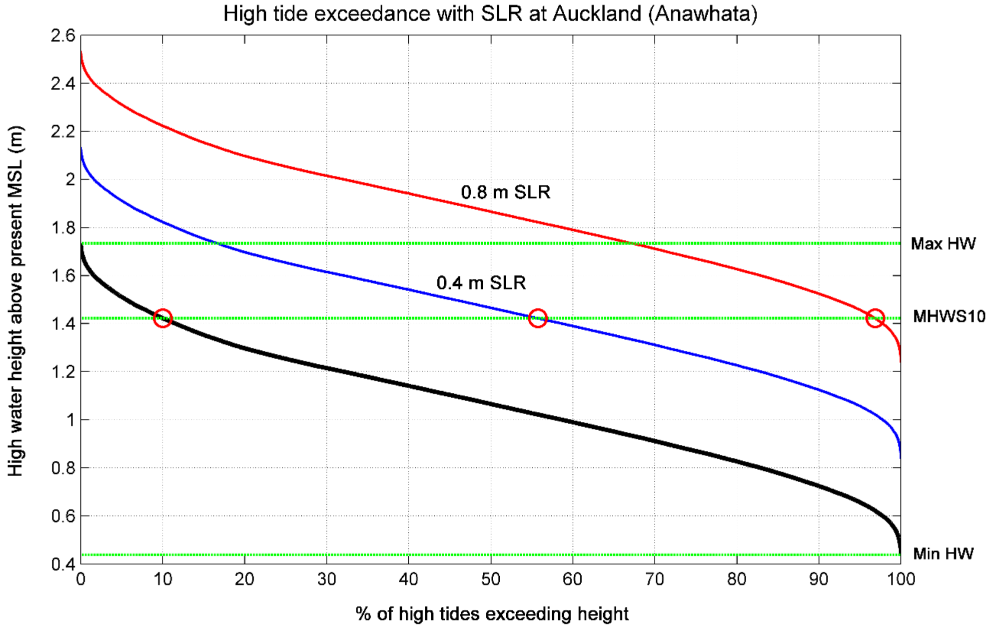

Figure 8-28: The frequency of occurrence of high tides exceeding different present-day tide marks at Anawhata (west coast). The tide marks for the present is shown by the heavy black line, 0.4 m of SLR (blue line) and 0.8 m of SLR (red line). ©NIWA.

Exposure to sea-level rise in Auckland

Several studies have analysed the potential impact of RSLR in parts of the Auckland Region. Presented here are recent pieces of work containing maps of RSLR inundation for wider parts of the region as well as local-scale maps of Mission Bay, Auckland Airport, Onehunga, Mangere and Manukau.

Low-lying coastal land in Auckland

Areas that are both low-lying and close to the coast are, in general, most vulnerable to RSLR. A 2015 report by the Parliamentary Commissioner for the Environment included maps showing coastal land elevation in low-lying areas (Parliamentary Commissioner for the Environment, 2015b). Figure 8-29 to Figure 8-33 show low-lying coastal land for parts of the Auckland Region. The bands show elevation above the 10th percentile mean spring high tide levels (MHWS-10), which highlights areas at risk from different levels of RSLR. Note however that the coloured areas on the maps are not coastal hazard zones as determined by local authorities. The methodology for producing these maps is discussed in Parliamentary Commissioner for the Environment (2015b).

The major low-lying areas in Figure 8-31 (the central city area) have not been densely built on. For instance, the large area below 50 cm in Devonport is a golf course, another in Northcote is the Onepoto Domain, and a third in Mangere is farmland. These areas are connected to the sea but sheltered from direct wave action. There are pockets of low-lying land in the city, including parts of the Central Business District, Mission Bay, Kohimarama, St Heliers, Onehunga, Mangere Bridge, and Devonport. There are also some relatively large areas of low-lying land along the west coast outside the Auckland urban area. These include parts of the towns of Parakai and Helensville that lie close to the Kaipara River (Figure 8-30). Further south, the beach at Muriwai, though not as low-lying, has been eroding at a rate of about one metre per year since the 1960s.

Vulnerable transport links include the Northern Motorway just north of the Harbour Bridge and the causeway on the Northwestern Motorway where it crosses the mud flats at Waterview. The latter has recently been raised by 1.5 m and widened, partly to allow for gradual subsidence from the soft marine mud and partly to allow for RSLR. Tamaki Drive, an important arterial road that provides access to the eastern suburbs, is also subject to increasing sea flooding from elevated storm-tides and wave overtopping, most frequently where it crosses Hobson Bay (Figure 8-31). Auckland Transport is planning to address coastal flooding at low spots on Tamaki Drive, between Lilliput minigolf and Ngapipi Bridge[14]. Part of the western end of Auckland Airport lies less than 1.5 metres above the spring high tide mark, with 180 hectares built on reclaimed land and protected by sea walls (Figure 8-31).

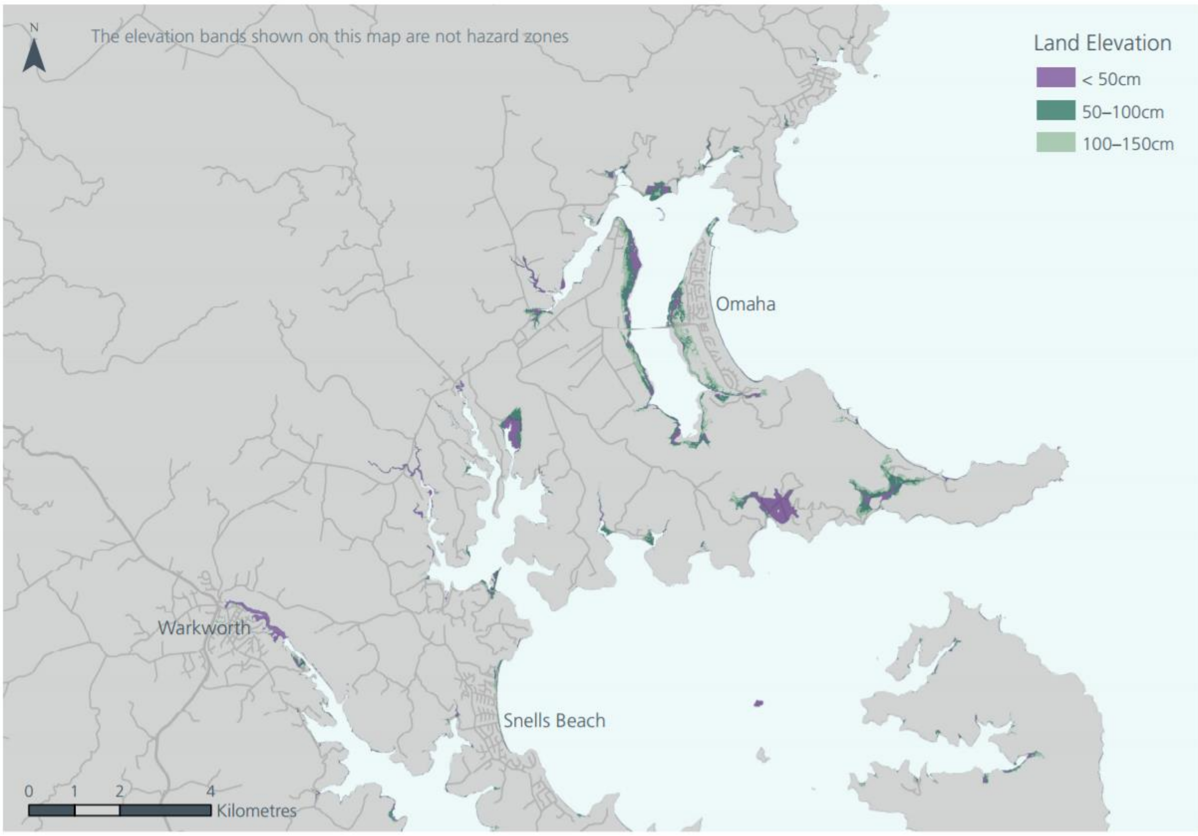

Figure 8-29: Low-lying land in northeast Auckland with elevation bands of <50cm, 50-100cm, and 100-150cm above MHWS-10. From Parliamentary Commissioner for the Environment (2015b).

[14] https://at.govt.nz/about-us/news-events/auckland-transport-to-address-flooding-along-tamaki-drive/

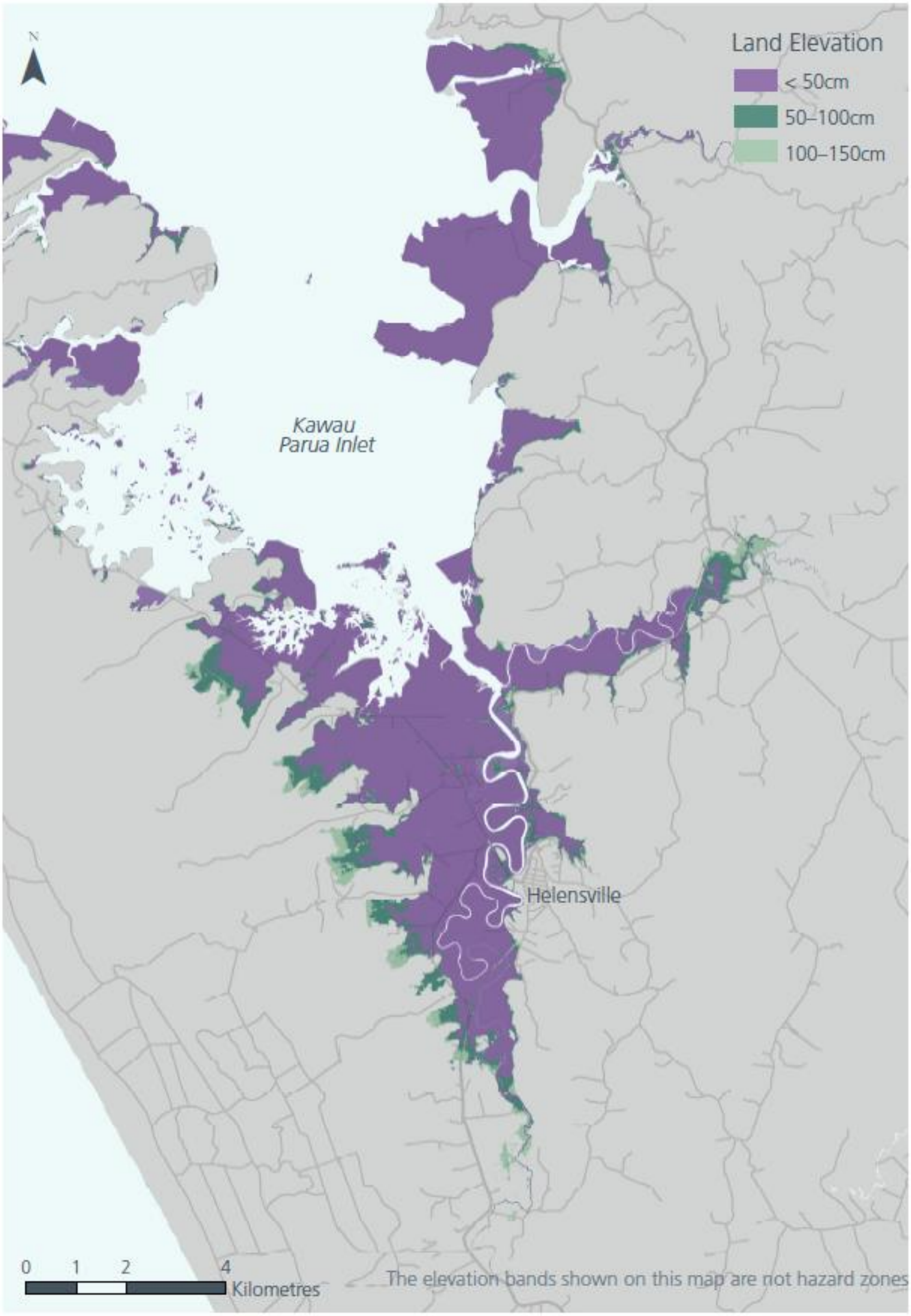

Figure 8-30: Low-lying land in northwest Auckland with elevation bands of <50cm, 50-100cm, and 100-150cm above MHWS-10. From Parliamentary Commissioner for the Environment (2015b).

Figure 8-31: Low-lying land in central Auckland with elevation bands of <50cm, 50-100cm, and 100-150cm above MHWS-10. From Parliamentary Commissioner for the Environment (2015b).

Figure 8-32: Low-lying land on Waiheke Island with elevation bands of <50cm, 50-100cm, and 100-150cm above MHWS-10. From Parliamentary Commissioner for the Environment (2015b).

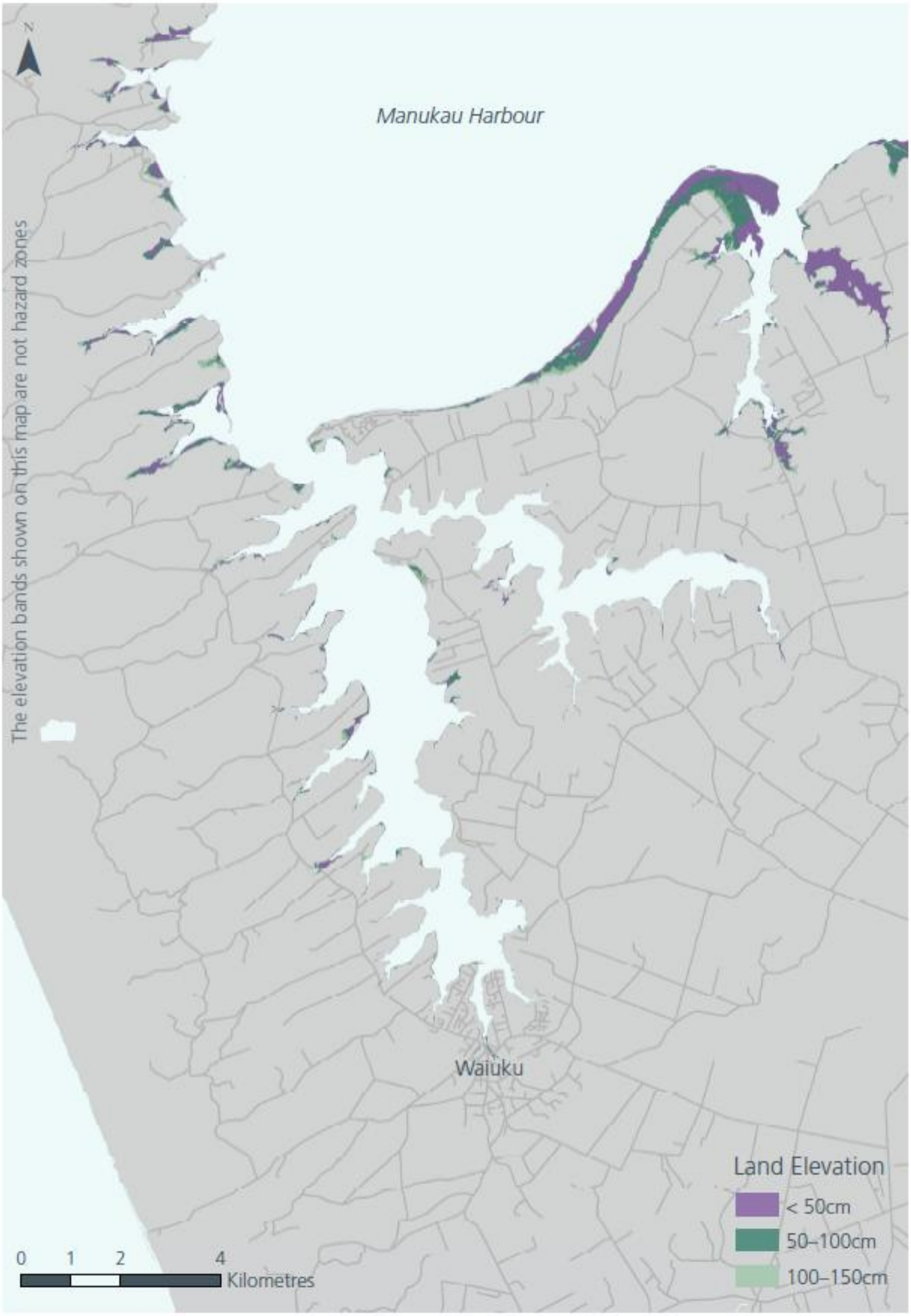

Figure 8-33: Low-lying land in southwest Auckland with elevation bands of <50cm, 50-100cm, and 100-150cm above MHWS-10. From Parliamentary Commissioner for the Environment (2015b).

Extreme sea levels in Auckland

Extreme sea levels were modelled for the entire coastline of the Auckland Region by Stephens et al. (2016c). This report was commissioned by Auckland Council and the council holds all the GIS inundation maps produced, which are publicly available on Auckland Council's GeoMaps website. Coastal extreme sea level elevations from storm-tides[15] and wave setup were calculated for different return periods. Present-day maps were produced as well as maps for +1 m and +2 m RSLR scenarios for 1% and 2% AEP (annual exceedance probability, i.e. 100-year and 50-year recurrence intervals, respectively). The coastal storm inundation layer comprising the 1% AEP inundation event + 1 metre RSLR is used in the Auckland Unitary Plan to define low-lying coastal areas where policies and rules apply to land-use planning e.g. Section E36, Natural hazards and flooding, Auckland Council Decisions Version (19 August 2016)[16].

Mission Bay

Future scenarios for coastal flooding at Mission Bay, central Auckland, were mapped in more detail by NIWA as part of a research project in improving hazard and risk assessments incorporating SLR (Stephens et al., 2017). SLR increments were mapped directly on top of present-day median 1% AEP storm-tide elevation. (Note: annual exceedance probability is the chance of a water level being exceeded in any year, and is equivalent to an event with a 1 in 100-year recurrence interval on average). Figure 8-34 clearly indicates how coastal storm inundation exposure might change incrementally with RSLR, depending on location. Properties on low-elevation land close to the sea will face inundation at lower RSLR, so will be affected sooner by small or modest increases in sea level. Properties located further inland on higher elevation land are less exposed and will have longer to adapt to rising sea level.

[15] Storm tide refers to the total observed sea level during a storm, which is the combination of storm surge (caused by low atmospheric pressure and by high winds pushing water onshore) and normal high tide.
[16] http://unitaryplan.aucklandcouncil.govt.nz/Images/Auckland%20Council%20Decision/Chapter%20E%20Auckland-wide/5.%20Environmental%20Risk/E36%20Natural%20hazards%20and%20flooding.pdf

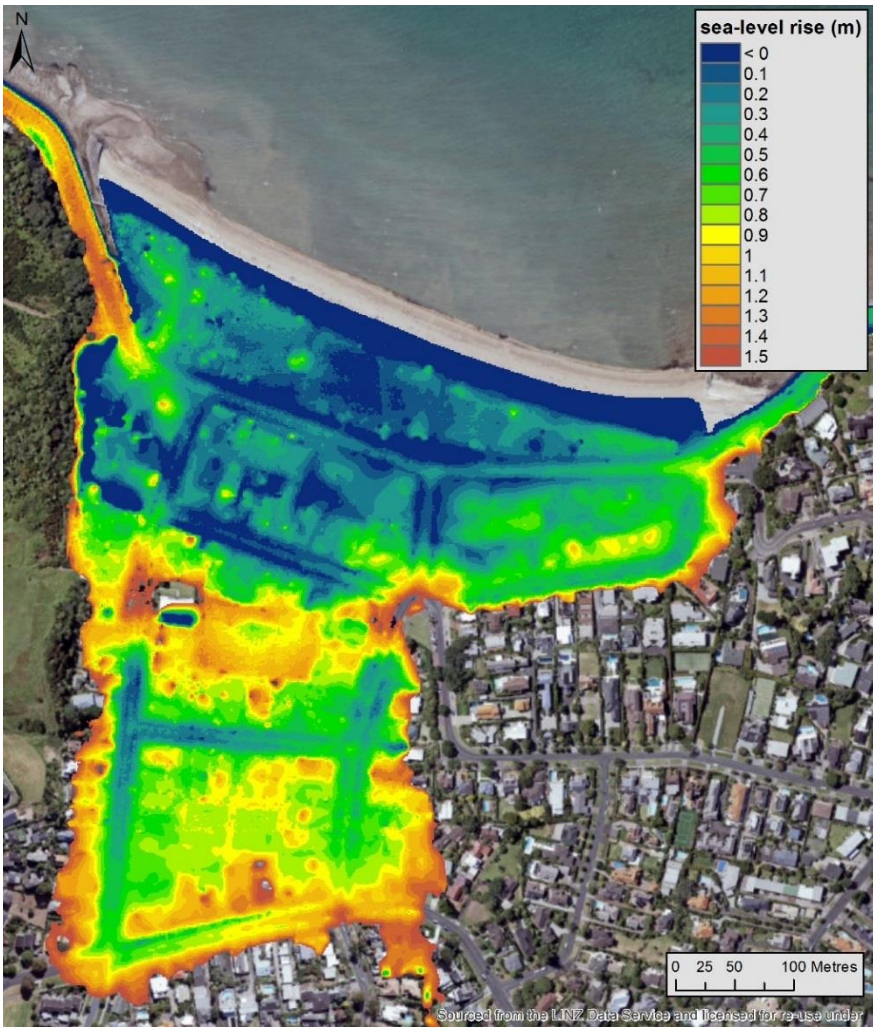

Figure 8-34: Effect of 0.1 m RSLR increments on coastal storm inundation exposure (1% AEP) at Mission Bay, Auckland. SLR increments have been added onto the 1% AEP storm-tide elevation, which was calculated for the present-day mean sea level Graphics: Sanjay Wadhwa, NIWA; based on Auckland Council LiDAR data. From Stephens et al. (2017).

Figure 8-35 shows the depth (and area) of inundation for a 1% AEP storm tide at present-day mean sea level, and two SLR scenarios, +0.4 m and +0.8 m. The maps show there is little exposure to coastal storm inundation at present, but this will increase as the sea rises. The maps also show the increasing depth (severity) of future inundation at Mission Bay. Figure 8-36 shows the frequency (and area) of inundation for a 1% AEP storm-tide at present-day mean sea level and the same two SLR scenarios. The maps show that coastal storm inundation is infrequent at present-day mean sea level but becomes increasingly likely with SLR. In combination with Figure 8-35, the maps show both the expected depth and frequency of future inundation. The combination of these plots provides information that is more useful for decision-making than any of the plots in isolation. For example, a property located beside the first street back from the sea is safe at present, but after 0.8 m of SLR can expect to be inundated about 10 times per year by about 0.5 m or more of water.

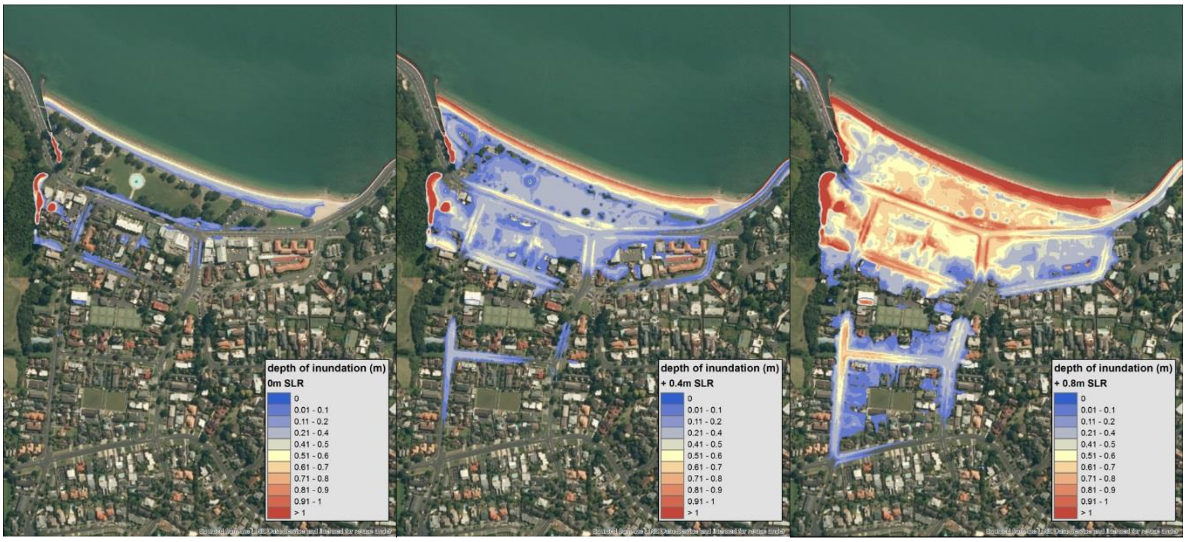

Figure 8-35: Depth of inundation (m) at Mission Bay, Auckland, for a 1% annual exceedance probability storm-tide covering present-day mean sea level and two SLR scenarios. Left: 1% AEP storm-tide at present-day mean sea level. Middle: plus 0.4m SLR. Right: plus 0.8m SLR. Derived from the study of Stephens et al. (2017).

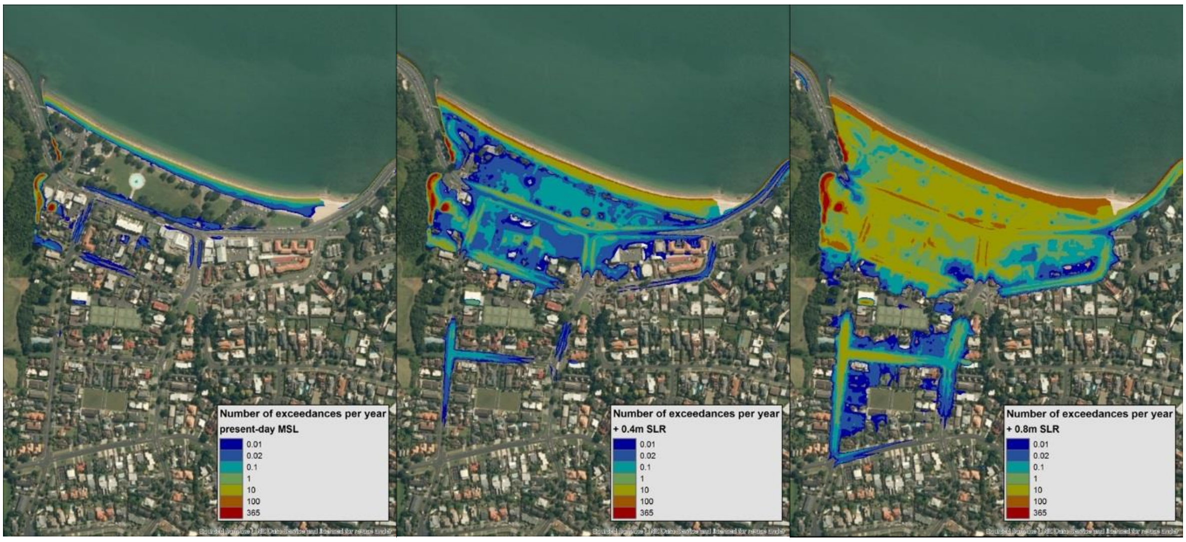

Figure 8-36: Frequency of inundation (exceedances per year) at Mission Bay, Auckland, for a 1% AEP storm-tide, covering present-day mean sea level and two SLR scenarios. Left: 1% AEP storm-tide at present-day mean sea level. Middle: plus 0.4m SLR. Right: plus 0.8m SLR. Derived from the study of Stephens et al. (2017).

Auckland International Airport

Maps of coastal-storm inundation were produced for land at Auckland Airport, both at present day mean sea level and for RSLR scenarios of 0.5, 1.0 and 1.5 m relative to present-day mean sea level (Stephens et al., 2016a) (Figure 8-37 to Figure 8-40).

Coastal-storm inundation (including wave setup but excluding wave run-up) of Auckland Airport is not expected at present-day mean sea level. However, an extreme coastal-storm inundation event would inundate land at the western edge of Auckland Airport after RSLR of 0.5 m. The areal extent (and frequency) of inundation would further increase after progressively higher RSLR. An extreme coastal-storm inundation event would first breach the western sea wall after 5–10 cm of RSLR, although the extent of inundation would be minor at such low RSLR.

At present-day mean sea level, Wiroa Island (southeast of the runway) is already likely to be inundated during an extreme coastal-storm inundation event. The areal extent of inundation on Wiroa Island during extreme events increases over only a relatively small part of the island with RSLR of up to 1.5 m, although the depth and frequency of inundation would increase.

The frequency of coastal-storm inundation will also increase with RSLR. After 0.5 m of RSLR we would expect about 0.3 inundation events per year, or one event every 3 years. After 1.0 m of RSLR we would expect about 64 inundation events per year, and after 1.5 m of SLR we would expect about 390 inundation events per year, which is about half of all high tides per year - but only in the areas highlighted in the maps below. Auckland International Airport Ltd. is actively working on stormwater and coastal inundation adaptation measures.

For more information about the methodology and other results from this study, the reader is directed to Stephens et al. (2016a).

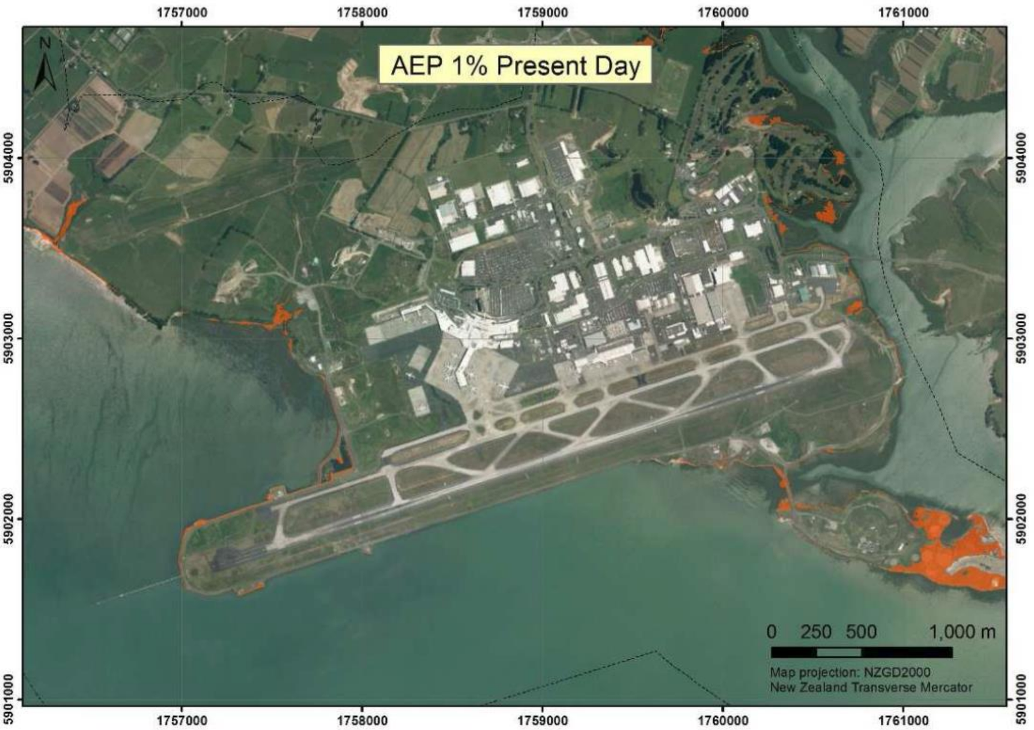

Figure 8-37: Map of the areal extent of coastal-storm inundation from a 1% AEP storm-tide + wave setup at present-day MSL at Auckland Airport. Orange shading indicates wet areas.

Figure 8-38: Map of the areal extent of coastal-storm inundation from a 1% AEP storm-tide + wave setup at present-day MSL + 0.5 m SLR at Auckland Airport. Orange shading = wet areas.

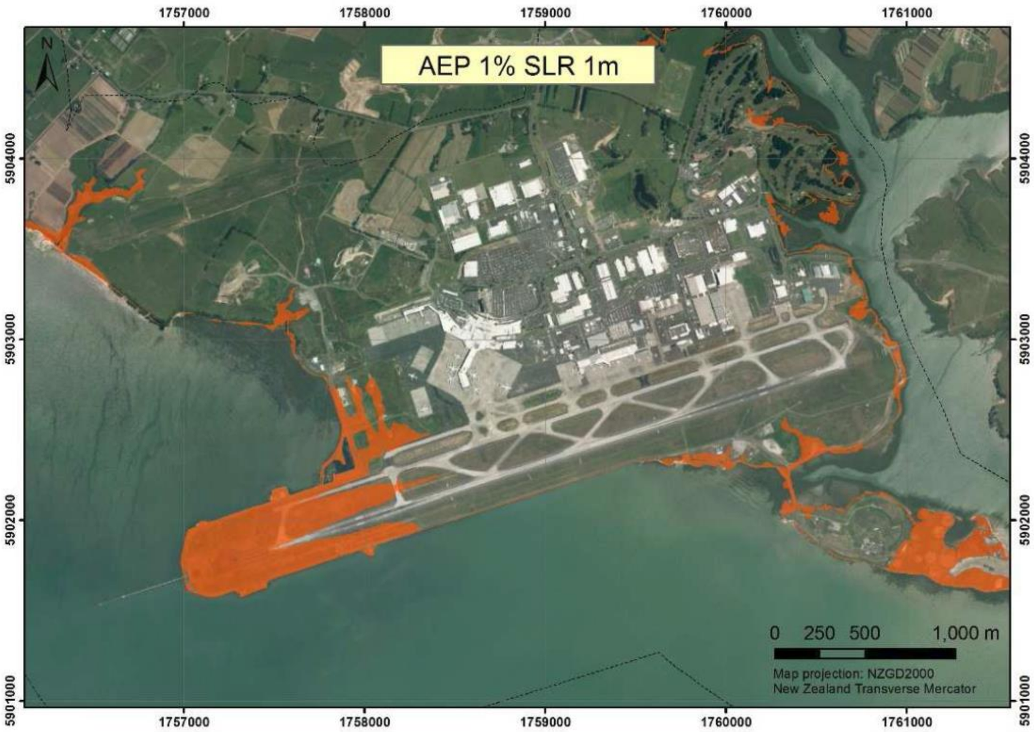

Figure 8-39: Map of the areal extent of coastal-storm inundation from a 1% AEP storm-tide + wave setup at present-day MSL + 1.0 m SLR at Auckland Airport. Orange shading = wet areas.

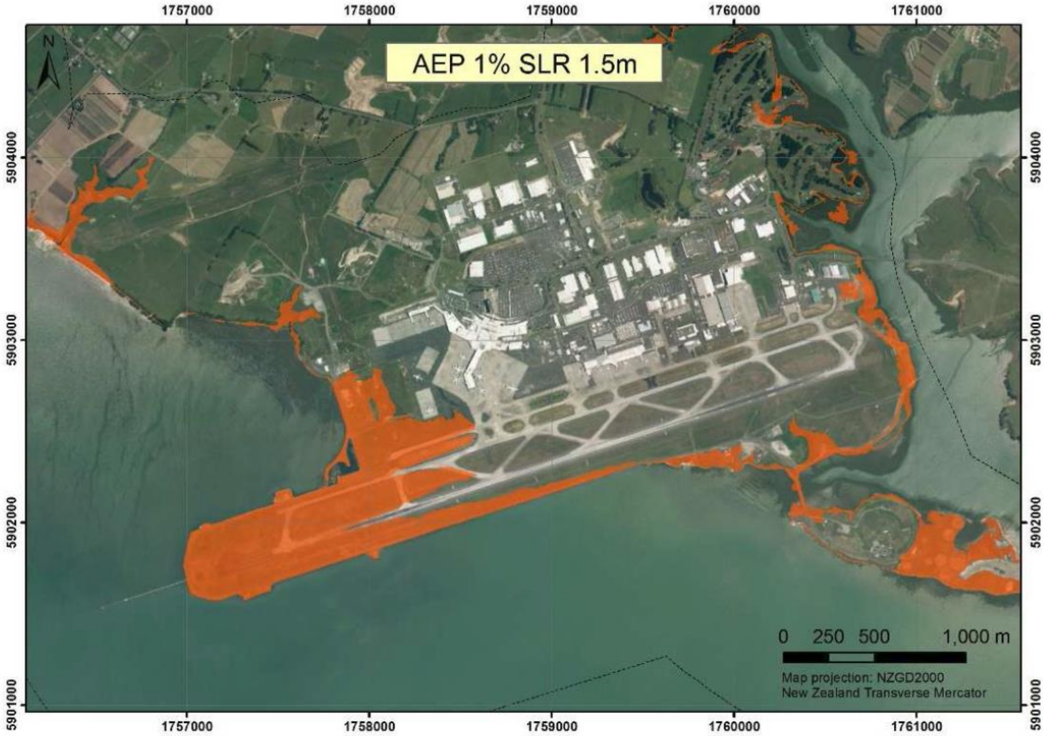

Figure 8-40: Map of the areal extent of coastal-storm inundation from a 1% AEP storm tide + wave setup at present-day MSL + 1.5 m SLR at Auckland Airport. Orange shading indicates wet areas.

Onehunga, Mangere and Manukau

Coastal hazard and SLR inundation exposure was examined for the Onehunga town centre and port land, the Mangere coastline, and the Manukau metropolitan centre and surrounds, plus the land seaward of these (Stephens et al., 2016b). Coastal-storm inundation was mapped at present-day mean sea level and for RSLR scenarios of 0.5, 1.0 and 1.5 m relative to present-day mean sea level.

The Manukau town centre is located ~4 km inland and is sufficiently elevated that it will not be exposed to coastal-storm inundation at present-day mean sea level, nor after a SLR of at least 1.5 m.

In Mangere, no substantial inundation is expected at present-day MSL, for either a 1% or 2% AEP storm-tide. Some properties along Waterfront Road and Moana Ave are projected to be vulnerable to inundation after SLR of ≥ 0.5 m, with the inundation depth and extent increasing with RSLR. Most of the land area that is projected to become inundated in the Mangere area is "greenfields" land, with no existing property development.

At Onehunga, no substantial inundation is expected at present day MSL, for either the 1% or 2% AEP storm-tide. Inundation of a few properties is expected after 0.5 m of RSLR, with the inundation occurring via flow through culverts. There is considerably more property inundation projected after 1.0 m and 1.5 m of RSLR in Onehunga (see Figure 8-44 and Figure 8-45 below). The sea is expected to flow into the area over the existing road for RSLR scenarios of +1.0 and +1.5 m (although the road could be raised when required in the future). The frequency of coastal-storm inundation will increase with RSLR. The road at the eastern end of Waikaraka Public Cemetery has the lowest elevation along the Onehunga coastline, and is the first location where we expect coastal-storm inundation to flow inland over the road. It is lower than the present-day 2% AEP storm-tide. Presently in the highlighted areas, we expect about 0.06 inundation events per year, or one event every 17 years on average.

After 0.5 m of RSLR we would expect about 14 inundation events per year. After 1.0 m of RSLR we would expect about 254 inundation events per year coinciding with high tides, and after 1.5 m of RSLR we would expect about 605 inundation events per year, which is 6 out of 7 high tides – only the lowest high tides would not flow over the road, assuming it was left at its present elevation.

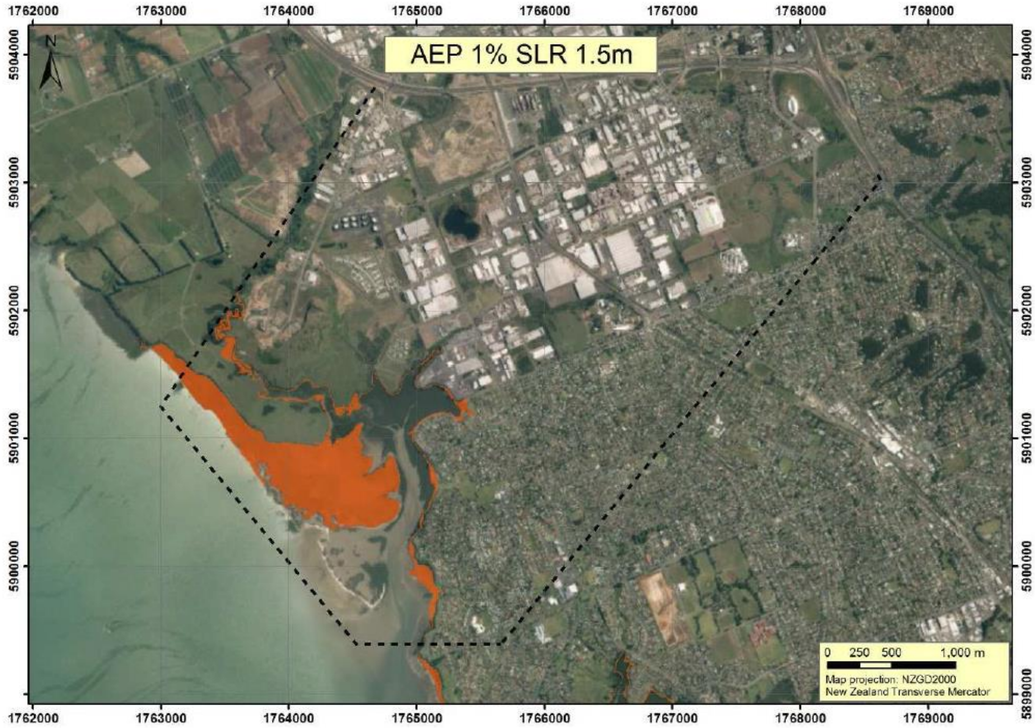

Figure 8-41: Map of the areal extent of coastal-storm inundation at Manukau from a 1% AEP storm-tide at present-day MSL + 1.5 m SLR. Orange shading indicates wet areas. Only the highest-elevation scenario (1% AEP storm-tide + 1.5 m SLR) is mapped for the Manukau area, because that scenario is sufficient to show that the Manukau town centre will not be exposed to coastal-storm inundation after a SLR of 1.5 m or less.

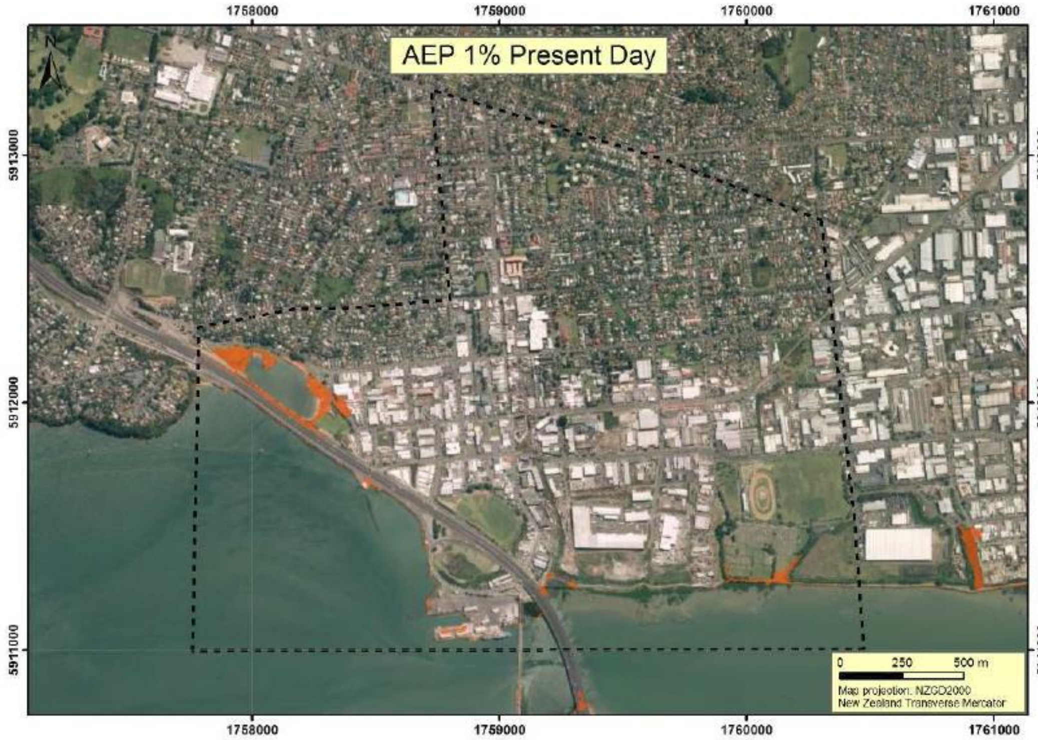

Figure 8-42: Map of the areal extent of coastal-storm inundation at Onehunga from a 1% AEP storm-tide at present-day MSL. Orange shading indicates wet areas.

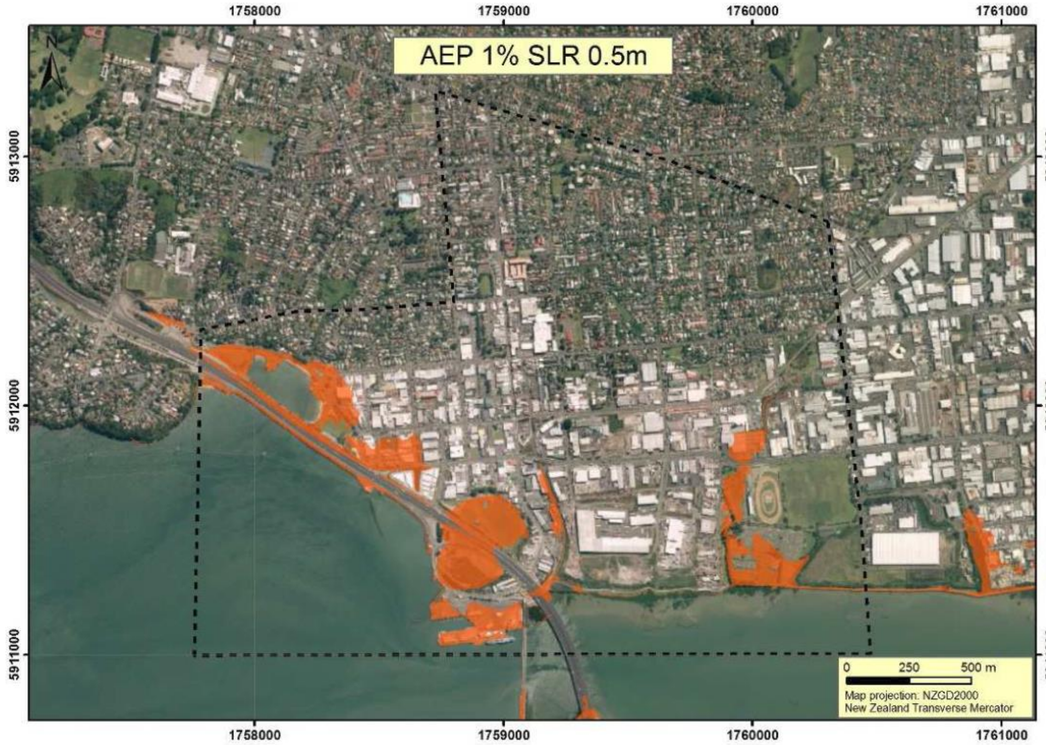

Figure 8-43: Map of the areal extent of coastal-storm inundation at Onehunga from a 1% AEP storm-tide at present-day MSL + 0.5 m SLR. Orange shading = wet areas.

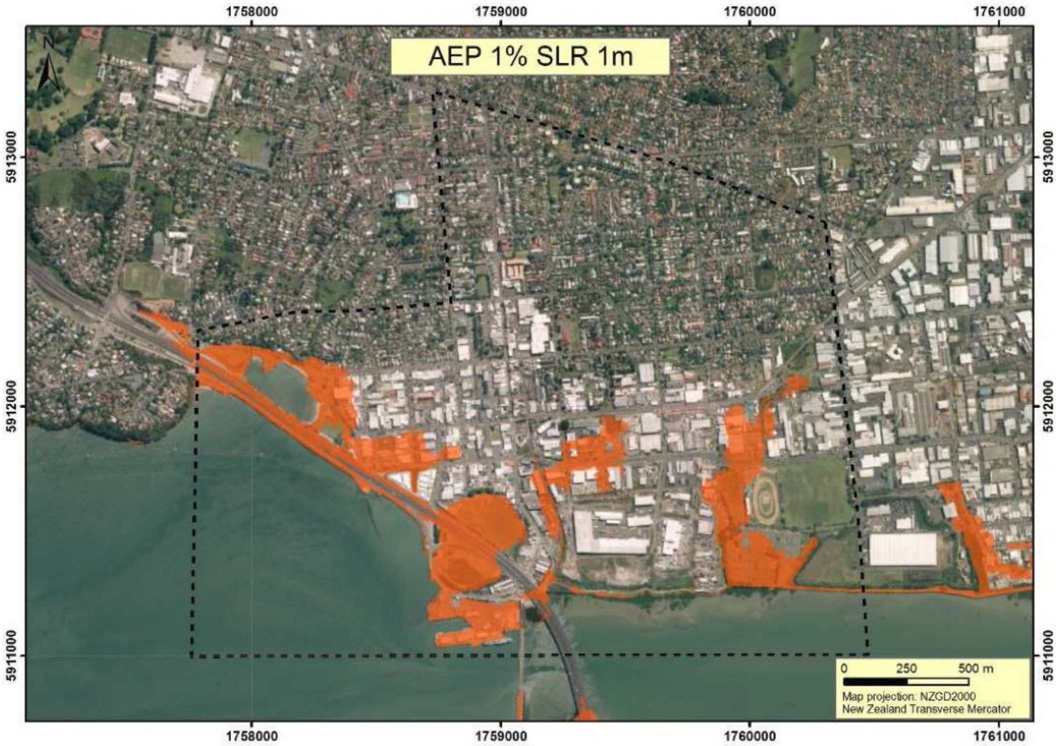

Figure 8-44: Map of the areal extent of coastal-storm inundation at Onehunga from a 1% AEP storm-tide at present-day MSL + 1.0 m SLR. Orange shading = wet areas.

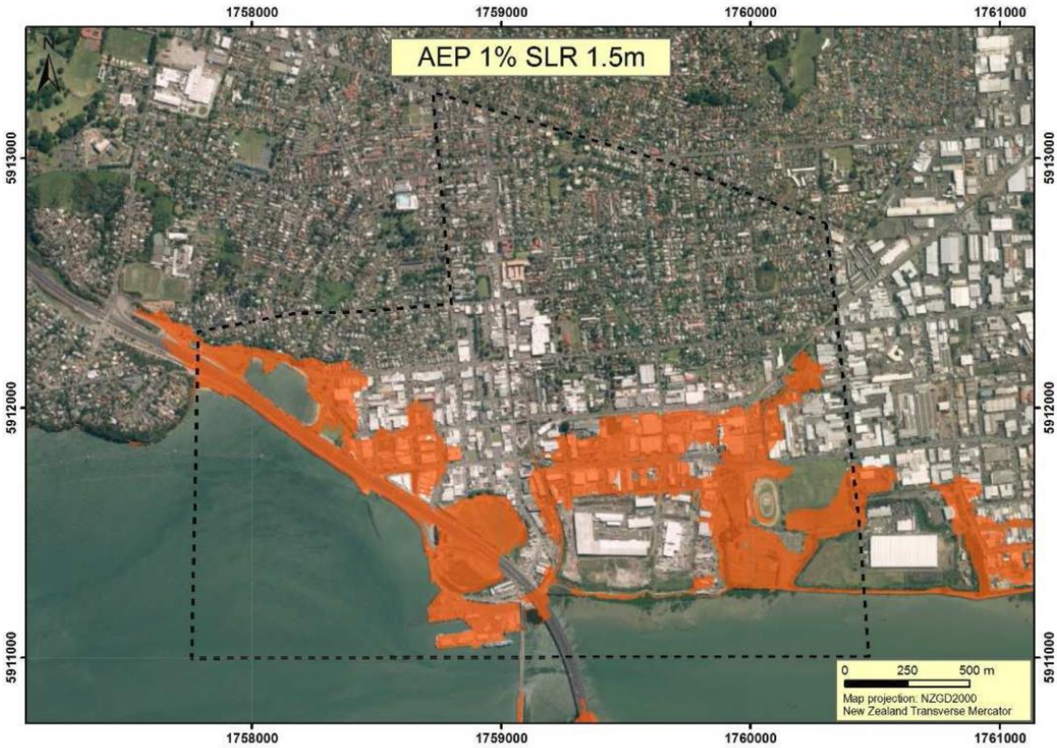

Figure 8-45: Map of the areal extent of coastal-storm inundation at Onehunga from a 1% AEP storm-tide at present-day MSL + 1.5 m SLR. Orange shading indicates wet areas.

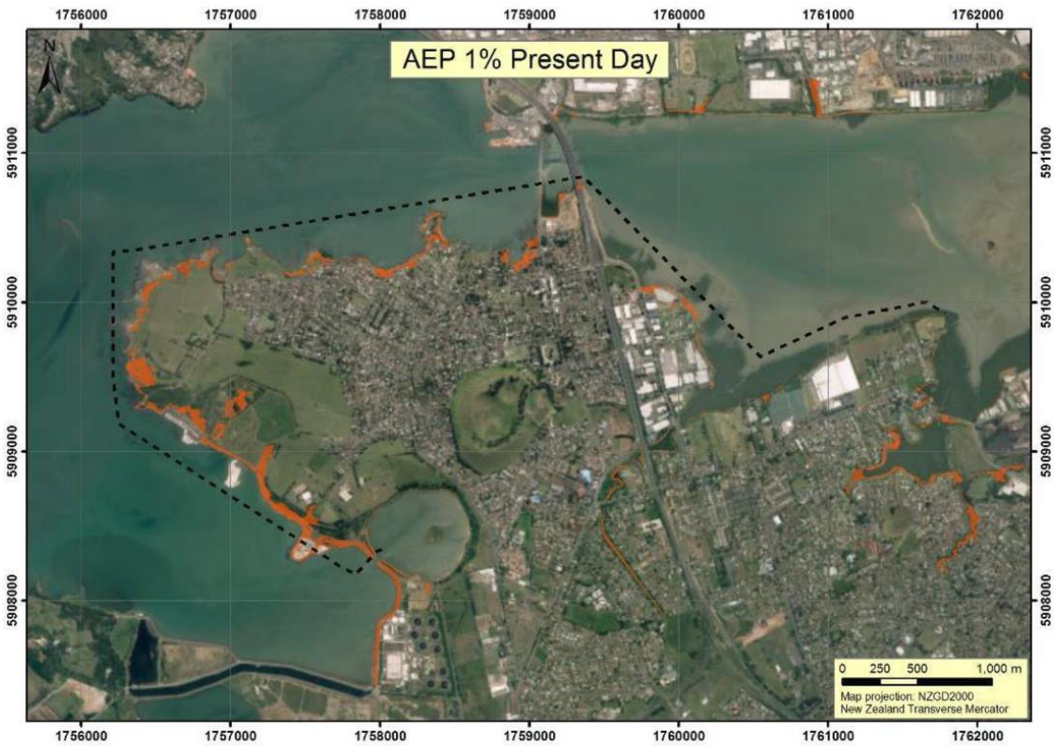

Figure 8-46: Map of the areal extent of coastal-storm inundation at Mangere from a 1% AEP storm-tide at present-day MSL. Orange shading indicates wet areas.

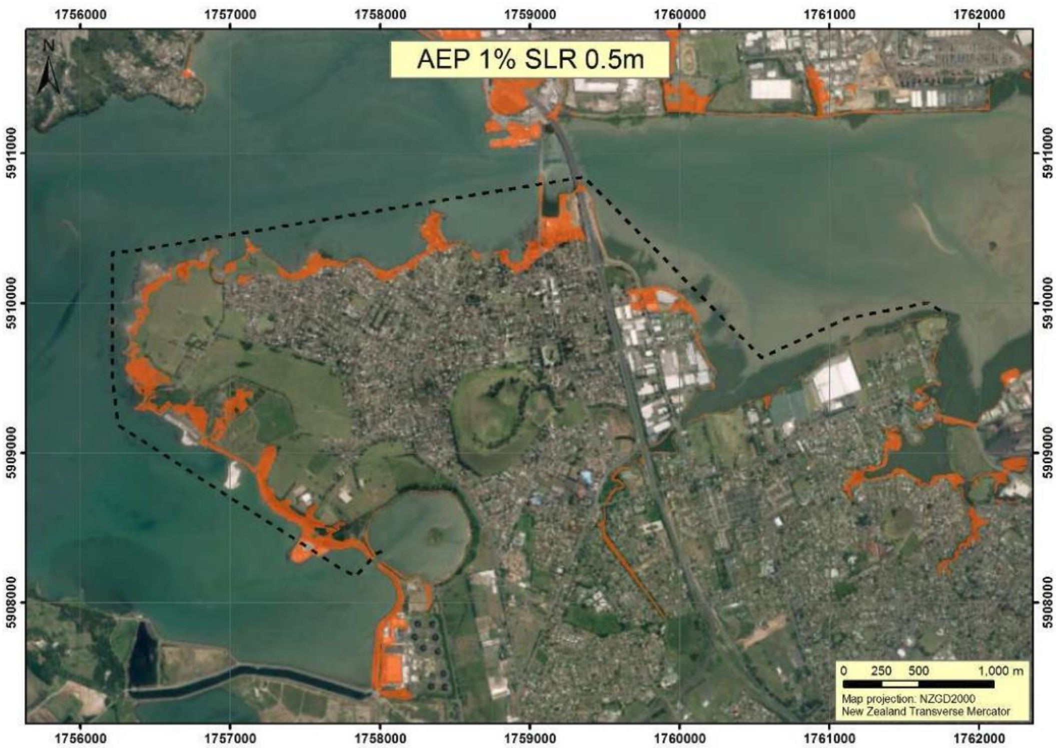

Figure 8-47: Map of the areal extent of coastal-storm inundation at Mangere from a 1% AEP storm-tide at present-day MSL + 0.5 m SLR. Orange shading = wet areas.

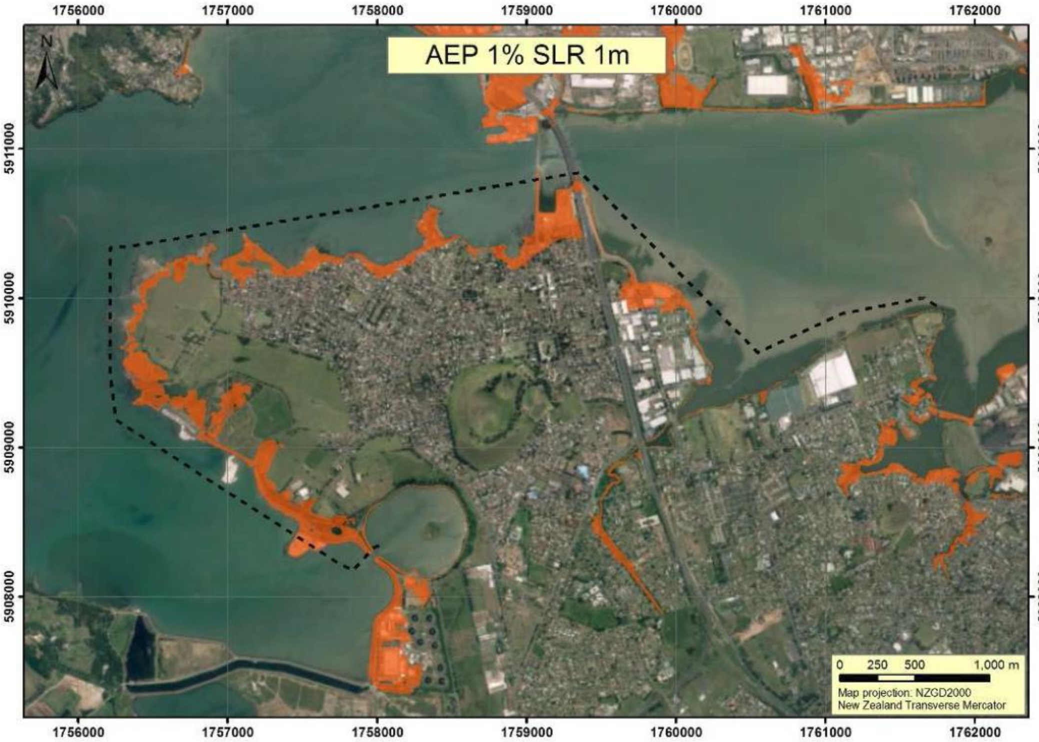

Figure 8-48: Map of the areal extent of coastal-storm inundation at Mangere from a 1% AEP storm-tide at present-day MSL + 1.0 m SLR. Orange shading = wet areas.

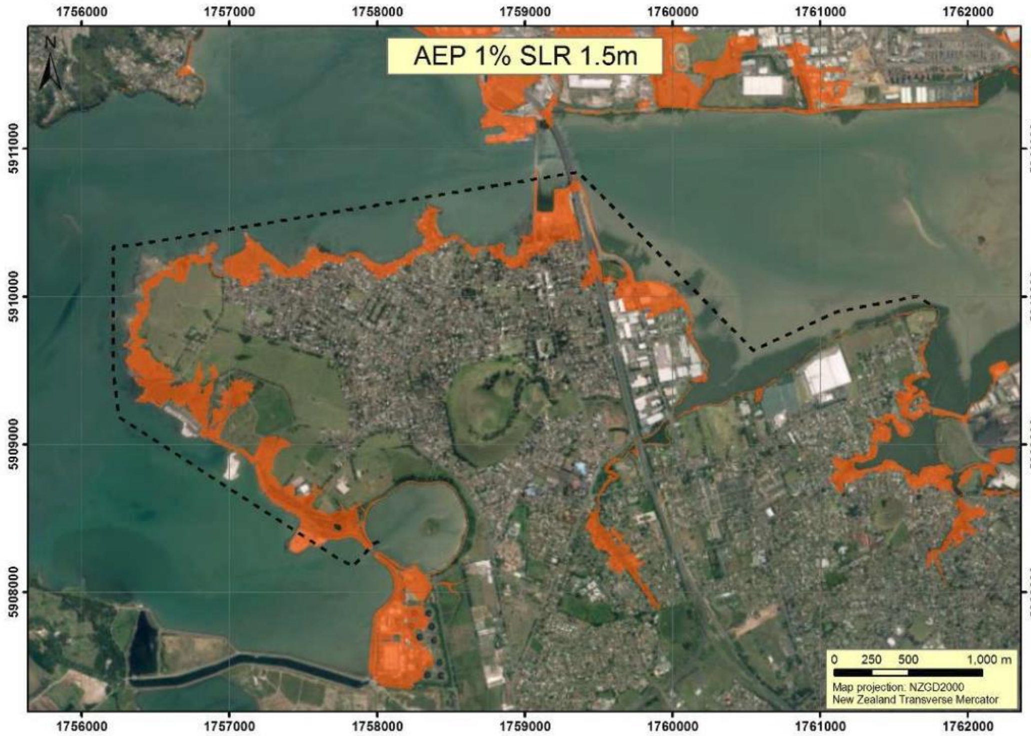

Figure 8-49: Map of the areal extent of coastal-storm inundation at Mangere from a 1% AEP storm-tide at present-day MSL + 1.5 m SLR. Orange shading indicates wet areas.

Coastal sensitivity indices in the Auckland Region

In 2012, NIWA completed a study on the sensitivity of New Zealand's coasts to the effects of coastal climate change (Goodhue et al., 2012). The assessment does not include present issues (e.g., with present or historic coastal erosion), but focuses on the sensitivity of coastal margins for any further change. In conjunction with available geomorphic and oceanographic information, Coastal Sensitivity Indices (CSI) were developed for coastal inundation and coastal erosion for New Zealand's soft shore coastline. These indices were created by combining four geomorphic (exposure, hinterland, sediment type and landform type) and three oceanographic (high tide range and change in storm surge and wave height) variables. Relative scores and weightings were then applied to these variables based on how likely they are to be affected by climate change. For more information on the methodology used to produce the CSI, the reader is directed to Goodhue et al. (2012).

Two national maps were produced, which can be used to identify coastal areas which are more sensitive than others to the potential impacts of climate change-induced coastal erosion and inundation. These have been provided here for the Auckland Region in Figure 8-50 for erosion and Figure 8-51 for inundation.

Figure 8-50 shows that the east coast of the Auckland Region is more sensitive to climate change-related erosion than the west coast, with the most sensitive areas being between Whangaparaoa Peninsula and North Head on the North Shore, and around the Maraetai-Kawakawa Bay coast in the southeast of the region. The least sensitive areas to climate-change related coastal erosion are from Kaipara South Head to the Manukau Heads on the west coast of Auckland.

Figure 8-51 shows a similar pattern, in that the east coast is more sensitive to future inundation (flooding by the sea) than the west coast. The most sensitive areas in the Auckland Region are Omaha Beach and Wenderholm in the northeast of the region, and areas near Clevedon in the southeast of the region. The least sensitive area to future coastal inundation is from Kaipara South Head to the Manukau Heads on the west coast.

The CSI is not an absolute measure of potential risk of future inundation or erosion under climate change, and consequently it should not be used as a replacement for local (beach scale) risk assessments. Rather the CSI has been designed to provide a high-level scoping index and comparison of the relative (higher or lower) sensitivity to climate change of one part of the coast compared to another.

RSLR will not only affect soft shorelines like beaches, but some soft cliffs may also be affected. Much of Auckland's eastern coastline is bordered by cliffs composed of sandstones with intercalated mudstones (Reinen-Hamill et al., 2006). Most of these cliffs are fronted by a gently sloping shore platform, some of which have a steep seaward edge. Erosion rates are likely to increase on these coasts under SLR, because deeper water on the platform will result in reduced nearshore wave dissipation and likely higher wave impact pressures on the cliffs. Any increase in storm frequency will also increase erosion rates. This process is non-linear, however, and it is not currently possible to estimate how much greater erosion rates will be at the cliff toe. The cliff faces will also be subject to sub-aerial weathering and erosion, along with increasing issues from more intense rainfall for managing stormwater and overland flow on adjacent land, which is partly why coastal cliff retreat is a non-linear process only partially related to increased sea level and wave activity at the base of the cliffs. The cliff top will also be sensitive to changes in drainage and moisture processes, such as extremes of prolonged drought punctuated by heavy rainfall events.

Reinen-Hamill et al. (2006) provided a regional overview of the area susceptible to coastal erosion in the Auckland Region for the next 100 years, with different likelihoods of erosion assessed. The reader is directed to this report for information on potential coastal erosion for specific parts of Auckland's coastline.

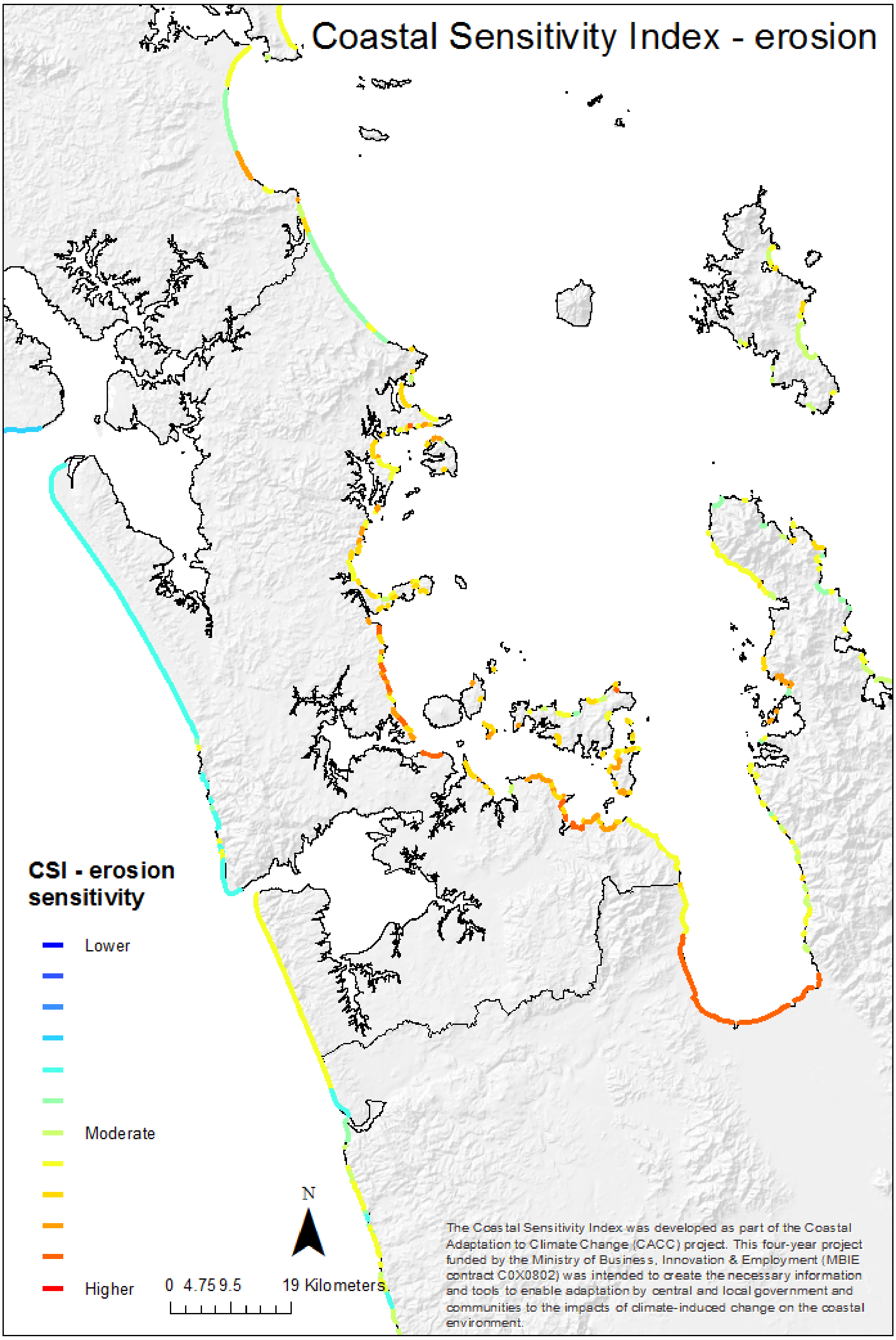

Figure 8-50: Coastal sensitivity index for erosion for the Auckland Region. After Goodhue et al. (2012).

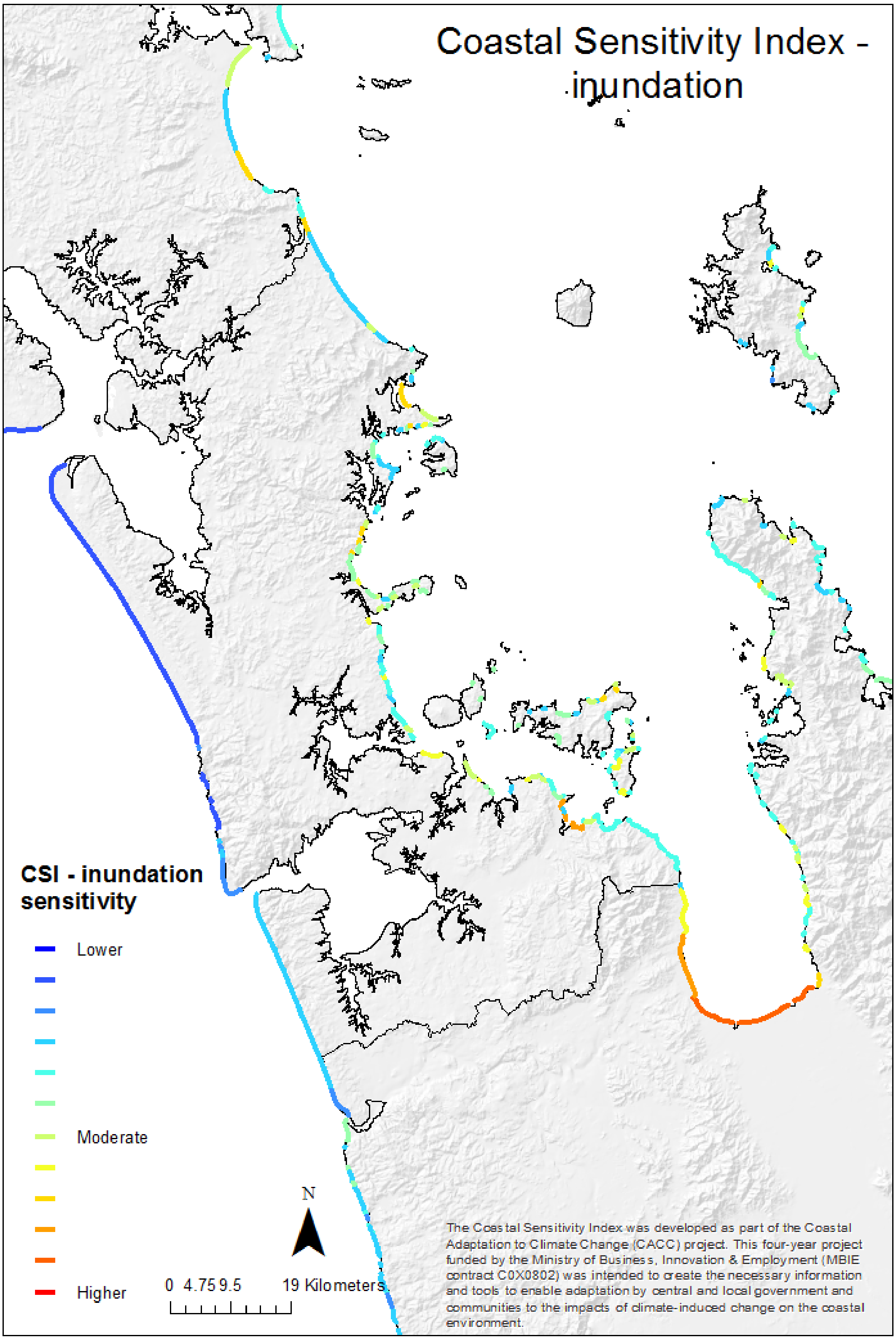

Figure 8-51: Coastal sensitivity index for climate change-induced inundation (flooding by the sea) for the Auckland Region. After Goodhue et al. (2012).

Risk of coastal assets to sea-level rise

In 2015, a report for the Parliamentary Commissioner for the Environment was published covering national and regional risk exposure in low-lying coastal areas (Parliamentary Commissioner for the Environment, 2015a). Some of these results are presented here for the Auckland Region in Figure 8-52 to Figure 8-59. Coastal risk exposure was expressed as built assets (e.g. buildings, roads, railways, three-waters infrastructure), land cover, and usually resident population present in the zone inundated by 100-year return period storm-tide event (1% AEP) at the present day and with 1 m and 2 m of RSLR. The types of buildings included in each category are defined in Table 8-2. The Replacement costs for buildings in New Zealand dollars as of 2011 were also calculated. The methodology used here for this updated Auckland risk-exposure assessment is the same as for Parliamentary Commissioner for the Environment (2015a), but with replacement values for buildings in 2016 NZ dollars[17].

Table 8-2: Building use categories for coastal asset risk analysis, after Parliamentary Commissioner for the Environment (2015a).

Building use category	Building uses in each category
Residential	Residential dwellings Commercial accommodation Rest home Lifestyle
Commercial	Business Fast Moving Consumer Goods
Industrial	Manufacturing Storage Chemical, energy, hazardous Forestry, mining Farm
Critical	Government Territorial Authority/Civil Defence Lifeline utilities Police Hospital/clinic Fire Station Education
Community	Community Religious
Other	Parking Clear site Other

By far the largest proportion of buildings at risk from a 1% AEP storm-tide event plus RSLR of +1 m or +2 m in the Auckland Region are residential buildings, with more than ten times the number of buildings than in any other category with +2 m of RSLR (Figure 8-52). The number of residential buildings affected increases from 1300 structures at present to 4450 structures with 1 m RSLR, and 9900 structures with 2 m SLR. As such, residential buildings have the highest replacement cost out of all building categories, although the replacement cost of affected industrial and commercial buildings is also quite high (Figure 8-53). In line with the effect on residential buildings, the usually-resident

[17] One minor difference in methodology is that the 'natural environment' land cover extent excludes 'estuarine, open water' and 'mangroves' in this report as these are seaward of MHWS-10.

population affected (based on census results from 2013) increases with different levels of SLR (Figure 8-54).

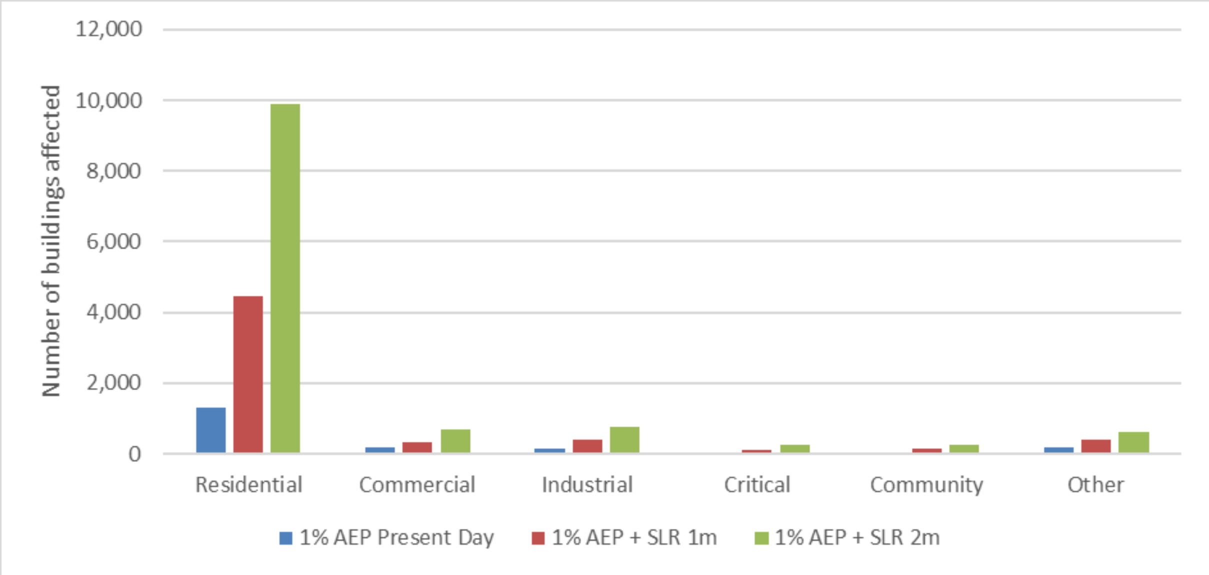

Figure 8-52: Number of buildings in the Auckland Region inundated by a storm-tide event with a 1% AEP at present day sea level and with 1 m and 2 m of RSLR. Types of buildings in each category are defined in Table 8-2.

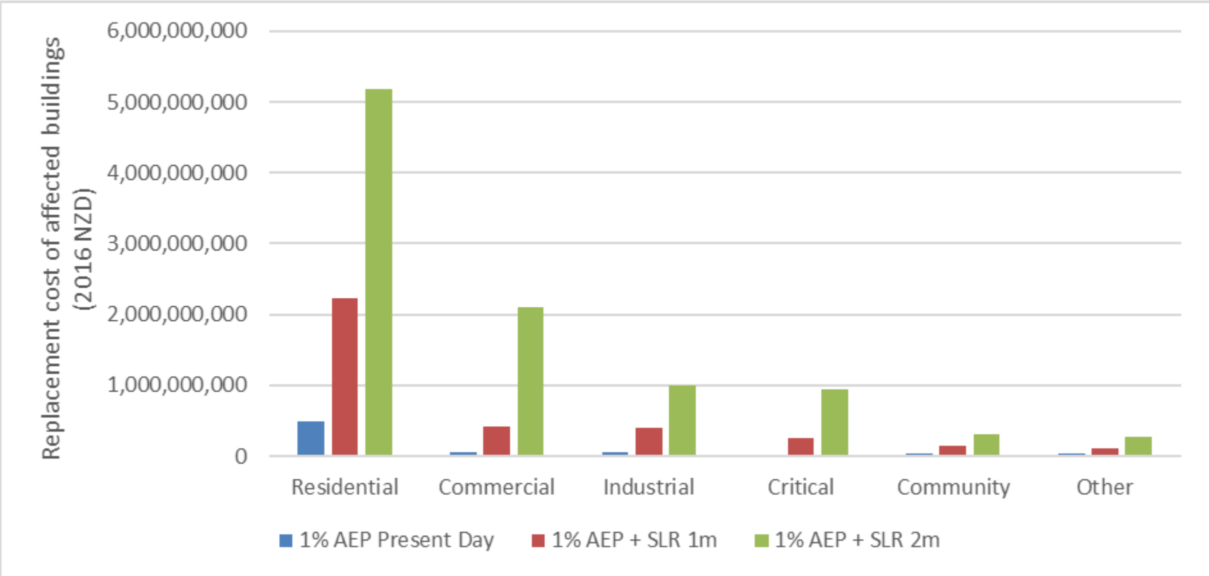

Figure 8-53: Replacement cost of buildings in the Auckland Region inundated by a storm-tide event with a 1% AEP at present day sea level and with 1 m and 2 m of RSLR. (2016 NZD$). Types of buildings in each category are defined in Table 8-2.

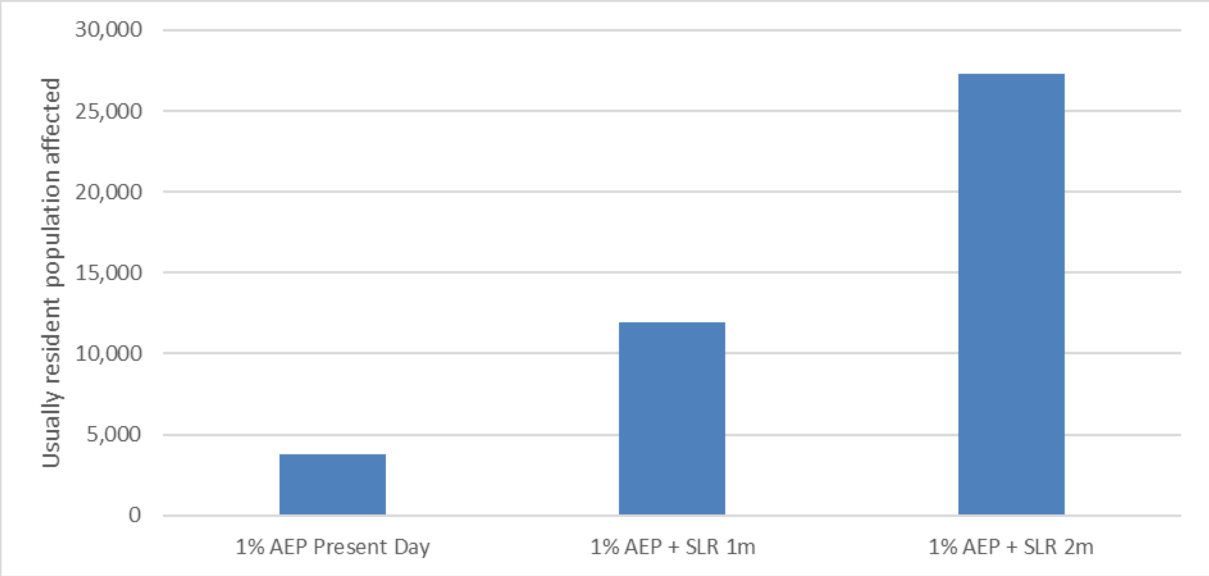

Figure 8-54: Usually resident population affected by a storm-tide event with a 1% AEP at present day sea level and with 1 m and 2 m of RSLR. Population data based on census 2013.

The cumulative length of roads that would be inundated with a 1% AEP storm-tide event and 1 m RSLR is more than double that of the present-day 1% AEP event, and four times more with 2 m RSLR (85 km exposed at present, 210 km with 1 m RSLR, and 342 km with 2 m RSLR) (Figure 8-55). With 2 m of SLR, almost three times more railway corridor would be inundated than at present-day with the 1% AEP storm-tide event (Figure 8-56).

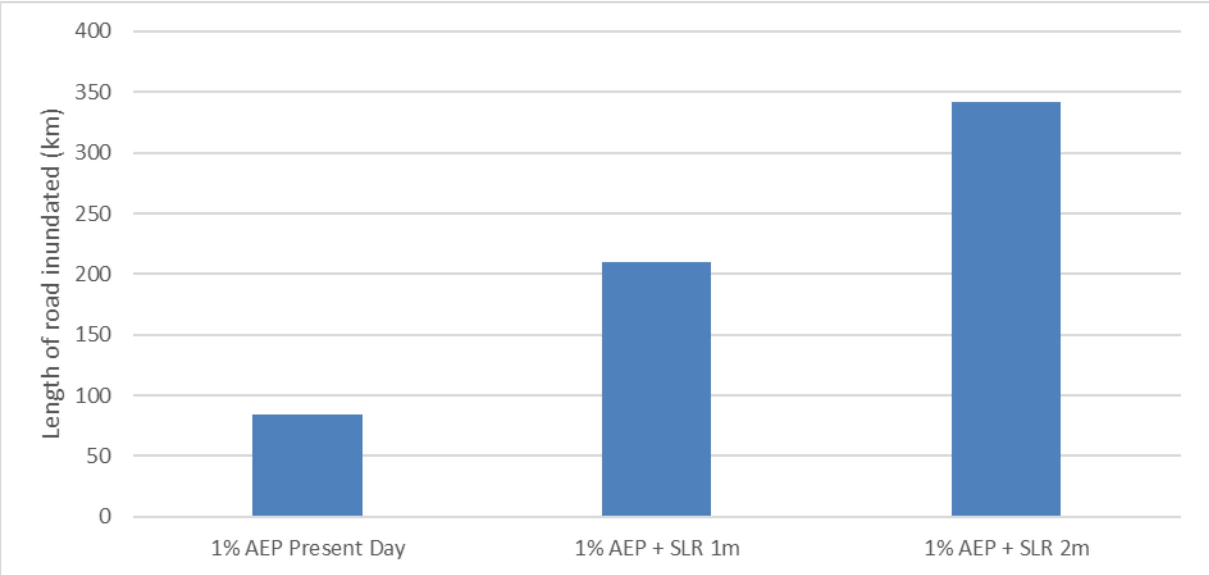

Figure 8-55: Length of road in the Auckland Region inundated by a storm-tide event with a 1% AEP at present day sea level and with 1 m and 2 m of RSLR.

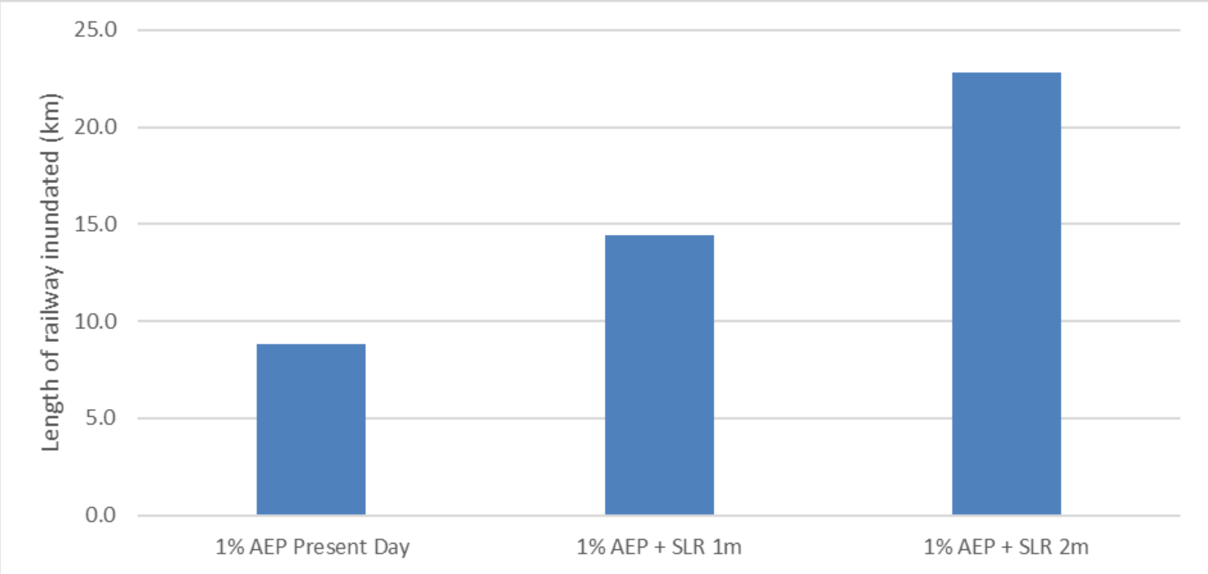

Figure 8-56: Length of railway in the Auckland Region inundated by a storm-tide event with a 1% AEP at present day sea level and with 1 m and 2 m of RSLR.

A considerable amount of three-waters infrastructure (potable water, wastewater and stormwater) is at risk from rising sea levels. In terms of the numbers of nodes affected (nodes for each type of water infrastructure are defined in Table 8-3), potable water and wastewater have a similar number of nodes affected (1000-1400 under present 1% AEP storm-tide event, 4500-5000 under 1 m RSLR, 9300-9600 under 2 m RSLR), but this number is approximately doubled for the number of stormwater nodes affected by RSLR (Figure 8-57). The length of pipes affected by a present-day 1% AEP storm-tide event for potable water, wastewater and stormwater, and stormwater drains and channels is less than 100 km for each type, but this increases substantially for all categories with RSLR of 1 m and 2 m (Figure 8-58). For example, over 400 km of wastewater pipelines are at risk from inundation for a 1% AEP storm-tide event + 2 m of RSLR.

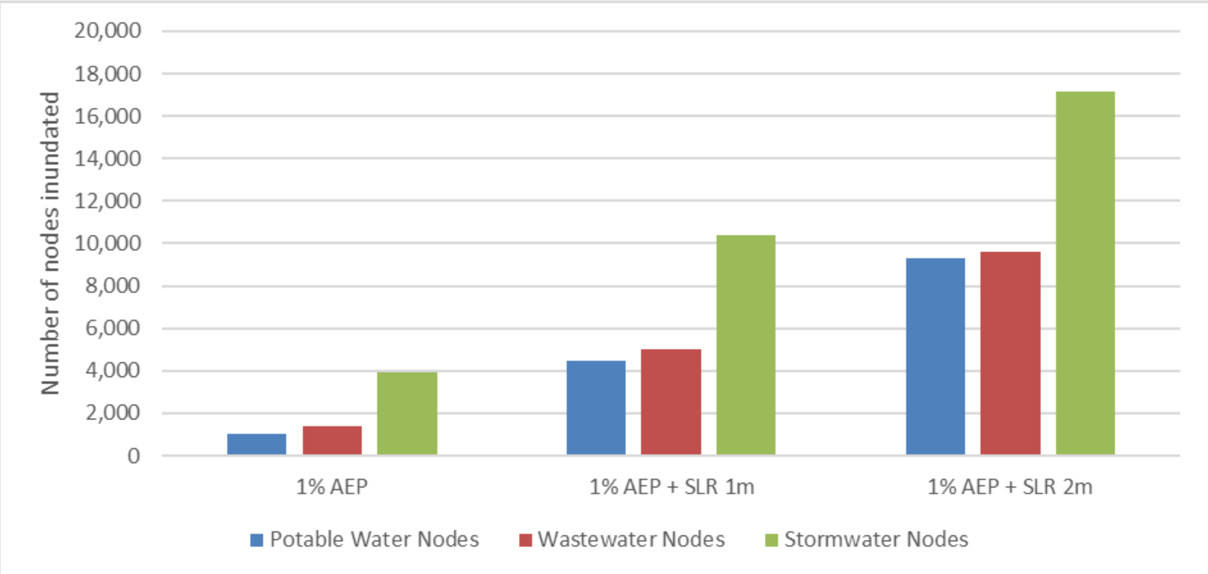

Figure 8-57: Number of potable water, wastewater and stormwater nodes in the Auckland Region inundated by a storm-tide event with a 1% AEP at present day sea level and with 1 m and 2 m of RSLR. Nodes are defined in Table 8-3.

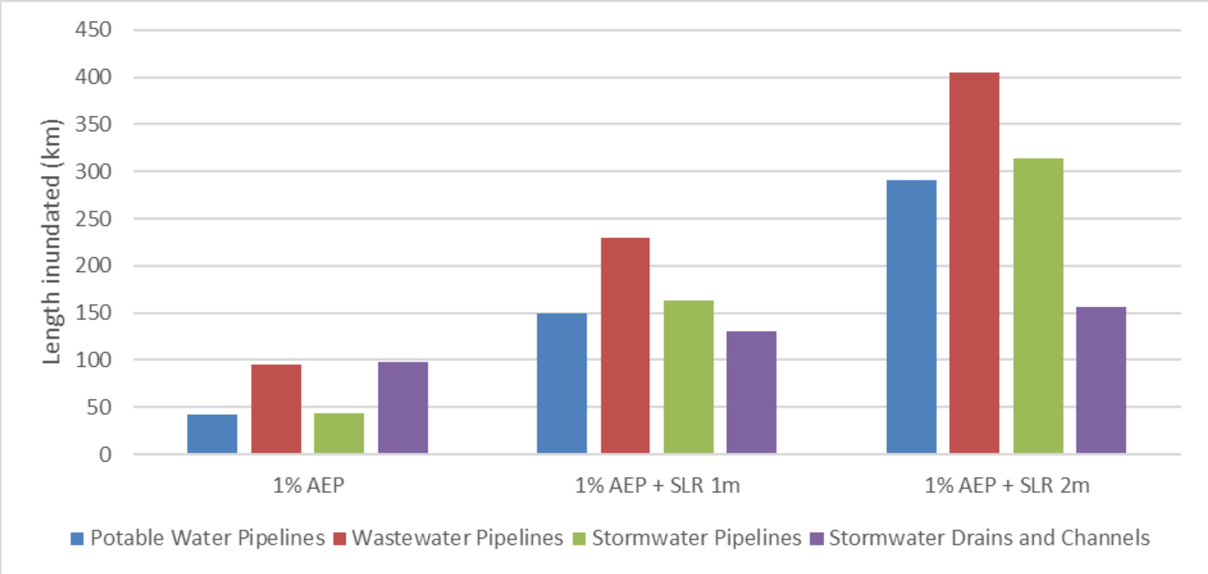

Figure 8-58: Length of potable water, wastewater and stormwater pipes and stormwater drains and channels in the Auckland Region inundated by a storm-tide event with a 1% AEP at present day sea level.

Table 8-3: Classification of potable water, wastewater and stormwater nodes and stormwater drains and channels by Auckland Council.

Potable Water	Wastewater	Stormwater	
Nodes	**Nodes**	**Nodes**	**Drains and Channels**
Cabinet	Chamber	Catchpit	Channel
Chamber	Fitting	Electrical	Forebay
Fitting	Manhole	Inlet and Outlet	Overland Flow path
Hydrant	Pump Station	Man hole and Chamber	Spillway
Meter	Structure	Natural Structure	Watercourse
Pump Station		Pump	
Reservoir		Septic Tank	
Valve		Soakage System	
		Water Treatment Device	
		Well	
		Water Treatment Facility	

Primary production land is most at risk from RSLR as it is the largest coastal land use by area in the Auckland Region (Figure 8-59). About 88 km^2 is exposed to inundation at present with a 1% AEP storm-tide event, but this increases to 120 km^2 with 1 m of RSLR and 140 km^2 with 2 m of RSLR. Exposure to coastal flooding of the built environment land area doubles with 1 m of RSLR compared to present, and quadruples with 2 m of RSLR compared to present (Figure 8-59).

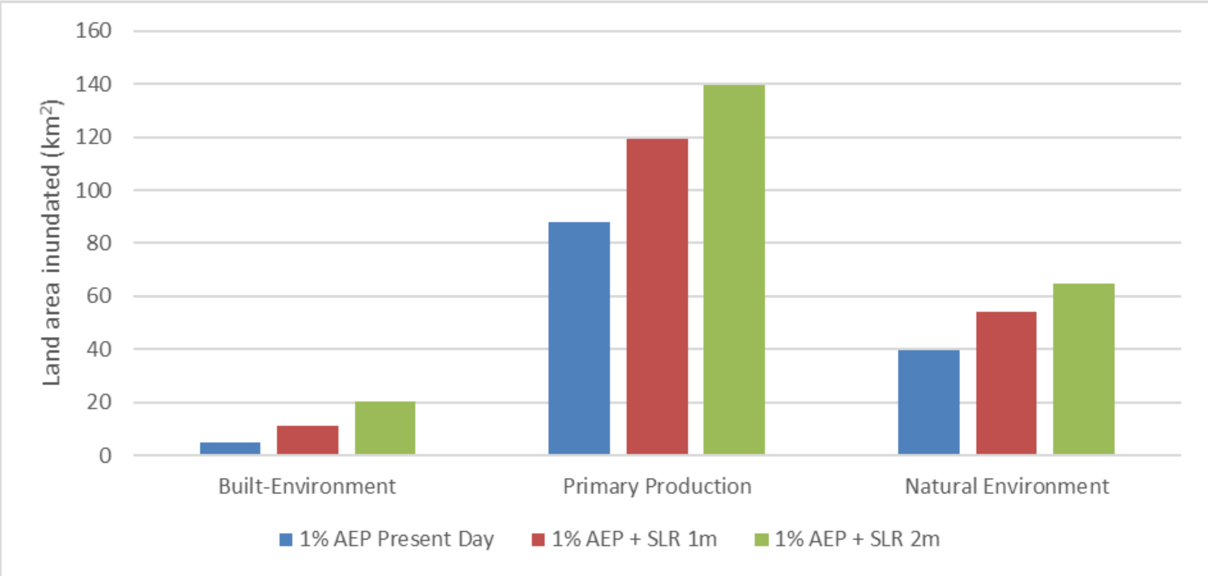

Figure 8-59: Land area in the Auckland Region inundated by a storm-tide event with a 1% AEP at present day sea level and with 1 m and 2 m of RSLR.

8.4 Air quality and climate change

Key messages

- How climate change will interact with emissions in Auckland is highly uncertain beyond broad, first principles-based descriptions.
- As winter temperatures rise, the demand for residential heating will diminish and so will high wintertime concentrations of black carbon and particulate matter from burning solid fuels like wood and coal.
- Changing rainfall patterns may result in heavier rainfall events but longer dry stretches, so pollutants may not be washed out of the atmosphere as often, increasing the annual pollutant concentrations.
- The impact of climate change on air masses over the Auckland region will impact air quality at the regional scale and impact the potential for high (and low) concentration periods.
- To predict future health impacts from air quality and climate interactions, air quality models will need to be run with the relevant climate and emissions projections.
- PM_{10} emissions from burning solid fuels in Auckland are projected to decline by 63% by 2040 compared with 2006.
- Transport emissions are projected to decline by 67% by 2040 compared with 2006.

Auckland's changing climate may have impacts upon its air quality. In this section, the general interactions between air quality and climate change are introduced. Then the specific projections described in previous sections of this report are reviewed considering potential impacts on air quality (Section 8.4.1). Section 8.4.2 reviews the international and local literature concerning air quality predictions and health impacts under different climate change scenarios, and the relationship between meteorology and air quality in Auckland.

Air quality pollutants are researched and regulated due to their known and suspected health impacts. This research (and regulation) has historically been separate from research regarding climate forcing pollutants due to the very different spatial and temporal scales at which each work. From a climate perspective, traditional air quality pollutants were seen as having a minor and relatively uncertain role. Mounting evidence of their diverse impacts has reduced those uncertainties to the point where the category of Short Lived Climate Pollutants (SLCPs) is now becoming commonplace, particularly as regulators strive for comparatively easy and quick reductions in climate forcing emissions. The SLCPs are:

- Methane
- Black carbon
- Tropospheric ozone
- Hydrofluorocarbons (HFCs)

The most recent United Nations Emissions Gap Report (UNEP, 2017) acknowledged the importance of strong actions on SLCPs like black carbon to reduce the short-term warming effect and thus achieve the targets as stated in the Paris Agreement.

There is some overlap between SLCPs and traditional air quality pollutants as regulated by the National Environmental Standards (NES) in New Zealand. The air quality pollutants of concern in Auckland (namely NO_2 (nitrogen dioxide) and PM_{10} (particles less than 10 µg m^{-3})) have limited impact on climate forcing, except for black carbon, which is a significant wintertime component of $PM_{2.5,}$ the finer fraction of PM_{10}, due burning solid fuels for heating.

In addition to certain air quality pollutants having an impact on climate, changes in climate may have an impact on atmospheric and airborne pollutant concentrations through these pathways:

- Increasing occurrence of meteorological conditions that can lead to greater or lesser generation of pollutant, either:
  - directly, for instance solar radiation driving ozone generation, or more high winds generating sea-spray
  - indirectly, through changing climate leading to changes in anthropogenic emissions due to behavioural changes
- Increasing occurrence of meteorological conditions that can lead to better or poorer dispersion or removal of pollutant once emitted. For example:
  - rainfall washing out pollutants
  - low wind speeds allowing accumulation of pollutants

Figure 8-60 is a schematic of these concepts.

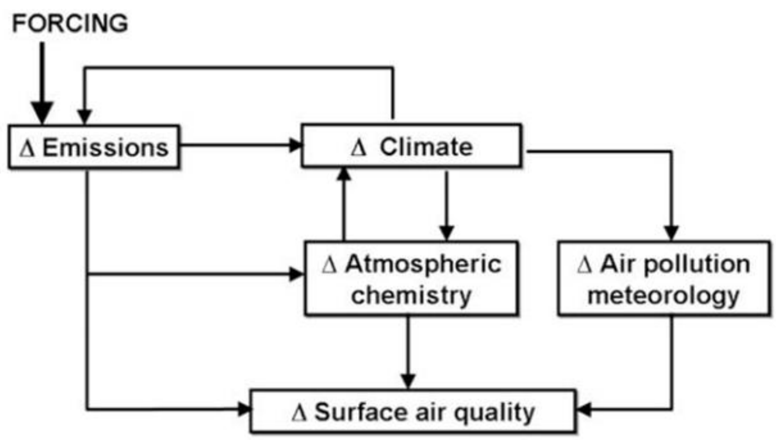

Figure 8-60: Effect of climate change on surface air quality placed in the broader context of chemistry – climate interactions (Jacob and Winner, 2009).

8.4.1 Climate Change in Auckland and potential impacts on air quality

Possible changes in air quality are described here based upon the projected climate changes in Auckland from RCP8.5, discussed earlier in this report. Figure 8-61 summarises the potential changes.

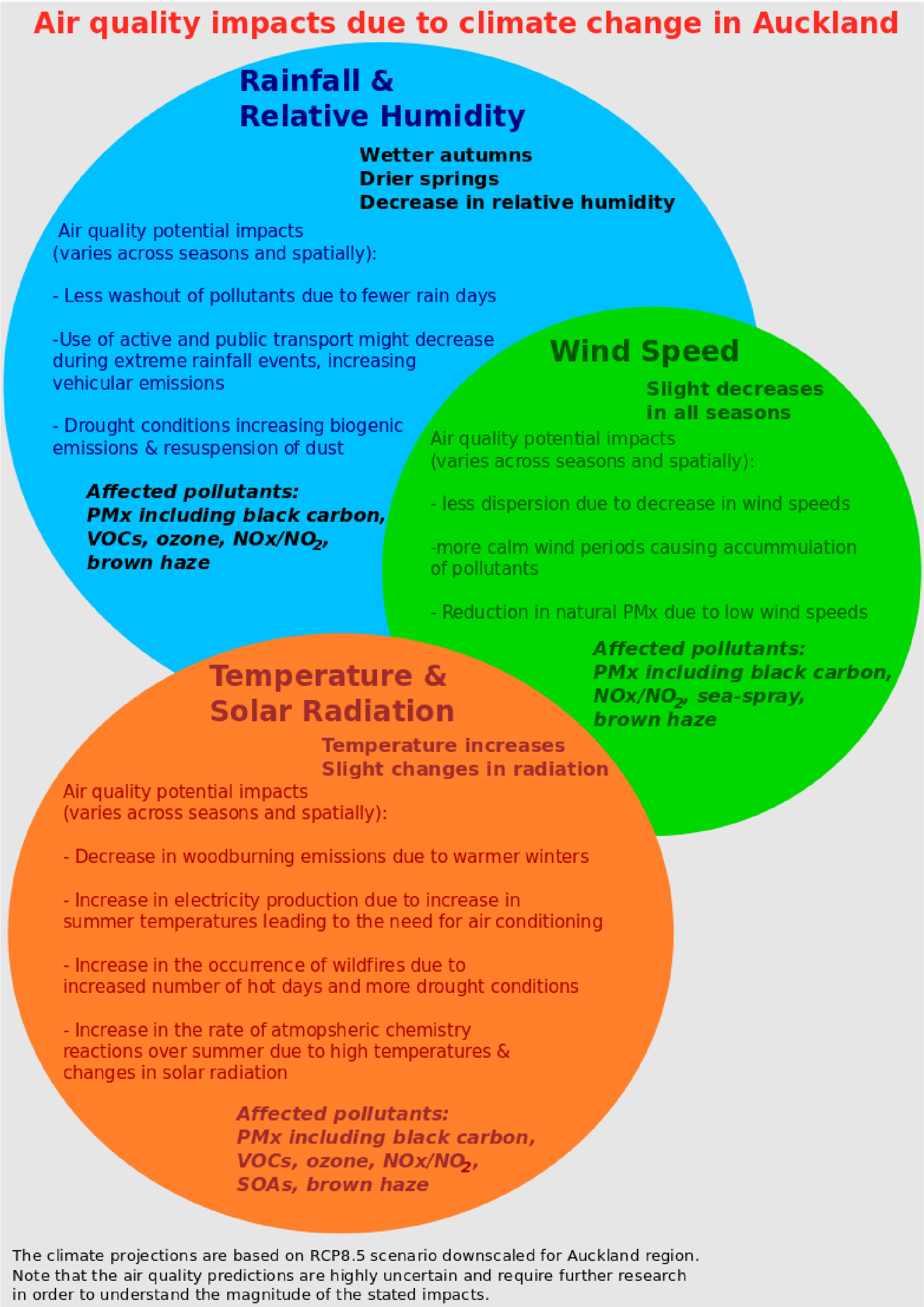

Figure 8-61: Potential air quality impacts attributable to climate projections in the Auckland Region.

Changes to temperature and solar radiation in Auckland

Changes in temperature may drive changes in anthropogenic air pollution emissions in Auckland. Winters are projected to get warmer and therefore less heating may be required. Assuming no other changes in pressures on wood burner use, wood burning emissions should decline. Summer temperatures are also projected to increase, which may stimulate more energy demand for air conditioning. Depending on the nature of the electricity production this may result in greater emissions outside of Auckland (at the point of electricity generation).

Very small changes in solar radiation are projected, which may slightly increase the rate of atmospheric chemistry reactions over summer. The net result of these increased rates on monitored pollutant concentrations is highly uncertain and would require further research to investigate the size and nature of expected impacts.

Changes to rainfall, drought and relative humidity in Auckland

Fewer, but increasingly intense rain days for all seasons except spring (depending on the climate scenario) may lead to less washout of pollutants from the urban atmosphere. Conversely, spring is projected to become drier which may exacerbate the resuspension of dust. More drought conditions may increase biogenic emissions of ozone precursors such as Volatile Organic Compounds (VOCs), as part of the vegetative stress response to drought. It may also make vegetation more susceptible to ozone damage, affecting crop production.

Relative humidity is projected to decrease slightly and this may affect aerosol chemistry and restrict the formation and evolution of secondary organic aerosols (SOAs). This may reduce concentrations but the magnitude of the change is highly uncertain and requires further research.

Changes to winds in Auckland

Small decreases are projected for both the mean wind speed and the number of windy days. This may slightly decrease the dispersion of pollutants. However, there may also be less sea-spray, which is generated on windy days and contributes to PM_X concentrations. Extreme winds from phenomena such as tropical cyclones and tornadoes would generate more sea-spray, but future projections of these phenomena are highly uncertain.

8.4.2 International and Auckland specific review of climate change effects on air quality

NO_X, NO_2 and brown haze assessment

Because urban Auckland sits upon a narrow isthmus it usually experiences good dispersive meteorological conditions, which maintains good air quality. However, Auckland also has high traffic volumes. The Auckland Air Emissions Inventory 2016 (Metcalfe and Sridhar, 2017) recognized road traffic as one of the major anthropogenic emission sources in Auckland. Motor vehicles are the major source of NO_X, comprising 66% of regional transport emissions and 70% of urban airshed transport emissions. Between 2006 and 2016, NO_X and NO_2 showed contrasting results. While NO_X emissions reduced by 34%, NO_2 levels went up by 1%. NO_X projections for 2040 show a 66% reduction, whereas NO_2 levels for 2040 are projected to decline by 36% compared to 2006 levels (Metcalfe and Sridhar, 2017).

To study the meteorological impacts on NO_X concentrations, Pearce et al. (2011) used ECMWF (European Centre for Medium-range Weather Forecasts) reanalysis data at a global scale. Due to an inconsistency in results, they concluded that synoptic-scale meteorology is not the major driver of high NO_X concentrations in Melbourne, Australia and thus the impact of climate change on synoptic-scale meteorology will have only a minor impact on air quality. In an Auckland-based brown haze study, Salmond et al. (2016), also showed that individual or isolated local or regional approaches were ineffective. They suggested that formation of brown haze over any urban area could be predicted by a combined approach of using local surface conditions, regional synoptic reanalysis and back trajectory modelling.

Jiang et al. (2014) demonstrated the usefulness of a combined approach by simultaneously evaluating the impacts of local, synoptic and large-scale meteorology on daily NO_2 concentrations observed in Auckland. They concluded the local meteorology to be the most significant driver of daily concentrations of NO_2 with two pathways: local transport and local emissions, consistent with most of the literature.

The implication from two of the Auckland-based studies, Salmond et al. (2016) and Jiang et al. (2014), is that the impact of climate change on air masses over the Auckland Region will impact air quality at the regional scale and impact the potential for high (and low) concentration periods.

Black carbon and carbon monoxide assessment

In 2011, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) studied the linkages between climate change and the formation of black carbon and the ozone precursors – methane, carbon monoxide, NO_X and VOCs (UNEP and WMO, 2011, Shindell et al., 2012). The study followed an integrated approach, identifying reduction measures and co-benefits by taking into consideration the net impact of all pollutants on climate change. It demonstrated a 50% reduction in black carbon emission trends by 2030 relative to the present-day emissions by full implementation of black carbon reduction measures. The declining concentration of black carbon was shown to be positively correlated with organic carbon (OC), total $PM_{2.5}$ (particles less than 2.5 $\mu g\ m^{-3}$) and carbon monoxide (CO) concentrations.

Bromley and Gray (2017) showed that in Auckland, CO levels have consistently declined even while the total vehicle kilometres travelled have increased. This decline is attributed to improved petrol vehicle emissions and fuel standards. The decline is evident at sites like urban Auckland such as Marylebone and North Kensington in London (Bromley and Gray, 2017). The major sources of black carbon in Auckland have recently been confirmed as domestic heating and transport sectors, in the city's first black carbon emissions inventory (Figure 8-62; P. Crimmins, pers. comm., MSc thesis, University of Auckland, under review).

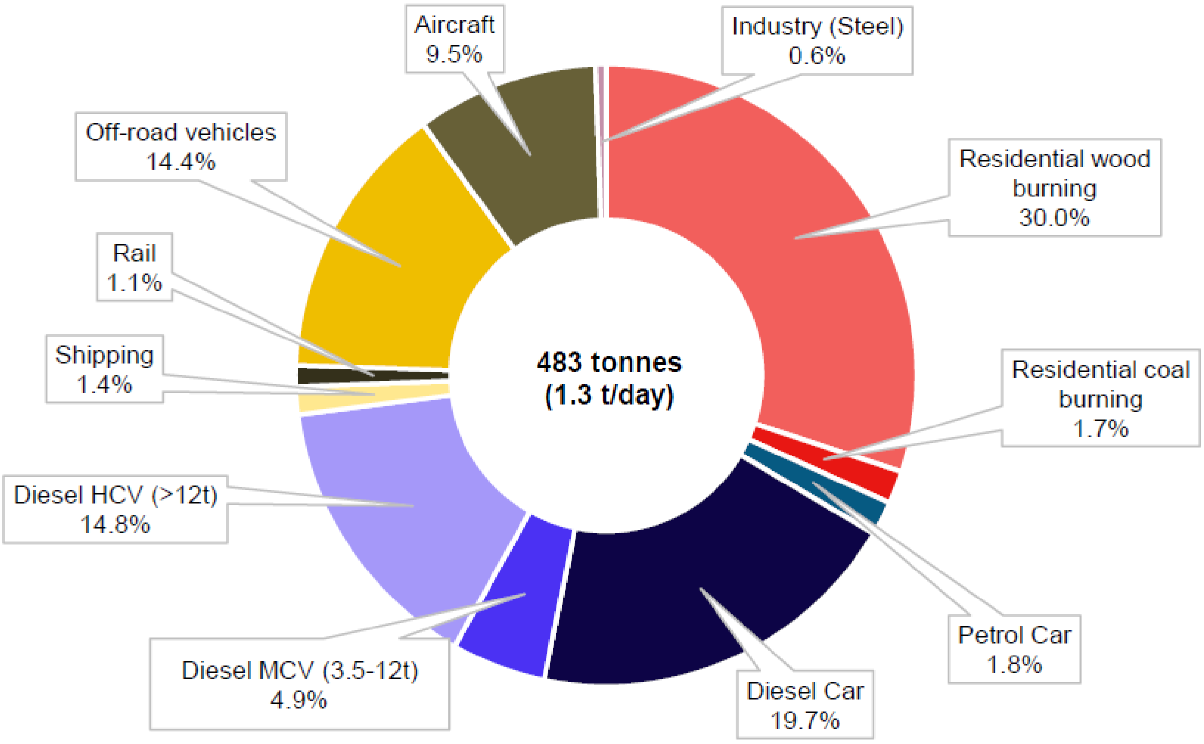

Figure 8-62: Total black carbon emissions in Auckland, 2013, as calculated from bottom-up emission inventory. From Paul Crimmins, pers. comm., November 2017.

The transport-related component shows a downward trend in concentrations (Figure 8-63), while black carbon from residential wood-burning is neither declining nor increasing.

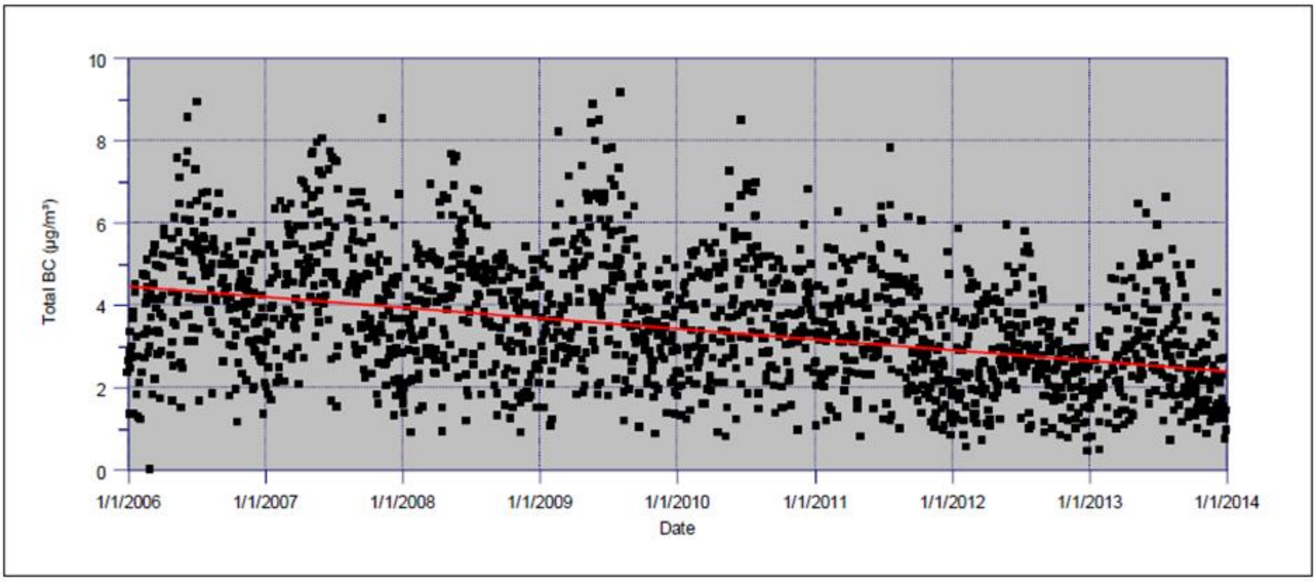

Figure 8-63: Seasonal-Kendall test for total black carbon concentrations at peak traffic sites in Auckland (Khyber Pass and Queen St), 2006-2013, showing a statistically significant decrease ($p < 0.001$). From Paul Crimmins, pers. comm., November 2017.

Mitchell et al. (2017) investigated black carbon from residential wood-burning in New Zealand and the United Kingdom and found that most of New Zealand had very low wintertime black carbon concentrations (less than 1 µg m^{-3}). The most polluted areas had wintertime averages of over 10 µg m^{-3} and were in the South Island where wintertime domestic wood-burning is more prevalent. Most of Auckland's wintertime black carbon concentrations ranged between 1-3 µg m^{-3}. They also noted that emissions from residential wood burning may be under-estimated in climate models.

Anenberg et al. (2011) examined the health benefits of halving the black carbon emissions between 2005 and 2030. The study suggested that halving black carbon emissions results in a reduction of around 2% $PM_{2.5}$ outdoor concentration and around 160,000 fewer deaths per annum globally. Health effects due to exposure to indoor air pollution, mainly due to domestic heating and infiltration of outdoor smoke, are ignored in these estimates. Also, rising temperatures are expected to reduce the demand for indoor heating and this reduction is not included in these estimated concentrations.

Auckland's black carbon source mixture is similar to countries mentioned in UNEP and WMO (2011). Therefore, New Zealand may greatly benefit from UNEP's recommended combining of GHG and black carbon emission reduction measures. However, the results of these models, especially as described in Anenberg et al. (2011), cannot be assumed to be directly applicable in New Zealand due to the coarse resolution of the model used. Further Auckland-based fine scale modelling is required.

Particulate Matter (PM) and Ozone

An overall rise in temperatures and occurrence of drought conditions for the Auckland Region is projected (Sections 3 and 4). Wang et al. (2017) studied the impact of increasing drought conditions on concentrations of various pollutants in the United States. This study concluded that $PM_{2.5}$ and ozone concentrations can be highly sensitive to drought conditions with a negative linear relationship, meaning that the most severe drought indicators result in the greatest increase in pollutant concentrations.

These climate-induced drought conditions may also increase the occurrence of wildfires (Fiore et al., 2015). Wildfires release many pollutants including CO, CO_2, PM_X (including black carbon) and ozone precursors. Wildfires can alter pollutant concentrations at a regional scale due to air mass movements. For example, ozone concentrations in Auckland from 1996 to 2012 met the WHO guidelines every year except 2002. This exceedance in 2002 was attributed to bush fires in Sydney (Ministry for the Environment and Stats NZ, 2014), which is an example of transboundary pollution or long-range transport. The risk of local wildfires may also increase with the projected drier climate in Auckland (Section 8.5).

In 2016, PM_{10} emissions from wood burning in Auckland were estimated to be 10 tonnes per winter day. This represented a 31% reduction from the baseline year of 2006, with a 63% reduction projected by 2040 (Metcalfe and Sridhar, 2017, Metcalfe et al., 2017). In the transport sector, a 30% reduction was estimated in 2016 compared with the Auckland Plan target of 50% reduction by 2016. The report predicted a 67% reduction by 2040, falling just short of the target of 70% reduction (Metcalfe and Sridhar, 2017).

Silva and colleagues studied the effect of past climate change on air pollution and premature mortality using global coupled chemistry-climate models in both Silva et al. (2016) and Silva et al. (2017). Silva et al. (2016) studied the net effect on future emission concentrations and related mortality attributable to both climate and emission change. The model ensemble showed an increase in ozone concentrations and a decrease in $PM_{2.5}$ concentrations in 2100 relative to 2000. They attributed the increase in ozone to rising temperatures and increasing methane emissions and the decrease in $PM_{2.5}$ was attributed to a decrease in total particulate and precursors to secondary organic aerosols. Conversely, Allen et al. (2016), using four of the same models as Silva et al. (2016), found a decrease in rainfall leading to an increase in $PM_{2.5}$ concentrations and hence, increased associated mortality.

Silva et al. (2017) discussed the changes in concentration and mortality attributable exclusively to changing climate by keeping emissions constant while modelling their baseline year of 2000 and all future projections. Five models were used – four of which projected increases in mortality and one projected decreases in mortality. Comparing these results to Silva et al. (2016) illustrated a 'climate penalty', whereby the decreases in $PM_{2.5}$-related mortality from projected reductions in emissions were offset by the mortality attributable to climate change. If there were no changes to the future climate, the overall $PM_{2.5}$ and ozone-related mortality would be further reduced, thus indicating the co-benefits of climate change mitigation policies to air quality and health. (Note that these conclusions are based on 2000 emissions, not present-day emissions.)

Tagaris et al. (2009) conducted a health impact assessment based on the climate-chemistry model GISS-E2-R, CMAQ, and the health impact model BenMap to study the climate-induced air quality related health impacts at various spatial scales for 2050 throughout the United States. They found $PM_{2.5}$-dominated health effects are more substantial than ozone-related health effects. Although Silva et al. (2017) and Targaris et al. (2009) used different climate change scenarios, the spatial variability in their results agreed in many regions.

Past and current estimates of health impacts attributable to air quality in New Zealand are based on the HAPINZ health effects model (Kuschel et al., 2012), which relies on monitored concentrations across the country. To predict future health impacts from air quality and climate interactions, air quality models would need to be run with the relevant climate and emissions projections.

Integrated assessment studies and policy implications

Silva et al. (2017) demonstrates the need for coordinating or combining management policies for climate change and air quality. Figure 8-64 shows how policy in a wide array of societal areas are impacted by climate change and have impacts on health outcomes because of climate change and air quality.

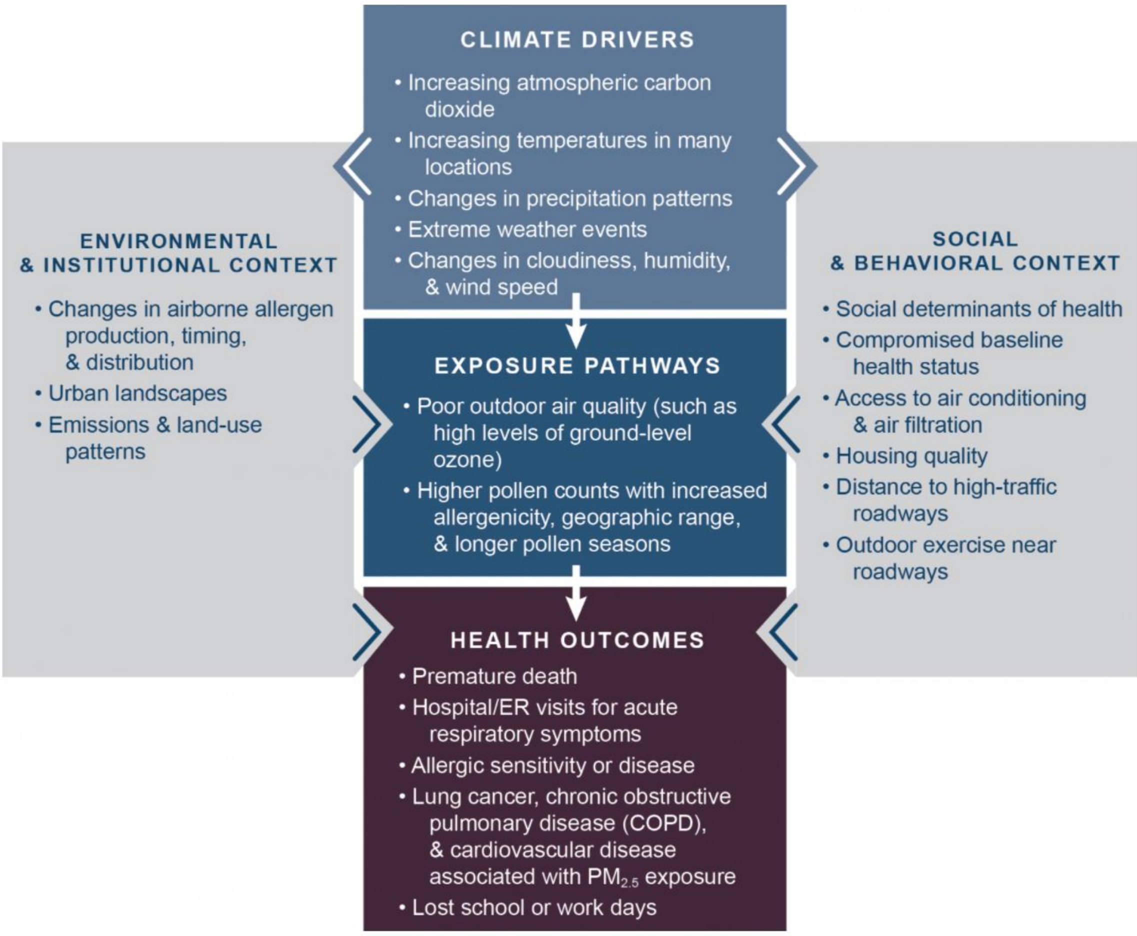

Figure 8-64: This conceptual diagram for an outdoor air quality example illustrates the key pathways by which humans are exposed to health threats from climate drivers, and potential resulting health outcomes. These exposure pathways exist within the centre boxes. The exposure pathways exist within the context of other factors that positively or negatively influence health outcomes (grey side boxes). (From Fann et al. (2016))

There have been various air quality improvement policies introduced in Auckland and globally. The reductions in emissions (NO_X, PM and CO) in Auckland can be attributed to stricter emission controls for imported vehicles and fleet turnover. The MfE air domain report (Ministry for the Environment and Stats NZ, 2014) also presented the health impacts of air quality and differences observed between 2006 and 2012. Their estimates were based on the health effects model formulated by HAPINZ (Kuschel et al., 2012). The report stated that the reductions in PM_{10} observed between 2006 and 2012, led to 14% fewer premature deaths and 15% fewer hospital admissions attributable to anthropogenic PM_{10}.

In 2008, MfE examined a range of possible measures and assessed the potential co-benefits for reducing greenhouse gas emissions, public health effects and costs through lower air pollution emissions (Fisher and Sherman, 2008). The focus of the analysis was on three sectors: domestic, vehicle, and industry, since they have impacts on both air pollution and greenhouse gases. Due to the lack of specific data, many assumptions were made to analyse these impacts. The air pollution and health data for this study was obtained from the HAPINZ study in 2007 (Fisher et al., 2007). There was a small reduction in greenhouse gas levels due to an increased wood burner use but significantly larger air pollution control and health costs. Biofuels appeared to offer strong co-benefits, although there was no evidence for air quality gains. Any measures to reduce fossil fuel energy use in the industrial sector seemed to have benefits for greenhouse gas emission reductions and air quality health gains, only if the process did not involve industry switching to using wood, in which case the health costs increase substantially.

Asikainen et al. (2017) also investigated the benefits of greenhouse gas emission reduction measures in Kuopio, Finland. These measures included four strategies: (1) energy efficiency improvements in residences, (2) increasing the use of biofuel for traffic-based improvements, (3) increased use of wood for domestic heating and (4) increased used of biomass in power generation plants. The changes in emissions due to climate foreseen in 2020 (under RCP8.5) relative to 2010 baseline were studied for CO_2, PM_{10}, $PM_{2.5}$, NO_X and sulphur dioxide (SO_2). Based on these changes in emissions, consequences for health and $PM_{2.5}$ ambient concentrations were assessed. Although the assessment showed nearly a 50% reduction in CO_2 emissions due to the abatement strategies, the $PM_{2.5}$ concentrations did not show any significant improvement (with increases observed by some reduction strategies) thus providing minimal health benefits. In conclusion, the case study suggested that the mitigation strategies focused on CO_2 reduction alone will not be sufficient to meet the local-emission standards and reduce health impacts.

Royal Society of New Zealand (2017) recognized the importance of air quality in analysing the impacts on health induced by climate change in New Zealand, especially for vulnerable groups such as the elderly and children. The report also suggests the increasing occurrence of drought and fire events will increase concentrations of ozone and particulate matter. The amount and distribution of allergic pollen is also expected to increase in New Zealand due to the rising temperatures (Royal Society of New Zealand, 2017). These changes in climate, introducing PM and pollen in the air, are responsible for increased cardiovascular diseases and asthma episodes. The report suggests designing urban areas so that walking or cycling become the primary choice of transportation, to reduce transport-related CO_2 emissions. This increased physical activity is expected to result in 116 fewer deaths per year nationally and a further fewer 5.6 deaths from reduced pollutant emissions.

Over longer timescales, human responses to climate change may also affect energy use, as well as how land is used and where people live. These changes would in turn modify emissions (depending on the fuel source) and thus further influence air quality. One example of such a study is BRANZ (2007). It identifies the impacts of climate change based on climate change scenarios, an assessment of user comfort and energy usage and expected social implications. Due to rising temperature, there is a risk of overheating due to increased number of days with uncomfortable indoor temperatures (> 25°C) expected in a year. The demand for air conditioning may go up and increase the greenhouse emissions in the atmosphere. This can be tackled by introducing energy efficient passive cooling into building designs. Conversely, less space heating will be required due to increasing temperatures. By 2030, the required heating energy in Auckland is expected to decrease by 12-70% and by 2070, it is expected to decrease by 69-79 % (BRANZ, 2007). There will be an opportunity to heat houses entirely using passive solar heating, especially in Auckland and most of Northland.

8.5 Wildfire and climate change

Key messages

- Fire risk is projected to increase in Auckland in the future due to increasing temperatures, lower rainfall and more drought
- A 10-30% increase in Seasonal Severity Rating is projected for Auckland in the mid and late 21st centuries compared to the historical period.
- An increase in the number of Very High and Extreme forest fire danger days is projected, with a 50-100% increase projected north of the Auckland isthmus and a 40-50% increase projected south of the isthmus by the end of the 21st century.
- Afforestation with exotic pine species may increase fire risk in Auckland.

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, Perry et al., 2014). Fires have a negative effect on biodiversity through killing vegetation and animals, encouraging weed spread and reducing the margins of habitat fragments. Some large native tree species which are found in the Auckland Region are sensitive to fire (e.g. kauri, tawa, taraire, kahikatea, rimu, totara, matai), however other species are fire-adapted (e.g. kanuka, manuka, cabbage trees, bracken) (Perry et al., 2014).

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 (note that winds are projected to decline in Auckland)
- 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 possibly windier periods) conditions will result in faster fire spread and greater areas burned

The following projections for fire risk are based on the IPCC Fourth Assessment Report. For Seasonal Severity Rating (SSR)[18], the 17-model average projection shows a 10-30% increase for Auckland Region (smaller increases in the east and larger increases in the west of the region) by the 2050s (2040-2059) compared to the 1980-1999 historical period (Pearce et al., 2010). Similar patterns were observed for the 2080s (2070-2089), with the 17-model average projection showing a 10-30% increase in SSR for the Auckland Region compared with the historical period. The average SSR over

[18] 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

fire season months (October-April) for Auckland Airport is projected to increase from 1.86 over the historical period to 2.24 in the 2050s and 2.26 in the 2080s.

The number of days of Very High and Extreme (VH+E) forest fire danger is projected to increase by 40-50% for the Auckland Region, for the 2050s compared to 1980-1999. For the 2080s, days of VH+E forest fire danger is projected to increase by 50-100% for the Auckland Region north of the isthmus, and by 40-50% south of the isthmus (17-model average), compared with the historical period. The historical number of VH+E forest fire danger days for Auckland Airport is 8.3 days, and this is projected to increase to 12.2 days in the 2050s and 12.4 days in the 2080s.

Note that some individual models project a higher increase in Very High and Extreme forest fire danger days, as noted by Reisinger et al. (2014). The reader is directed to Pearce et al. (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 (e.g. *Pinus radiata*), one of the most popular climate change mitigation strategies, may increase the fire hazard in the Auckland 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). New Zealand indigenous plants are generally not very flammable (aside from kauri which is one of the rare flammable species) (Singers et al., 2017).

8.6 Indigenous biodiversity impacts from climate change

Key messages

- Auckland's vulnerable forest and wetland ecosystems may be put under pressure due to changes to rainfall patterns and increasing frequency and intensity of drought.
- Endangered native bird species with small populations and low genetic diversity may be less able to cope with climate change-related challenges (e.g. those on sanctuary islands in Auckland).
- Increased intensity of extreme rainfall events is likely to encourage more slips and soil erosion, leading to sedimentation in waterways and receiving environments as well as habitat loss. This is an issue for ecosystems on the bed of the sea, lakes, and streams.
- Increased freshwater temperatures may be lethal for some indigenous species, and life cycle patterns are expected to change. Changes to flow regimes will also affect indigenous biodiversity in Auckland.
- Sea-level rise and coastal fortification will result in the loss of coastal habitats in Auckland.
- Mangrove habitats in Auckland may be at risk of inundation if sea-level rise occurs faster than the mangrove forests can keep up. Sedimentation of estuaries in response to climate change will also impact the future extent of mangroves in Auckland.
- Growth rates of native marine species may increase with increased sea temperatures, and the growing season may also increase in length.
- Marine species found in Auckland such as paua, oysters, and sea urchins will be affected by ocean acidification, including impacts on growth rates and shell formation.
- Indigenous biodiversity is at risk from an increase in pest species due to climate change (e.g. from temperature increases).

The Auckland Region, like the rest of New Zealand, is part of a terrestrial biodiversity hotspot with a diverse range of ecosystem types and associated species. It is widely recognised, however, that indigenous biodiversity in the Auckland region is under threat from continued loss and fragmentation of indigenous land cover, ongoing impact and increasing threat of invasive species and diseases, overharvesting, pollution, development pressures of New Zealand's most populous region, and climate change (Singers et al., 2017). Many ecosystem types in the Auckland region are thought to have been reduced from pre-human times to less than 10% of their original extent, and others are considered to have been naturally uncommon.

Climate change is projected to be a powerful stressor on terrestrial and freshwater ecosystems in the second half of the 21st century, especially under high-warming scenarios. Through to 2040 globally, direct human impacts such as land use change, pollution, and water resource development will continue to dominate threats to most freshwater and terrestrial ecosystems (IPCC, 2014a).

Many indigenous New Zealand species are already and will be at further risk from climate-related impacts such as river water abstraction for irrigation (in response to reductions in rainfall), 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). Many species will be at risk from new and existing pests that are able to colonise and spread further in New Zealand because of climate change (see Section 8.7).

8.6.1 Terrestrial biodiversity

Most New Zealand plants and animals are adapted to cooler average conditions than those prevailing at present, due to much of the past 2.5 million years being mostly colder than now. According to McGlone and Walker (2011), climate change will result in a range of different adverse 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, many species that will be unable to migrate due to existing habitat fragmentation will find their current range increasingly unsuitable.
- *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 mycorrhizal 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 already observed to extend the breeding seasons of some mammalian predators (e.g. rodents, goats, pigs and possums).

The natural environment during past warm periods, particularly at the height of the present interglacial (7000-9000 years ago; mean temperatures of at least 1-1.5°C warmer than present in parts of New Zealand) may be used to infer potential future changes to New Zealand's indigenous biodiversity. It is expected that with warming and other changes in climate, species may adjust their geographic range. However, McGlone and Walker (2011) suggest that non-climatic factors such as soils, ecosystem inactivity and dispersal limitations may prevent rapid spread of many species, despite warming climates.

Auckland's indigenous forests may be put under pressure in the future due to changing rainfall patterns and increasing frequency and severity of droughts (Section 4). Coastal broadleaved forests close to Auckland's beaches and estuaries may be at risk from future sea-level rise, and Auckland's dune forests may be more at risk due to increased soil erosion from changes to rainfall patterns. Kauri (*Agathis australis*) forests are one of the few New Zealand forest types prone to fire, so increases to wildfire risk with climate change may negatively impact Auckland's kauri forests. Kauri respond to drought by shedding leaves, which reduces water loss and protects the plant from water stress (Macinnes-Ng and Schwendenmann, 2015). Kauri trees also tend to have drier soils around the base of the trunk so this influences which other plant species can grow nearby (Wyse et al., 2013). Auckland's kahikatea forests are at risk of increased drought and lowering of the water table, which will facilitate introduction of more plant species (Singers et al., 2017). Changes to the abundance of pests (both animal and plant) in Auckland with climate change will influence distribution and pressures on Auckland's indigenous forests.

Wetlands are highly sensitive areas and are amongst the most threatened ecosystems in New Zealand (Singers et al., 2017). In the future, wetlands will be threatened by changes to rainfall patterns and surface and groundwater hydrology. Increases in droughts projected in Auckland may negatively impact wetland ecosystems. Wetlands close to the coast will also be at risk from sea-level rise (inundation and erosion) and changes to salinity of groundwater which may impact the distribution and assemblage of species.

Endangered native bird species with small populations and low genetic diversity, such as those that survive only on sanctuary islands (e.g. Tiritiri Matangi Island in the Auckland Region), may be less able to cope with challenges such as a changing climate (Parliamentary Commissioner for the Environment, 2017). Although the Auckland Region makes up just 2% of New Zealand's land area, the region contains about 20% of the country's threatened terrestrial vertebrates and plants (Auckland Council, 2015), so these species may be particularly vulnerable to climate change. Climatic changes may also affect some exotic species, an example being myna populations contracting to the northern North Island following introductions across New Zealand (McGlone and Walker, 2011). Auckland's indigenous bird populations will be impacted by future changes to pests such as rats, which may survive in greater numbers during mild winters.

Increasing temperatures may lead to positive or negative effects for indigenous reptiles, 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 cautious 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 to predict, 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 8.7) 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 (e.g. *Pinus radiata*) 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 where native forest was either absent or limited, and creating flammable forest communities

(McGlone and Walker, 2011). The conversion of native scrub and shrub land to forestry may also cause the direct loss of native ecosystems.

8.6.2 Freshwater biodiversity

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

The composition of riparian vegetation species 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 mitigation or adaptation 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. Gross primary production and macrophyte growth in streams is partially related to shading from riparian vegetation (Burrell et al., 2014), so changes to riparian vegetation as a result of climatic changes may have follow-on effects for macrophytes and other instream plant growth.

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 (Figure 8-65).

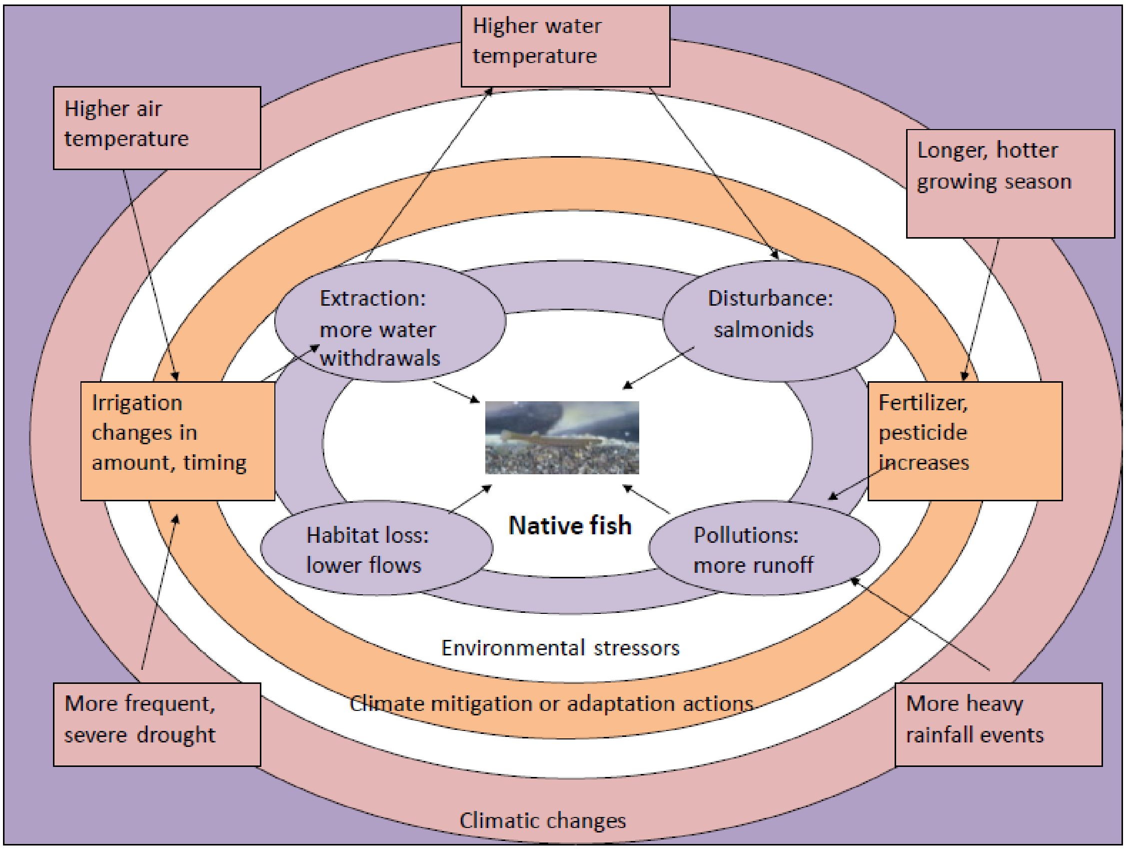

Figure 8-65: Diagram of some interactions between climate change and other anthropogenic stressors on native freshwater fish (from Death et al., 2016).

Reductions in rainfall, potential increases in severe floods, as well as the human impact of greater abstraction of freshwater for irrigation and increasing storage (in the form of reservoirs) for hydroelectricity and urban water supply, will lead to impacts on freshwater ecosystems (Parliamentary Commissioner for the Environment, 2012). The role of floods in New Zealand rivers is extremely important for ecological servicing in stream channels, which helps to maintain ecological integrity, so changes to the hydrological regime may have dramatic impacts on biological communities (Death et al., 2016, Crow et al., 2013). Altered natural flow patterns may result in invasive predators gaining increased access to habitats crucial for sensitive life cycle stages (e.g. islands in river channels used by nesting birds) and changes in habitat type, and some aquatic species (e.g. invertebrates) are likely to be impacted more than others, depending on their life cycles (McGlone and Walker, 2011). 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. In addition, terrestrial insects and mammals (e.g. mice) from riparian zones also form a major component of the diet for many fish at certain times of the year, so changes to terrestrial communities from climate alteration will also feed back to animals within the water.

Sea-level rise may increase salinity at river mouths and further upstream than at present, thereby reducing freshwater habitats, particularly in short catchments. Increases in rainfall may lead to more sedimentation and turbidity in waterways. Increased intensity in extreme rainfall events (Section 4.6) is likely to increase erosion and habitat loss in affected stream catchments. This was observed in early 2017 in the Hunua Ranges following extreme rainfall there[19]. 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). Other oceanic changes (e.g. changes to salinity, sea temperatures, and pH; Section 8.2) may also have an impact on diadromous fish species and their migration patterns.

Water temperatures are projected to increase because of increases in air temperature. Increased water temperatures will affect many species through decreased dissolved oxygen in water (Woodward et al., 2010) and heat stress (McGlone and Walker, 2011). For ectotherms ('cold-blooded' animals, which all New Zealand freshwater species are), warming rates will directly affect their metabolism, with growth rates in temperate species projected to increase initially as temperatures rise, but then decline as individuals struggle to maintain cardiac function and respiration in the face of increased metabolic demands (Neuheimer et al., 2011). If water temperatures increase outside of tolerance ranges for native fish and invertebrates, this will be lethal (Olsen et al., 2012). Olsen et al. (2012) provided details on upper ultimate lethal water temperatures for many native New Zealand freshwater fish species; most are in the range of 28-35°C. Some heat-tolerant native species may fare better than some introduced fish species (e.g. salmonids), although new warm-water invasive species are expected to be favoured (Office of the Prime Minister's Chief Science Advisor, 2017). Life cycle patterns are expected to change in response to water temperature increases, including growth, spawning times, locations, and triggers for migration (Olsen et al., 2012). For example, August and Hicks (2008) found that water temperatures >22°C almost completely inhibited migration of eels (*Anguilla australis* and *Anguilla dieffenbachii*). Many New Zealand freshwater systems currently have water quality issues (Office of the Prime Minister's Chief Science

[19] http://www.watercare.co.nz/about-watercare/news/Pages/Scale-of-devastation-caused-by-Tasman-Tempest-revealed.aspx

Advisor, 2017), and warmer water temperatures could exacerbate water quality problems in areas with high loadings of nutrients, causing algal or cyanobacterial blooms to become more frequent or have earlier onset times in the warm season and high concentrations of primary producer biomass (e.g. macrophytes) (Settele et al., 2014). See Olsen et al. (2012) for more details about the impacts of increased water temperature on native freshwater fish.

A side-effect of future changes to rainfall and a trend towards renewable energy, as well as potential increases in municipal water storage for Auckland's urban areas, means that more dams may be constructed (Parliamentary Commissioner for the Environment, 2012). 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).

It is worth noting again that there is considerable uncertainty in river flow modelling, as discussed in Section 8.1.7, which is then compounded by the paucity of studies on some freshwater systems, particularly wetlands, estuaries, and lakes (Collins, 2016). However, with the intervention of structures in streams (dams, culverts, fords etc.) combined with climate change, ecological servicing from flushing flows are likely to be much different in a changed climate than in an unmodified environment.

8.6.3 Coastal and marine biodiversity

Coastal systems are particularly sensitive to three key drivers related to climate change: sea level, ocean temperature, and ocean acidity (Wong et al., 2014). There is a long-term commitment for the coast to experience the impact of sea-level rise because of a delay in the response of the ocean to air temperature increases. Marine and coastal ecosystems in New Zealand and around the world are likely to be influenced by changes in sea level, increases in sea water temperature, increases in storm events, and more variable rainfall 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 (rocky and consolidated cliffs) shores. Due to the extensive development near beaches, estuaries and marshes, it is unlikely that natural adjustment of the coast will be readily allowed in the future (i.e. coastal retreat and reconfiguration as sea level rises). A potential human response to sea-level rise will be by building hard barriers, 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 destroy large areas of habitat at the current coastal margin (McGlone and Walker, 2011). This is a significant issue as several of Auckland's most threatened and naturally uncommon ecosystems occur in coastal environments. These areas support native species such as shorebirds and threatened plants that are adapted to coastal habitats and are unable to survive elsewhere (Singers et al., 2017).

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*). Loss of ecosystems and species habitats by coastal squeeze is already apparent in some places where coastal dunes have been developed upon or forested. The effects of changes in waves and freshwater inputs will also have significant adverse impacts for coastal ecosystems (Hewitt et al., 2016). Many parts of New Zealand are bases for many internationally-migrating bird species (e.g. Miranda in the Firth of Thames). The population and distribution of these bird species may be affected by climatic changes in New Zealand but also in the other bases on their migratory journeys (e.g. the bar-tailed godwit has bases in northern Australia, parts of eastern Asia, Russia, and Alaska as well as New Zealand).

Mangrove (*Avicennia marina*) habitats, which are common throughout the Auckland Region's estuaries, provide coastal protection, are long-term sinks for contaminants (e.g. from stormwater), and support biodiversity and detrital food webs through primary production (Figure 8-66). Because mangrove forests occupy a narrow elevation range in the intertidal zone above mean sea level elevation, they are sensitive to changing sea level. Thus, the long-term fate of mangrove forests depends on tidal-flat surface elevation increasing at a rate equal to or exceeding the rate of sea-level rise. The projected rapid rate of sea-level rise by 2100 in New Zealand is comparable to the rate during the early Holocene, where mangrove forests were inundated as they were unable to keep up with sea-level rise (McBride et al., 2016), although they did move further south of their current range to Gisborne and Hawkes Bay during this time (Mildenhall, 2001). Mangrove communities are affected by sediment supply to the coast as well as coastal development itself. Increased sedimentation from land runoff (e.g. due to extreme rainfall events or intensified land uses) may increase mangrove habitat, but reduction in sediment supply to the coast (e.g. from reforestation under schemes to increase carbon sequestration) may reduce mangrove habitat (McBride et al., 2016). Sediment supply combined with the rate of sea-level rise will determine the future distributions of mangrove habitats in the Auckland Region.

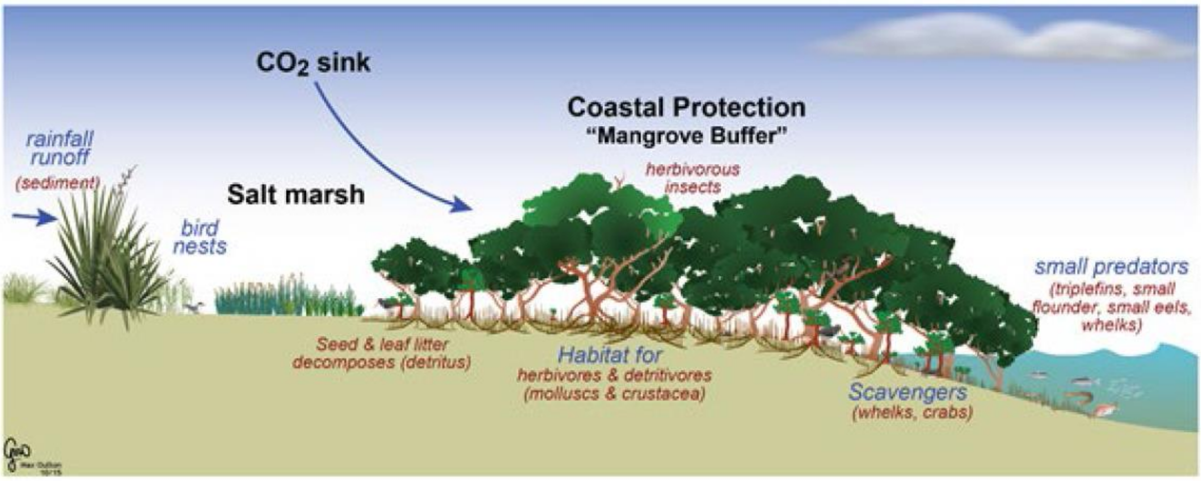

Figure 8-66: Ecological services provided by mangrove forests. From McBride et al. (2016).

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). Gillanders et al. (2012) found that the growth rate of parore (*Girella tricuspidata*), a temperate reef fish found along the coast of northern New Zealand, increased with higher sea temperatures. In addition, a negative correlation with the ENSO index was found (due to El Niño events generally bringing cooler sea temperatures around New Zealand). Higher temperatures may directly influence metabolism and growth, and extend the growing season. However, increased temperature is only likely to benefit growth up to a critical temperature threshold, after which negative effects on growth will be experienced, due to increased metabolic demands. This is supported by Neuheimer et al. (2011), who found that red moki (*Cheilodactylus spectabilis*), a fish that is found on rocky reefs around New Zealand, grew fastest between 14-16°C but growth declines were observed in sites where sea temperatures were >17°C at spawning time.

Ocean acidification is likely to have significant impacts on many marine species in the Auckland Region. Experimental work on the impacts of acidification in New Zealand waters on juvenile paua (*Haliotis iris*) has shown that while survival was not affected, growth was significantly reduced, and dissolution of the shell surface was evident (Cunningham, 2013). Similar effects were found for growth and shell surfaces of flat oysters (*Ostrea chiliensis*) (Cummings et al., 2013, Cummings et al., 2015). In addition, there is clear evidence of malformation of sea urchin larvae, in tropical to Antarctic species including species from New Zealand, under higher dissolved CO_2. This may result in smaller larvae and an increased duration in the planktonic phase, reducing the chances of survival to the adult stage (Byrne et al., 2013, Clark et al., 2009). Macroalgae community structure in coastal regions may be altered in response to ocean acidification with a decline in encrusting coralline algae that use carbonate, while red algae found in deeper waters may benefit from an increase in dissolved CO_2 (Hepburn et al., 2011, Tait, 2014). Changes in the biomineralisation or species distribution of coralline red algae may occur in response to ocean acidification, particularly in species producing high-magnesium calcite (James et al., 2014, Smith et al., 2013).

Fish may also be affected by ocean acidification. The behaviour of Australian reef fish is affected by ocean acidification, with olfaction, hearing, visual risk assessment and activity altered due to the impact on neurotransmitter function (Munday et al., 2014). However, larvae of kingfish (*Seriola lalandi*), a large pelagic fish found throughout the sea surrounding the Auckland Region, did not show detrimental effects of increasing acidification (Munday et al., 2015). Work is ongoing at NIWA about the effects of ocean acidification on snapper larvae (*Pagrus auratus*). More work is required to understand potential impacts on kingfish and other pelagic fish species at further stages of development.

There has been interest in generating electricity from the Kaipara Harbour's tidal flow with turbines (Beehive, 2011). Although this project is currently on hold (since 2013) (New Zealand Herald, 2013), it could potentially return to favour in the future. Although it is a source of renewable energy, 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).

8.6.4 Sediment discharge to the coast

Terrestrial sediment can be a serious environmental contaminant when discharged into the sea. It may degrade coastal habitats and is toxic to many marine organisms. Increasing sediment load has been ranked third-highest of 65 identified threats to marine habitats in New Zealand (Hauraki Gulf Forum, 2014). Deposited sediments accumulate in sheltered estuaries or deep coastal areas, where wave and current energy is too weak to remobilise them. Sedimentation trends in coastal areas are generally reflections of changes in land use.

Sedimentation of receiving environments is an increasing issue in the Auckland Region. Many sites near older urban centres are 'unhealthy' in terms of benthic health, particularly in the Waitemata Harbour and Tamaki Estuary (Auckland Council, 2015).

Auckland Council has a sediment monitoring programme in east coast estuaries on the fringes of Auckland's metropolitan area. The monitored estuaries include Puhoi, Waiwera, Orewa, Mangemangeroa, Turanga, Waikopua, Whangateau, and Okura. Increases in very fine sediment particles have been observed in many monitored locations, but these estuaries are generally in moderate to good health (Hewitt and McCartain, 2017). As these estuaries have catchments that are rural or only semi-urban, they are not representative of fully urban catchments and estuaries.

Sedimentation in coastal areas may be affected by climate change with changes to rainfall and runoff. Extreme rainfall events are projected to increase under a warming climate (Section 4.6) which will have an impact on slips and landslides and soil erosion in the Auckland Region, thereby increasing the amount of available sediment to be transported to marine environments (Section 8.1.8). In addition, changes to land use, including opening new areas for development, will determine future locations of sediment source hotspots. Measures to reduce sedimentation (e.g. riparian planting, increasing forest cover etc.) will also influence future coastal sedimentation rates and may dampen climate change (i.e. extreme rainfall) induced sedimentation.

8.7 Biosecurity impacts from climate change

Key messages

- Auckland is home to many threatened ecosystems which may be impacted by changes to pests in the future brought about by climate change.
- The most important driver of pest invasion is likely to be temperature.
- The arrival of new pest plants and increased invasiveness of existing weeds is likely to be a significant consequence of climate change.
- Increased use of subtropical plants and introduction of new species may make Auckland more susceptible to invasion by new pests and diseases.
- Some pests and weeds may currently be dormant in Auckland, awaiting some perturbation such as climate change to allow them to spread and flourish, e.g. locusts and army worms.
- Kauri dieback may be exacerbated in Auckland by increasing temperatures and higher drought frequency. Fungal diseases such as myrtle rust may spread further in New Zealand and may be affected by changes to wind, atmospheric circulation, and storminess.
- Increasing water temperatures (freshwater and seawater) may allow invasive tropical aquatic species to survive and spread in the Auckland Region. The strengthening East Auckland Current may promote establishment of new tropical or subtropical species.
- New mosquito species may become established in a warmer Auckland Region, with the potential for tropical diseases such as dengue and Ross River virus to be transmitted by these disease vectors. This is a concern for Auckland, with New Zealand's largest airport and sea port.

8.7.1 Terrestrial biosecurity

Climate change is widely regarded as one of the greatest challenges facing indigenous ecosystems in the coming century. As New Zealand (and much of the Auckland Region outside of the urban centre) has an economy based on very efficient primary production systems, the risk of exotic pests and diseases affecting the primary industries also needs to be minimised. Climate change will create new biosecurity challenges by allowing establishment of new exotic pest animals, weeds and diseases which are currently prevented by New Zealand's climate. The potential establishment of subtropical pests and current seasonal immigrants are of greatest concern, along with species that are already recognised as high risk (Kean et al., 2015). Auckland is traditionally the point of entry for many high-profile pest species in New Zealand because it has the largest sea port and international airport.

The Hauraki Gulf Marine Park contains numerous sanctuary islands (e.g. Little Barrier and Tiritiri Matangi Islands), and there are several sanctuary peninsulas (e.g. Tawharanui, Shakespear) that are home to many vulnerable species and are protected by various biosecurity measures (Bassett et al., 2016). Auckland is also home to many threatened terrestrial and wetland ecosystems (Singers et al., 2017). Climate change could impact the protection of these vulnerable ecosystems against invasive species in the future.

Although climate change may affect organisms and ecosystems in a range of ways, the most important driver of pest invasion is likely to be temperature, modified by rainfall, humidity and carbon dioxide (Kean et al., 2015). In addition, changes in large-scale weather patterns will influence the frequency and intensity of extreme weather events (e.g. flooding, drought, damaging wind). Regional winds and currents may affect the ability of potential invaders to reach New Zealand and establish. The recent arrival of the fungal plant disease myrtle rust[20] (*Austropuccinia psidii*) in New Zealand may have resulted from wind-blown spores from Australia (see below).

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. 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). Subtropical fruit flies are already considered major threats to the New Zealand horticulture industry. A modelling exercise done for 17 different fruit fly species (Figure 8-67) showed that Auckland is one of the regions with the greatest potential for increase in fruit fly establishment (in terms of climate suitability) in the late 21st century (along with Coromandel, northern Waikato, East Cape, and Wairarapa) (Kean et al., 2015). In 2015, a small population of Queensland fruit fly was found in the Auckland suburb of Grey Lynn. It took 10 months and cost $15.7 million to eradicate the pest – over $1 million for each individual insect that was found[21].

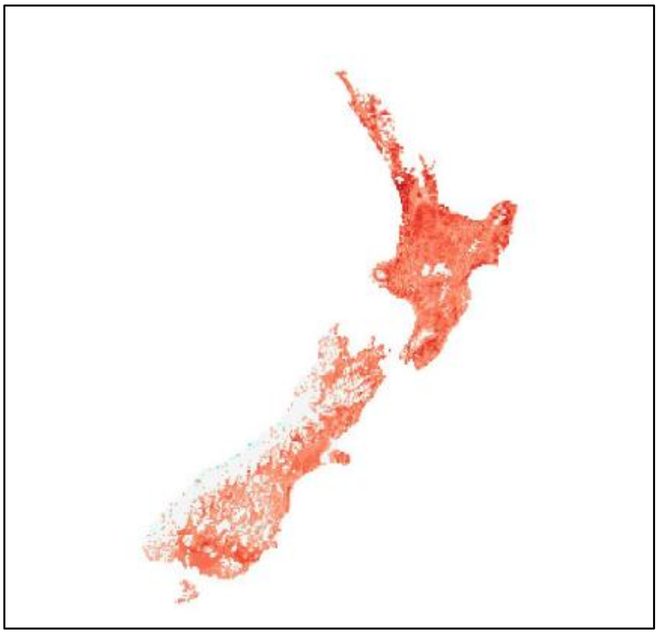

Figure 8-67: Change in climate suitability from 2015 to 2090 for 17 different fruit fly species. Darker shades of red indicate the greatest increase in the number of species that might establish. From Kean et al. (2015).

The arrival of new pest plants and the increased invasiveness of existing weeds is one of the most significant likely consequences of climate change. More plant species are present in warmer regions, so as frost declines in frequency and more insect pollinator species are able to survive in warmer temperatures, a much larger range of weed species will be able to compete with local species (McGlone and Walker, 2011). It is expected that farmers and growers in the Auckland Region will

[20] http://www.mpi.govt.nz/protection-and-response/responding/alerts/myrtle-rust/
[21] https://www.radionz.co.nz/news/national/300805/fourteen-flies-cost-$15-point-7m-to-eradicate

increase their usage and dependence on existing subtropical plant species and introduce new commercial species. This increased use of subtropical plants may make the Auckland Region more susceptible to invasion by subtropical pests and diseases and new host-pest associations (Kean et al., 2015). Ornamental plants may escape cultivation when climatic constraints (such as frosts) are reduced and subsequently may naturalise and become invasive (Sheppard et al., 2016). Sheppard (2013) modelled the potential distribution of recently naturalised plant species in New Zealand with future climate change (*Archontophoenix cunninghamiana* (bangalow palm), *Psidium guajava* (common guava), and *Schefflera actinophylla* (Queensland umbrella tree)). All three species, which are currently only present in northern New Zealand (including Auckland), have the potential to significantly increase their range further southward in the future, particularly into coastal areas around the country.

The shift towards reliance on drought and heat tolerant plants (in particular, pasture grasses) may cause new pest species to spread and for new host/pest associations to develop (Kean et al., 2015). The 2014 emergence of two native moths (*Epyaxa rosearia* and *Scopula rubraria)* as major plantain (a variety of pasture grass) pests demonstrates how a large increase in usage elevated these previously harmless species to pest status. In addition, as kikuyu grass (*Cenchrus clandestinus*) is likely to become the most prevalent forage grass with increasing temperatures, pests that affect kikuyu grass are likely to be important. Some pest species from Australia (e.g. the *Sphenophorus venatus vestitus* weevil) 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 dormant in New Zealand, awaiting some perturbation, such as climate change, to allow them to spread and flourish. These types of pests are often weeds but may also be invertebrates. A few examples of sleeper invertebrate pests that are affected by temperature include (after Kean et al. (2015)):

- Migratory locust *Locusta migratoria,* found in grassland from Christchurch northwards. Because existing temperatures are not usually high enough to trigger swarming behaviour, the insect currently is not regarded as a pest. However, the locusts have retained the capacity to swarm with a small swarm observed near Ahipara, Northland in the 1980s.
- Tropical armyworm *Spodoptera litura.* While this pest can be found through many lowland North Island districts, epidemic outbreak populations, when caterpillars move ‘like an army’ through crops and pastures, are rare. However, the combination of events that cause outbreaks will be more common under projected climate change scenarios and include above average summer and autumn temperatures, allowing for additional generations to develop.

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.

Kauri dieback and myrtle rust

Kauri dieback, caused by the pathogen *Phytophthora agathadicida,* is a major biosecurity issue in the Auckland Region. *P. agathadicida* is a soil-borne microbe that first affects the roots of the kauri tree and subsequently disrupts tree function, causing lesions on the lower trunk, leaf chlorosis, canopy dieback and ultimately the death of the tree (Landcare Research, 2014). All ages and size classes can be affected and there is currently no known cure for kauri dieback. The Waitakere Ranges Regional Park (WRRP) currently represents the most heavily kauri dieback infected area in New Zealand (Hill et al., 2017). The recorded distribution of kauri dieback relative to kauri area within the WRRP has risen from 7.9% infected and a further 2.7% possibly infected in 2011 to 18.95% infected and a further 4.65% possibly infected in 2016. Other kauri forests in the Auckland Region (and northern New Zealand) are also infected with kauri dieback, but the Hunua Ranges are currently free of the disease.

Phythophthora species cause destruction to indigenous vegetation around the world. Another highly invasive subspecies *Phytophthora cinnamomi* (which is currently present in much of northern New Zealand), thrives in areas with relatively warm and wet winter and spring conditions where conditions are ideal for zoospore proliferation and host infection, while long dry summers place plants, with compromised root or vascular systems, at risk of drought-induced mortality (Burgess et al., 2016). Therefore, increases in temperature and changes to rainfall patterns and drought may allow *P. agathadicida* to survive and thrive wherever kauri are found as the pathogen will be less limited by cool temperatures.

Myrtle rust (*Austropuccinia psidii*) is a fungus that has been recently (in 2017) found in northern New Zealand. It attacks plants belonging to the Myrtaceae family, including pohutukawa, manuka, rata, and feijoa. The fungal spores may have spread to New Zealand from Australia on strong wind currents. There is concern that myrtle rust may spread further in New Zealand and other fungi that are spread by wind may become established in the country in the future with changes to atmospheric circulation, wind patterns, and storminess.

8.7.2 Aquatic biosecurity

The primary source of entry for aquatic biosecurity risk organisms into New Zealand is and will remain to be through international shipping. These risk organisms are contained within ballast water or attached to the hulls of ships. However, changes in water temperature and ocean currents into the future, because of climate change, may result in species (including pests and pathogens) not usually seen in New Zealand waters to arrive and establish. Sea temperatures are projected to increase around New Zealand, particularly to the west of the country, and seawater is likely to decrease in pH (Section 8.2; Royal Society of New Zealand, 2016).

Long-term changes in marine environmental variables, such as seawater temperature, may lead to new ecological compatibilities and may alter existing host-pathogen interactions. It is commonly accepted that warmer sea and fresh water temperatures modify host-pathogen interactions by increasing host susceptibility to disease. Such changes could contribute to the emergence of aquatic diseases in new regions (Castinel et al., 2014). Of concern for Auckland is a strengthening East Auckland Current off the east coast of the northern North Island. This strengthening current is expected to promote establishment of tropical or subtropical species that currently occur as vagrants in warm La Niña years (Willis et al., 2007). The establishment of these species may have negative impacts on wild fisheries and on aquaculture operations.

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

As is discussed in Section 8.7.1 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'.

8.7.3 Disease vectors

A particular concern for agriculture and human health with climate change is the establishment of disease vectors (e.g. ticks, mosquitos, plant-sucking insects) that would facilitate the spread of animal and plant diseases (Kean et al., 2015, Royal Society of New Zealand, 2017). There has never been a confirmed indigenously-acquired case of mosquito-borne disease in humans in New Zealand (Derraik and Slaney, 2015), so the potential for mosquito-borne diseases in New Zealand is a major concern. 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).

Twelve mosquito species were present in New Zealand before human settlement, and four exotic mosquitoes have since established. However, over 30 other mosquito species have been intercepted at national entry ports (Derraik and Slaney, 2007). The most important mosquito species that carry human disease worldwide, *Aedes aegypti* and *Aedes albopictus,* are not established in New Zealand (Derraik and Slaney, 2015). However, these species are regularly intercepted in New Zealand and could be more likely to survive after arrival under rising temperatures and changing rainfall patterns (Derraik and Slaney, 2007). This would result in New Zealand having an increased risk from mosquito-borne diseases, such as dengue, zika, and Ross River viruses, which regularly arrive in the country with infected travellers (Kramer et al., 2011). In addition, some mosquito species already present in New Zealand have been found to be potential vectors of viruses such as Chikungunya virus, dengue virus, Ross River virus, and Barmah forest virus (Kramer et al., 2011). This is a particular concern for Auckland considering the region contains New Zealand's largest airport and sea port.

Mosquito vectors of West Nile virus are already present in New Zealand and are projected to increase in both abundance and distribution with climate change (Kean et al., 2015). With multiple competent host species also present, preventing West Nile virus emergence in New Zealand may be either or both of: the prevention of the virus from entering the country, and the management of the existing mosquito populations at potential points of incursion (Kean et al., 2015). Another high-risk mosquito-borne disease is bovine ephemeral fever virus. As for West Nile virus, the mosquito vectors for this disease are already present in New Zealand.

Along with temperature increases, extreme weather events, such as drought followed by rewetting, can increase mosquito populations by changing water table levels, vegetation, and populations of aquatic predators (Royal Society of New Zealand, 2017).

Other disease-causing agents that have medium to high risks to production animal health in New Zealand are vectored primarily by ticks. Some tick species are already present in New Zealand (e.g. the cattle tick, *Haemaphysalis longicornis*) so as for mosquitos, it is important to prevent the diseases themselves from entering the country rather than the vectors (Kean et al., 2015).

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).

9 Conclusions and recommendations

This report presents detailed climate change projections for the Auckland Region for the mid- and late-21st century and early 22nd century. Present-day and historic climatic conditions in Auckland are presented to provide a context for future changes. Some of the potential climate change-related impacts on environments and other sectors in the Auckland Region are discussed.

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

Future changes to the Auckland Region's climate are likely to be significant. A large increase in hot days, larger extreme rainfall events, and increases in drought potential are some of the main impacts. Sea-level rise will have an impact on much of the region, especially where urban areas and infrastructure are very close to the coast.

There is inherent uncertainty in climate change projections and the associated impacts as future changes depend on future concentrations of greenhouse gases in the atmosphere and the response of the global climate system to those concentrations. The six climate models used to project New Zealand's future climate were chosen by NIWA because they produced the most accurate results when compared to historical climate and circulation patterns in the New Zealand and southwest Pacific region. They were as varied as possible to span the likely range of model sensitivity. The average of outputs from all six models (known as the 'ensemble average'), is presented in the climate change projection maps in this report. The ensemble-average was presented as this usually performs better in climate simulations than any individual model (the errors in different models are compensated). The following sections summarise the projections of different climate variables and the impacts on sectors and environments in the Auckland Region. Finally, future recommendations are suggested.

9.1 Temperature changes

The Auckland Region's mean annual temperature has increased by about 1.6°C over the past century and this trend is projected to continue. Warming is projected under all climate change scenarios, for all models, throughout Auckland. By 2110 the Auckland Region's mean annual temperature is projected to increase by 1.4°C for RCP4.5 and by 3.3°C for RCP8.5. Warming is projected for the entire Auckland Region. The most warming is projected for autumn, while the least warming is projected for winter and spring.

Daily maximum and daily minimum temperatures are also projected to increase. Mean daily maximum temperatures and mean daily minimum temperatures are projected to increase the most in autumn. Mean daily maximum temperatures are projected to increase faster than mean daily minimum temperatures, resulting in an increase in diurnal temperature range.

In line with mean temperatures increasing, Auckland's extreme temperatures are also projected to increase. The number of annual hot days (daily maximum temperature > 25°C) has been increasing over time and this is projected to continue throughout the Auckland Region. At present, most of the region experiences 15-24 hot days per year. By 2110, an increase of 30-40 hot days per year is projected for most of the Auckland Region under RCP4.5 and an increase of more than 70 hot days per year is projected for most of the region under RCP8.5. Increasing numbers of hot days are likely to impact the health of Auckland's communities and environments.

The number of cold nights or frosts (daily minimum temperature < 0°C) has been decreasing over time in Auckland. Currently, most of the region experiences fewer than two cold nights or frosts per year, with more experienced in higher elevations. The eastern and isthmus areas of the Auckland Region are projected to be frost-free under all climate change scenarios at all time periods. A small number of frosts are projected to remain in the highest elevations of the Waitakere Ranges and the Hunua Ranges, and also in the northwest of the region, at 2110 under RCP8.5.

Growing degree-days express the sum of daily temperatures above a selected base temperature (e.g. 10˚C) that represent a threshold of plant growth. For example, a daily average temperature of 18°C would have a GDD base 10°C value of 8 and a GDD base 5°C value of 13. Since the mid-20th century, there has been an upward trend in the number of growing degree-days in Auckland, and this is projected to continue. This will likely influence the growing rate of plants, harvest times, and the types of plants able to be grown in the Auckland Region.

9.2 Rainfall changes

Annual total rainfall in Auckland is projected to change by less than 5% for most of the region in the future. However, the seasonal distribution of rainfall is projected to change. Rainfall in spring is projected to decline by up to 15% for some parts of the region and rainfall in autumn is projected to increase by up to 15% for some parts of the region. These projections vary depending on the time slice and climate change scenario.

The amount of rain that falls during each event in Auckland is projected to change. There are projected to be fewer small rainfall events, as the number of rain days (days with > 1 mm of rain) is projected to decline across Auckland. Slightly more large rainfall events are projected for some areas, with the number of heavy rain days (days with > 25 mm of rain) projected to increase for most of the region. However, a decrease in the number of heavy rain days is projected in the northeast of the region. By the end of the 21st century, under RCP8.5, there is an increased frequency of consecutive days with > 40 mm of rainfall across the Auckland Region.

The intensity of extreme rainfall events is also projected to increase, because a warmer atmosphere can hold more moisture. The magnitude of 99th percentile of daily rainfall events (the 1-2 wettest days of the year on average) is projected to increase across most of the region, and by more than 25% for southeast parts of the region by 2110 under RCP8.5. An increase in intensity of the more extreme, rare rainfall events is also likely. The intensity of short-duration events is projected to increase by up to 14% per degree of warming, while the intensity of the longest-duration events is projected to increase by 5-6% per degree of warming. These events are likely to have impacts on slips and landslides as well as Auckland's built infrastructure.

Auckland is projected to become more drought-prone in the future. An increase in the number of dry days (days with < 1 mm of rain) is projected, with up to 21 more dry days per year by 2110 under RCP8.5. Spring is generally the season when the largest increase in dry days is projected. Potential evapotranspiration deficit (PED) is the gap between water demand and water availability. It affects soil moisture retention and plant growth, and a higher amount of PED means that soils are drier. The amount of PED is projected to increase across the Auckland Region in the future, with the largest increases projected for Waiheke Island and the southeast of the region. In addition, soils are projected to become drier with increasing numbers of days of soil moisture deficit projected throughout the Auckland Region. Soil moisture projections for at least two additional weeks of deficit per year region-wide indicate it is likely that there will be widespread increased water demand. Increasing frequency and severity of drought is likely to have impacts on Auckland's primary industries and indigenous biodiversity.

9.3 Air pressure, wind, and storm changes

Mean sea level pressure is projected to increase over New Zealand in summer, potentially leading to more anticyclonic (settled, fine) conditions over the country. This is likely to influence mean annual and seasonal wind speeds across the Auckland Region, which have been decreasing since the mid-20th century and are projected to continue decreasing. However, the rate of decrease in wind speed for Auckland is projected to slow (compared with historic trends) due to changes in the trend of the Southern Annular Mode. In line with the projected decrease in mean wind speed, the number of windy days (> 10 m/s) is projected to decrease across the Auckland Region, as is the magnitude of the 99th percentile of daily mean wind speeds (the three windiest days of the year, on average). A projected reduction in mean sea level pressure in winter is likely to result in increased westerly winds over central and southern New Zealand, and this is reflected in the Auckland projections with small increases in winter mean wind speed by 2090 and 2110 under RCP8.5.

Future changes to storms including ex-tropical cyclones are uncertain. The intensity (rain rate and wind speed) of tropical cyclones is projected to increase, but their frequency is projected to remain similar to present. Ex-tropical cyclones that approach Auckland in the future may be stronger due to retaining tropical cyclone characteristics further south than at present. The climate models used in this report do not have the spatial resolution to realistically simulate tropical cyclones, so the impacts from these storms on the Auckland Region are likely to be underestimated in the projections.

The frequency of mid-latitude storms (the low pressure systems that affect New Zealand every few days, with origins outside of the tropics) is not expected to change by more than a few percent. However, there is significant uncertainty about the influence of the increasing strength of the mid-latitude jet to the south of New Zealand on the future frequency and magnitude of storms affecting the country.

9.4 Solar radiation and relative humidity changes

Minimal changes are projected for both annual and seasonal solar radiation in the Auckland Region. The largest increases are projected for summer and the largest decreases are projected for winter. Relative humidity is projected to decrease by a few percent across the Auckland Region, with the largest decrease projected for spring. A small increase in relative humidity is projected for autumn.

9.5 Hydrology impacts

Auckland's hydrology will be affected by future changes to rainfall patterns and drought. Projections of mean discharge are variable across the region, but decreases in mean discharge are generally larger for the later time slices and higher RCP, particularly in the northern Auckland Region. Mean annual low flow is projected to decrease across almost the entire Auckland Region under both time slices and scenarios, with increasing severity under RCP8.5 at the end of the 21st century. Future changes to floods are very uncertain. The projections show that mean annual flood is projected to decrease for most of the region under RCP4.5 at both time slices. However, for RCP8.5, mean annual flood is projected to increase for the whole Auckland Region at the end of the century by up to 40-60% in some areas. Mean annual flood is a relatively low threshold for engineering purposes, and upcoming projects at NIWA will focus on projections for more extreme, rare flood events.

Hydrologic drought conditions are projected to be more frequent and severe in Auckland. Low river flows and dry soil conditions are projected to occur earlier in the hydrologic year (1 July-30 June), which could have impacts on indigenous biodiversity as well as primary industries. Mean seasonal soil moisture is projected to decline by up to 16% in spring and summer under RCP8.5 at the end of the century, and for summer under RCP4.5 at mid-century.

Groundwater recharge may decline due to projected reductions in soil moisture and mean annual low flow, and increases in potential evapotranspiration deficit. Coastal aquifers may also be affected by sea-level rise in terms of flow velocities and salinity.

Projected increases to extreme rainfall in Auckland may have impacts on slips and landslides in the region, as well as soil erosion. The soft cliffs on Auckland's east coast may be prone to erosion due to the influence of extreme rainfall as well as sea-level rise. In addition, the intensive horticultural area around Pukekohe and urban subdivisions in Auckland have been identified as hotspots for sheet erosion. Increased soil movement could lead to increased sedimentation of Auckland's water habitats, with impacts on indigenous biodiversity and local communities.

9.6 Oceanic impacts

The global oceans have responded to anthropogenic climate change, and this will continue. The uptake of atmospheric CO_2 by the oceans has led to ocean acidification, and rising air temperatures have caused sea temperatures to increase. Changes to the oceans will have impacts on the distribution, species composition, and health of marine life in the Auckland Region. A further sea surface temperature increase of 2.5°C is projected by 2100 under RCP8.5 for the Southwest Pacific, including New Zealand. Ocean acidification is projected to continue, which will have impacts on marine food webs and ocean carbon uptake. Some ocean nutrients are projected to decline by the end of the 21st century, impacting phytoplankton growth and ocean productivity. At the local scale for Auckland, future changes to coastal salinity will depend on changes to rainfall and runoff patterns. It is possible that increasing air temperatures may increase evaporation and therefore slightly increase sea-surface salinities in the East Auckland Current.

9.7 Sea-level impacts

Future sea-level rise (SLR) is a significant issue for Auckland as a large amount of the region's communities and infrastructure are located near the coast. Sea level has risen at the Port of Auckland by 1.60 ± 0.08 mm per year since the early 20th century, with an acceleration in recent years. For New Zealand, 0.5 m of SLR is projected to occur between 2060 and 2110, and 1 m of SLR is projected for between 2100 and after 2200, depending on the climate change scenario. However, cumulative global greenhouse gas emissions to date have already committed the Earth to an eventual 1.6-1.7 m of global SLR relative to the present, even if a complete reduction in emissions was to occur. This SLR could take 1-2 centuries depending on future emission trends.

In the Auckland Region, low-lying coastal areas are more vulnerable to SLR. This includes parts of the Central Business District, eastern bays (e.g. Mission Bay), Onehunga, Mangere Bridge, Devonport, and Helensville among others. Auckland's east coast is more sensitive to climate change-related erosion and inundation than the open west coast, due to different exposure, geology, landforms, tidal ranges, and changes to wave heights and storm surge. In addition, SLR and changes to extreme rainfall events are likely to increase erosion rates of the soft cliffs on Auckland's eastern coastline.

Coastal assets are at risk from SLR in Auckland due to their proximity to the sea. Residential buildings will be the most affected building category in Auckland, with 4500 buildings affected during a 1-in-100-year storm-tide event with 1 m of SLR (1315 buildings affected under current conditions with the same storm-tide event), which has a replacement cost of $2.2 billion 2016 NZD. This will affect a usually resident population of about 12,000 people. In addition, significant amounts of road, rail, and three-waters (potable water, stormwater, wastewater) infrastructure will be affected by SLR in Auckland.

9.8 Air quality impacts

The interactions between climate change and air quality in Auckland are highly uncertain. However, it is projected that as winter temperatures rise, the demand for residential heating will diminish and so will high wintertime concentrations of black carbon and particulate matter from burning solid fuels like wood and coal. Changing rainfall patterns in Auckland may result in heavier rainfall events but longer dry stretches, so pollutants may not be washed out of the atmosphere as often, thereby increasing the annual pollutant concentrations. In addition, increased occurrence of drought and higher risk of wildfires may increase the concentration of dust and other particulate matter in the atmosphere around Auckland. Increases in the concentrations of particulates may cause respiratory health problems for Auckland residents.

9.9 Wildfire impacts

Fire risk is projected to increase in Auckland due to increasing temperatures, lower rainfall, and more drought-like conditions. In addition, climate change mitigation strategies such as afforestation with exotic pine species may increase the fire risk in Auckland as they are generally more flammable than indigenous plant species.

9.10 Indigenous biodiversity impacts

Climate change in Auckland is likely to have significant impacts on many of the vulnerable indigenous species in the region. On land, Auckland's indigenous forest and wetland ecosystems may be put under pressure due to changing rainfall patterns and potential increases in the intensity and frequency of drought, as well as sea-level rise affecting habitats close to the coast. In addition, projected larger extreme rainfall events are likely to encourage more slips and soil erosion, leading to habitat loss and sedimentation in waterways. Auckland's sanctuary islands and peninsulas are home to many endangered animal species which, because of their small populations and low genetic diversity, may be less able to cope with climate change-related challenges.

Water temperatures are likely to increase, so freshwater and marine species may undergo life cycle changes. Potentially large increases in water temperature could be lethal to some species. Changes to river flow regimes may influence the migration and distribution of freshwater species in the Auckland Region. Marine species are likely to be impacted by ocean acidification, which can reduce growth rates and shell formation for species like paua and oysters. Many coastal habitats are at risk from inundation and erosion resulting from sea-level rise, as well as human responses to sea-level rise (coastal fortification) resulting in 'coastal squeeze' and habitat loss. Mangrove habitats in Auckland may be at risk of inundation if sea-level rise occurs faster than the mangrove forests can keep up. Sedimentation of estuaries in response to climate change will also impact the future extent of mangroves in Auckland.

Pest species are likely to become more of a threat to Auckland's indigenous biodiversity because of climate change. This issue is discussed further below.

9.11 Biosecurity impacts

Biosecurity in Auckland is likely to be impacted by climate change, particularly by temperature increases. Increased temperatures may allow pests (both animals and plants) that are currently marginal or absent from the region to survive and thrive in Auckland. In addition, pests that are currently present in Auckland may spread further throughout New Zealand due to warmer temperatures further south. Some pests may be currently dormant in Auckland, awaiting a perturbation such as climate change to allow them to proliferate (e.g. naturalisation of some garden weeds). Warmer winters are likely to allow many species to survive in larger populations (e.g. rats) and this will impact Auckland's indigenous bird populations.

Warmer ocean temperatures may allow invasive marine species from tropical waters to survive for longer in the Auckland Region. In addition, the strengthening East Auckland Current may promote establishment of tropical or subtropical species that currently only visit the area during the warm season.

There are likely to be increases in disease vectors due to warmer temperatures in Auckland. Some of the most important disease-carrying mosquitos are currently unable to survive in New Zealand as it is currently too cold, but this may change. This is a concern for Auckland as the region has New Zealand's largest airport and sea port where many of many disease-carrying species have been intercepted in the past.

Kauri dieback is a major problem in many of Auckland's kauri forests. Potential increases to drought severity in the region may make kauri trees more susceptible to infection by the *Phytophthora agathadicida* pathogen, and higher temperatures may allow the pathogen to survive in areas that are currently too cool. Fungal diseases such as myrtle rust, discovered in Northland and Taranaki in early 2017 and in west Auckland in late 2017, have the potential to significantly affect Auckland's indigenous forest. There is concern that myrtle rust may spread further in New Zealand, and other fungi spread by wind may become established in the country with changes to atmospheric circulation, wind patterns, and storminess.

9.12 Future recommendations

This report has drawn upon many existing sources of information about potential climate change impacts in Auckland and wider New Zealand. There is a need to further investigate some of the impacts presented here, including the following:

- The influence of atmospheric rivers and ex-tropical cyclones on extreme rainfall events in Auckland and how this may change.
- Establishing the role of multidecadal variability in guiding Auckland's climate.
- Investigating the long-term history of drought (including megadrought) for Auckland as a guide to severity of future events that can potentially unfold.

- Groundwater modelling to understand future groundwater flows and recharge in Auckland.
- Impacts of changes to rainfall in Auckland on slips and landslides in the region.
- Modelling of impacts of oceanic changes around Auckland and the North Island such as ocean acidification and sea surface temperature increases.
- The impacts of climate change on the health of Auckland residents, including the role of air quality.

Due to the preliminary nature of the review material and current knowledge gaps presented in Section 8.4 about air quality, additional recommendations for future work can be made. They include:

- Understanding the combined and isolated impacts of future air quality and climate change on health.
- Understanding the feedbacks from climate change that make air quality management more difficult.
- Understanding the projected changes of daily weather situations and how classification of these situations (and forecasting them) might benefit air quality management.
- More monitoring of short lived climate pollutants and linking them to the National Environmental Standards pollutants.
- Understanding the relationship between Black Carbon and PM in Auckland.
- Understanding the spatial variability in black carbon (potentially through low-cost sensor networks).
- Understanding the aerosol-climate interactions over the Auckland Region, particularly regarding changing emissions patterns in shipping and rural land use.
- Assessing the future air quality impacts of climate change management plans and strategies to identify any synergies or unintended consequences.
- The integration of both climate change and air quality into the core of urban planning and transport planning is essential to manage their impacts.
- Coupled climate change-air quality modelling approaches with regional downscaling to further understand the air quality impacts of climate change in Auckland. This information would benefit health impact models and economic assessments.

It is important to continuously monitor Auckland's climate and environments to understand long-term changes and the impact that climate change and other stressors may have. Auckland Council has a large monitoring network and it is important that this network be maintained and expanded, particularly for locations and variables that are underrepresented. In particular, increased monitoring of the marine environment around Auckland is recommended to underpin and validate models of oceanic change.

The New Zealand Earth System Model (NZESM) is being developed as part of the Deep South National Science Challenge (www.deepsouthchallenge.co.nz). The NZESM, in partnership with the UK Meteorological Office, is a global climate modelling system that will contain improved formulations of Southern Ocean and Antarctic processes based on observational data collected under the Deep South Challenge. This will allow New Zealand scientists to contribute to global understandings of climate change and make more accurate projections of future climate in New Zealand and the surrounding region. NIWA is also setting up an upgraded regional climate model, with improved physics and dynamics, and higher resolution than the model used to generate the projections in this report. The next generation of New Zealand climate change projections will make use of this regional model to downscale the NZESM, and potentially allow downscaling of the global projections of the IPCC Sixth Assessment Report (due to be produced in 2021).

10 Acknowledgements

The following NIWA staff are acknowledged for their contributions towards this project: Colin Barkus, Stuart Mackay, Tilmann Steinmetz, Scott Stephens, Christian Zammit, Stephen Stuart, Sara Mikaloff-Fletcher, and Graham Rickard. Stanley Bellgard from Manaaki Whenua Landcare Research is acknowledged for providing information on *Phytophthora.* We also acknowledge the useful feedback provided by Auckland Council during the preparation of this report.

11 Glossary of abbreviations and terms

Term/abbreviation	**Definition**
99th percentile	The top 1 percent of a population.
Adaptation	The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.
Afforestation	Planting of new forests on lands that historically have not contained forests, or have not recently contained forests.
Air mass	A widespread body of air, the approximately homogeneous properties of which (1) have been established while that air was situated over a region of the Earth's surface, and (2) undergo specific modifications while in transit away from the source region.
Annual exceedance probability (AEP)	The probability of a given event (e.g. flood or sea level or wave height) being equalled or exceeded in elevation, in any given calendar year. AEP can be specified as a fraction (e.g., 0.01) or a percentage (e.g., 1%).
Anomaly	The deviation of a variable from its value averaged over a reference period.
Anthropogenic	Human-induced; man-made. Resulting from or produced by human activities.
Anthropogenic emissions	Emissions of greenhouse gases, greenhouse gas precursors, and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use changes, livestock production, fertilization, waste management, and industrial processes.
AOGCM	Atmosphere-ocean global climate model – a comprehensive climate model containing equations representing the behaviour of the atmosphere, ocean and sea ice and their interactions.
AR4	IPCC Fourth Assessment Report 2007.
AR5	5th Assessment Report of IPCC – published in 2013/14 covering three Working Group Reports and a Synthesis Report.
Atmosphere	The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium and radiatively active greenhouse gases such as carbon dioxide (0.035% volume mixing ratio) and ozone. In addition, the

	atmosphere contains the greenhouse gas water vapour, whose amounts are highly variable but typically around 1% volume mixing ratio. The atmosphere also contains clouds and aerosols.
Augmentation factor	The percentage increase of rainfall per degree of warming contained within depth-duration-frequency tables in this report.
Average recurrence interval (ARI)	The average time interval (averaged over a very long time period and many “events”) that is expected to elapse between recurrences of an infrequent event of a given large magnitude (or larger). A large infrequent event would be expected to be equalled or exceeded in elevation, once, on average, every “ARI” years, but with considerable variability.
Baseline/reference	The baseline (or reference) is the state against which change is measured. A baseline period is the period relative to which anomalies are computed.
BCC-CSM1.1	The Beijing Climate Centre Climate System Model version 1.1. A fully coupled global climate-carbon model. Part of CMIP5.
BenMap	Environmental Benefits Mapping and Analysis Program. The tool operates on 4 input variables: air quality changes, population, baseline incidence rates and an effect estimate. The resulting health impact function estimates the number and economic value of health impacts resulting from changes in fine particulate matter and ground level ozone.
Benthic	The benthic zone is the ecological region at the lowest level of a body of water such as an ocean or a lake, including the sediment surface and some sub-surface layers.
Bias correction	Procedures designed to remove systematic climate model errors.
Biogeochemical	Relating to or denoting the cycle in which chemical elements and simple substances are transferred between living systems and the environment.
Black carbon (BC)	Black Carbon is one of the components of particulate matter and it mainly comprises of soot. It can absorb sunlight, thus increasing the net radiative forcing. Black Carbon has a net warming effect on the planet. It is generally formed during the incomplete combustion of fuels or biomass burning. The main sources of black carbon can be both natural and man-made such as volcanoes, wildfires, domestic heating and road traffic. Black carbon can lead to various carcinogenic effects, respiratory and cardiovascular illnesses and at high concentrations, it can lead to mortality.
Brown Haze	A local or regional scale phenomena that causes a poor atmospheric visibility mostly associated with high pollution levels, also known as smog.
Business as Usual (BAU)	Business as usual projections assume that operating practices and policies remain as they are at present. Although baseline scenarios could incorporate some specific features of BAU scenarios (e.g., a ban on a specific technology), BAU scenarios imply that no practices or policies other than the current ones are in place. RCP8.5 is known as the 'business as usual' climate change scenario.
Carbon dioxide (CO_2)	A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas and coal of burning

	biomass, of land use changes and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1.
Carbon dioxide (CO_2) fertilisation	The enhancement of the growth of plants because of increased atmospheric carbon dioxide (CO_2) concentration
Carbon Monoxide (CO)	CO is a colourless, odourless gaseous pollutant. The sources of carbon monoxide are similar to those of black carbon. Carbon monoxide can be readily absorbed into the blood stream thus causing weakness, dizziness and at high concentrations, it can lead to mortality.
Carbon sequestration	Carbon sequestration is the process involved in carbon capture and the long-term storage of atmospheric carbon dioxide. Carbon sequestration involves long-term storage of carbon dioxide or other forms of carbon to mitigate or defer global warming.
CESM1-CAM5	The Community Earth System Model, version 5 of the Community Atmosphere Model primarily developed at the National Center for Atmospheric Research in the USA. Part of CMIP5.
Clausius–Clapeyron equation/relationship	The thermodynamic relationship between small changes in temperature and vapour pressure in an equilibrium system with condensed phases present. For trace gases such as water vapour, this relation gives the increase in equilibrium (or saturation) water vapour pressure per unit change in air temperature.
Climate	Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, rainfall and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.
Climate change	Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.
Climate change scenario	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as the observed current climate. A climate

	change scenario is the difference between a climate scenario and the current climate.
Climate model	A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented or the level at which empirical parametrizations are involved. Coupled Atmosphere–Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near or at the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and inter-annual climate predictions.
Climate projection	A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/ radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.
Climate system	The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land use change.
Climate variability	Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).
Climate variable	An element of the climate that is liable to vary or change e.g. temperature, rainfall.

CMAQ	Community Multiscale Air Quality Modelling System. It is usually used to model estimates of particulate, ozone and other toxics.
CMIP5	Coupled Model Inter-comparison Project, Phase 5, which involved coordinating and archiving climate model simulations based on shared model inputs by modelling groups from around the world. This project involved many experiments with coupled atmosphere-ocean global climate models, most of which were reported on in the IPCC Fifth Assessment Report, Working Group I. The CMIP5 dataset includes projections using the Representative Concentration Pathways.
Coastal squeeze	A narrowing of coastal ecosystems and amenities (e.g., beaches, salt marshes, mangroves, and mud and sand flats) confined between landward-retreating shorelines (from sea level rise and/or erosion) and naturally or artificially fixed shorelines including engineering defences (e.g., seawalls), potentially making the ecosystems or amenities vanish.
Cold nights	In this report, a cold night (or frost) is defined when the daily minimum temperature is below 0°C.
Confidence	The validity of a finding based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement. Confidence is expressed qualitatively.
Depth duration frequency table	Rainfall depth-duration-frequency (DDF) curves or tables describe rainfall depth as a function of duration for given return periods and are important for the design of hydraulic structures.
Diadromous	Fishes that migrate between the sea and freshwater.
Disease vector	In epidemiology, a disease vector is any agent that carries and transmits an infectious pathogen into another living organism; most agents regarded as vectors are organisms, such as intermediate parasites or microbes, but it could be an inanimate medium of infection such as dust particles.
Diurnal temperature range	The difference between the maximum and minimum temperature during a 24-hour period.
Downscaling (statistical, dynamical)	Deriving local climate information (at the 5 kilometre grid-scale in this report) from larger-scale model or observational data. Two main methods exist – statistical and dynamical. Statistical methods develop statistical relationships between large-scale atmospheric variables (e.g., circulation and moisture variations) and local climate variables (e.g., rainfall variations). Dynamical methods use the output of a regional climate/weather model driven by a larger-scale global model.

Drought (meteorological, hydrologic)	A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term; therefore, any discussion in terms of rainfall deficit must refer to the rainfall-related activity that is under discussion. For example, shortage of rainfall during the growing season impinges on crop production or ecosystem function in general (due to soil moisture drought, also termed agricultural drought), and during the runoff and percolation season primarily affects water supplies (hydrological drought). Storage changes in soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in rainfall. A period with an abnormal rainfall deficit is defined as a meteorological drought. A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.
ECMWF	European Centre for Medium Range Weather Forecasts. ECMWF reanalysis dataset is used in describing the recent history of the atmosphere, land surface, and oceans.
Ecosystem	An ecosystem is a functional unit consisting of living organisms, their non-living environment, and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases, they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or are influenced by the effects of human activities in their environment.
Ectotherm	Cold blooded animal. All New Zealand freshwater species are ectotherms.
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.
Emission scenario	A plausible representation of the future development of emissions of substances that act as radiative forcing factors (e.g., greenhouse gases, aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships.
Ensemble	A collection of model simulations characterizing a climate prediction or projection. Differences in initial conditions and model formulation result in different evolutions of the modelled system and may give information on uncertainty associated with model error and error in initial conditions in the case of climate forecasts and on uncertainty associated with model error and with internally generated climate variability in the case of climate projections.

ENSO	El Niño-Southern Oscillation. A natural global climate phenomenon involving the interaction between the tropical Pacific and the atmosphere, but has far-reaching effects on the global climate, especially for countries in the Pacific rim. ENSO is the strongest climate signal on time scales of one to several years, characteristically oscillating on a 3-7-year timescale. The quasi-periodic cycle oscillates between El Niño (unusually warm ocean waters along the tropical South American coast and west-central equatorial Pacific) and La Niña (colder-than-normal ocean waters off South America and along the central-east equatorial Pacific).
ESM	Earth system model. Refers to an AOGCM that also includes interactions with biological processes and natural cycles of chemical components such as ozone, carbon dioxide, nitrogen, and sulphur.
Eustatic sea-level rise	Absolute level of sea-level rise, measured relative to the centre of the earth. In contrast to relative sea-level rise which is measured relative to the land nearby.
Eutrophication	Over-enrichment of water by nutrients such as nitrogen and phosphorus. It is one of the leading causes of water quality impairment. The two most acute symptoms of eutrophication are hypoxia (or oxygen depletion) and harmful algal blooms.
Evapotranspiration	The combined process of evaporation from the Earth's surface and transpiration from vegetation.
Extra-tropical cyclone or mid-latitude cyclone	A large-scale (of order 1000 km) storm in the middle or high latitudes having low central pressure and fronts with strong horizontal gradients in temperature and humidity. A major cause of extreme wind speeds and heavy rainfall especially in wintertime.
Field capacity	The amount of soil moisture or water content held in the soil after excess water has drained away and the rate of downward movement has decreased. This usually takes place 2–3 days after rain or irrigation in pervious soils of uniform structure and texture.
Flood	The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.
Flow reliability	The fraction of time river flow is below a minimum flow threshold related to water abstraction (based on the Proposed National Environmental Standard for Ecological Flows). Flow reliability reflects the frequency of drought conditions.
GCM	Global climate model. These days almost all GCMs are AOGCMs (atmosphere-ocean global climate models). See also climate model.
Geomorphic	Relating to the form of the landscape and other natural features of the earth's surface.
GFDL-CM3	The Coupled physical model version 3, developed by the Geophysics Fluid Dynamics Laboratory at NOAA in the USA. Part of CMIP5.

GIS	A geographic information system (GIS) is a system designed to capture, store, manipulate, analyse, manage, and present all types of geographical information for informing decision making.
GISS-E2-R	The E2-R climate model developed by NASA Goddard Institute for Space Studies in the USA. Part of CMIP5.
Global mean surface temperature	An estimate of the global mean surface air temperature. However, for changes over time, only anomalies, as departures from a climatology, are used, most commonly based on the area-weighted global average of the sea surface temperature anomaly and land surface air temperature anomaly.
Greenhouse effect	The radiative effect of all infrared-absorbing constituents in the atmosphere. Greenhouse gases, clouds, and (to a small extent) aerosols absorb terrestrial radiation emitted by the Earth's surface and elsewhere in the atmosphere. These substances emit infrared radiation in all directions, but, everything else being equal, the net amount emitted to space is normally less than would have been emitted in the absence of these absorbers. This is because of the decline of temperature with altitude in the troposphere and the consequent weakening of emission. An increase in the concentration of greenhouse gases increases the magnitude of this effect; the difference is sometimes called the enhanced greenhouse effect. The change in a greenhouse gas concentration because of anthropogenic emissions contributes to an instantaneous radiative forcing. Surface temperature and troposphere warm in response to this forcing, gradually restoring the radiative balance at the top of the atmosphere.
Greenhouse gas (GHG)	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are many entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).
Groundwater recharge	The process by which external water is added to the zone of saturation of an aquifer, either directly into a geologic formation that traps the water or indirectly by way of another formation.
Growing degree-days (GDD)	Growing degree-days (GDD) express the sum of daily temperatures above a selected base temperature (e.g. 10˚C) that represent a threshold of plant growth. The daily GDD total is the amount the daily average temperature exceeds the threshold value (e.g. 10°C) per day. For example, a daily average temperature of 18°C would have a GDD base 10°C value of 8 and a GDD base 5°C value of 13.

	The daily GDD values are accumulated over the period 1 July to 30 June to calculate an annual GDD value.
Gully erosion	The removal of soil along drainage lines by surface water runoff. Once started, gullies will continue to move by headward erosion or by slumping of the side walls unless steps are taken to stabilise the disturbance.
Gyre	Basin-scale ocean horizontal circulation pattern with slow flow circulating around the ocean basin, closed by a strong and narrow (100 to 200 km wide) boundary current on the western side. The subtropical gyres in each ocean are associated with high pressure in the centre of the gyres; the subpolar gyres are associated with low pressure.
HadGEM2-ES	Climate model developed by the UK Met Office Hadley Centre, from the UK Unified Model. Part of CMIP5.
Hazard	The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts.
HIRDS	High Intensity Rainfall Design System (http://hirds.niwa.co.nz). HIRDS uses a regionalized index-frequency method to predict rainfall intensities at ungauged locations and returns depth-duration-frequency tables for rainfall at any location in New Zealand. Temperature increases can be inserted and corresponding increases in rainfall for each duration and frequency are calculated.
Holocene	The Holocene Epoch is the most recent geologic subdivision in the Quaternary Period, extending from 11.65 ka (thousand years before 1950) to the present. It is also known as Marine Isotopic Stage (MIS) 1 or current interglacial.
Hot days	In this report, a hot day is defined as a day with a maximum temperature over 25°C.
Humidity	*Specific* humidity is the ratio of the mass of water vapour to the total mass of the system (water plus air) in a parcel of moist air. *Relative* humidity is the ratio of the vapour pressure to the saturation vapour pressure (the latter having a strong dependence on temperature).
Hydrologic drought	Hydrologic drought occurs when low water supply becomes evident, especially in streams, reservoirs, and groundwater levels, usually after an extended period of meteorological drought.

Ice sheet	A mass of ice of continental size that is sufficiently thick to cover most of the underlying bed, so that its shape is mainly determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base). An ice sheet flows outward from a high central ice plateau with a small average surface slope. The margins usually slope more steeply, and most ice is discharged through fast flowing ice streams or outlet glaciers, in some cases into the sea or into ice shelves floating on the sea. There are two main ice sheets in the modern world, one over Greenland and one over Antarctica. Ice sheets that are grounded below sea level, including consideration of isostatic rebound, are called marine ice sheets. West Antarctica is primarily a marine based ice sheet.
Impacts (Consequences, Outcomes)	Effects on natural and human systems. In this report, the term impacts is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.
Industrial Revolution	A period of rapid industrial growth with far reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of fossil fuels and emission of, in particular, fossil carbon dioxide.
Interglacial	An interglacial period is a geological interval of warmer global average temperature lasting thousands of years that separates consecutive glacial periods within an ice age. The current Holocene interglacial began at the end of the Pleistocene, about 11,650 years ago.
Invasive species	A species introduced outside its natural past or present distribution (i.e., an alien species) that becomes established in natural or semi-natural ecosystems or habitat, is an agent of change, and threatens native biological diversity.
IPCC	Intergovernmental Panel on Climate Change. This body was established in 1988 by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) to objectively assess scientific, technical and socioeconomic information relevant to understanding the scientific basis of risk of human induced climate change, its potential impacts and options for adaptation and mitigation. Its latest reports (the Fifth Assessment) were published in 2013/14 (see www.ipcc.ch/).

IPO	Interdecadal Pacific Oscillation – a long timescale oscillation in the ocean–atmosphere system that shifts climate in the Pacific region every one to three decades.
Land use and Land use change	Land use refers to the total of arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation). Land use change refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land use change may have an impact on the surface albedo, evapotranspiration, sources and sinks of greenhouse gases, or other properties of the climate system and may thus give rise to radiative forcing and/or other impacts on climate, locally or globally.
Likelihood	The chance of a specific outcome occurring, where this might be estimated probabilistically.
Macrophyte	An aquatic plant large enough to be seen by the naked eye.
Mean annual flood	The average of the maximum flood discharges experienced in a river over a period, which should have a recurrence interval of once every 2.33 years.
Mean annual low flow	The mean of the lowest 7-day average flows in each year of a projection period.
Mean discharge	The average annual streamflow or discharge of a river.
Mean high water springs (MHWS)	The high tide height associated with higher than normal high tides that result from the beat of various tidal harmonic constituents. Mean high water springs occur every 2 weeks approximately.
Mean sea level (MSL)	The surface level of the ocean at a point averaged over an extended period such as a month or year. Mean sea level is often used as a national datum to which heights on land are referred. Mean sea level changes with the averaging period used, due to climate variability and long-term sea-level rise.
Meridional	North-south, i.e. a meridional trend is a north-south trend.
Meteorological drought	A period with an abnormal rainfall deficit; when dry weather patterns dominate an area, and resulting rainfall is low.
Mitigation (of climate change)	A human intervention to reduce the sources or enhance the sinks of greenhouse gases.
Model spread	The range or spread in results from climate models, such as those assembled for Coupled Model Intercomparison Project Phase 5 (CMIP5). Does not necessarily provide an exhaustive and formal estimate of the uncertainty in feedbacks, forcing or projections even when expressed numerically, for example, by computing a standard deviation of the models' responses. To quantify uncertainty, information from observations, physical constraints and expert judgement must be combined, using a statistical framework.
Mycorrhizal	A mycorrhiza is a symbiotic association between a fungus and the roots of a vascular host plant. The term mycorrhiza refers to the role of the fungi in the plants' root system.

NorESM1-M	The Norwegian Earth System Model. Part of CMIP5.
NO_X and NO_2	NO_X is the common term used for both Nitrogen Oxide (NO) and Nitrogen Dioxide (NO_2) in the atmosphere. It is one of the precursors of tropospheric ozone. It is one of the major pollutants from tailpipe emissions of petrol and diesel cars.
Ocean acidification	Ocean acidification refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity.
Open coast	Coastline located outside of sheltered harbours and estuaries, in locations subject to ocean waves and swell.
Orographic rainfall	Precipitation that is produced when moist air is lifted as it moves over a mountain range. As the air rises and cools, orographic clouds serve as the source of the precipitation, most of which falls upwind of the mountain ridge.
Ozone	Ozone, the triatomic form of oxygen (O_3), is a gaseous atmospheric constituent. In the troposphere, it is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Tropospheric ozone acts as a greenhouse gas. In the stratosphere, it is created by the interaction between solar ultraviolet radiation and molecular oxygen (O_2). Stratospheric ozone plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.
Paris agreement	The Paris Agreement aims to respond to the global climate change threat by keeping a global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C.
PED	Potential evapotranspiration deficit. PED can be thought of as the amount of water needed to be added as irrigation, or replenished by rainfall, to keep pastures growing at levels that are not constrained by a shortage of water. The unit of PED is millimetres.
Pelagic	Pelagic fish live in the water column of coastal, ocean, and lake waters, but not on or near the bottom of the sea or the lake.
Percentiles	The set of partition values which divides the total population of a distribution into 100 equal parts, the 50th percentile corresponding to the median of the population.
Permutation	Each of several possible ways in which a set or number of things can be ordered or arranged.
pH	pH is a dimensionless measure of the acidity of water (or any solution) given by its concentration of hydrogen ions (H^+). pH is measured on a logarithmic scale where pH = $-\log10(H^+)$. Thus, a pH decrease of 1 unit corresponds to a 10-fold increase in the concentration of H^+, or acidity.
Phenology	The relationship between biological phenomena that recur periodically (e.g., development stages, migration) and climate and seasonal changes.

Phytoplankton	Plankton consisting of microscopic plants.
PM or PM_X	Particulate Matter. It comprises of a combination of dust, soot, pollen and many other solid or liquid droplets. In this review, PM_{10} stands for particles less than 10 µg m^{-3} and $PM_{2.5}$ stands for finer particulate less than 2.5 µg m^{-3}. The main sources of PM are road traffic, domestic heating, shipping emissions, industrial emissions, wildfires and volcanoes. Depending on the species of PM, its presence might result in net warming or cooling of the atmosphere. PM is inhalable and can result in coughing, asthma, lung cancer, morbidity and mortality.
Potable water	Water that is safe to drink.
Precipitation	Describes all forms of moisture that falls from clouds (rain, sleet, hail, snow, etc). 'Rainfall' describes just the liquid component of precipitation.
Pre-industrial	Conditions at or before 1750. See also Industrial revolution.
Projection	A numerical simulation (representation) of future conditions. Differs from a forecast; whereas a forecast aims to predict the exact time-dependent conditions in the immediate future, such as a weather forecast a future cast aims to simulate a time-series of conditions that would be typical of the future (from which statistical properties can be calculated) but does not predict future individual events.
Radiative forcing	A measure of the energy absorbed and retained in the lower atmosphere. More technically, radiative forcing is the change in the net (downward minus upward) irradiance (expressed in W/m^2, and including both short-wave energy from the sun, and long-wave energy from greenhouse gases) at the tropopause, due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the sun.
Regional Climate Model (RCM)	A numerical climate prediction model run over a limited geographic domain (here around New Zealand), and driven along its lateral atmospheric boundary and oceanic boundary with conditions simulated by a global climate model (GCM). The RCM thus downscales the coarse resolution GCM, accounting for higher resolution topographical data, land-sea contrasts, and surface characteristics. RCMs can cater for relatively small-scale features such as New Zealand's Southern Alps.
Relative sea level	Sea level measured by a tide gauge with respect to the land upon which it is situated. Relative sea-level rise (RSLR) is the sea-level rise relative to the land adjacent.
Representative Concentration Pathways (RCPs)	Representative concentration pathways. They describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. The four RCPs, RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m^2, respectively)

Resolution	In climate models, this term refers to the physical distance (metres or degrees) between each point on the grid used to compute the equations. Temporal resolution refers to the time step or time elapsed between each model computation of the equations.
Return period	An estimate of the average time interval between occurrences of an event (e.g., flood or extreme rainfall) of (or below/above) a defined size or intensity.
Riparian	The interface between land and a river or stream.
Scenario	In common English parlance, a 'scenario' is an imagined sequence of future events. The IPCC Fifth Assessment describes a 'climate scenario' as: A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. The word 'scenario' is often given other qualifications, such as 'emission scenario' or 'socio-economic scenario'. For the purpose of forcing a global climate model, the primary information needed is the time variation of greenhouse gas and aerosol concentrations in the atmosphere.
Sea ice	Ice found at the sea surface that has originated from the freezing of seawater. Sea ice may be discontinuous pieces (ice floes) moved on the ocean surface by wind and currents (pack ice), or a motionless sheet attached to the coast (land-fast ice).
Sea level change	Sea level can change, both globally and locally due to (1) changes in the shape of the ocean basins, (2) a change in ocean volume as a result of a change in the mass of water in the ocean, and (3) changes in ocean volume as a result of changes in ocean water density.
Sea surface temperature (SST)	The sea surface temperature is the subsurface bulk temperature in the top few metres of the ocean, measured by ships, buoys and drifters.
Seasonal Severity Rating	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.
Seven-station series	This refers to seven long-term temperature records used to assess New Zealand's warming on the century time-scale. The sites are located in Auckland, Wellington, Masterton, Nelson, Hokitika, Lincoln, and Dunedin.
Sheet erosion	The uniform removal of soil in thin layers by the forces of raindrops and overland flow. It can be a very effective erosive process because it can cover large areas of sloping land and go unnoticed for quite some time.
Simulation	Simulation is the imitation of the operation of a real-world process or system over time. The act of simulating something first requires that a model be developed; this model represents the key characteristics, behaviours and functions of the selected physical

	or abstract system or process. The model represents the system itself, whereas the simulation represents the operation of the system over time.
SLR	Sea-level rise
SOI	Southern Oscillation Index, representing seesaws of atmospheric pressure in the tropical Pacific, one pole being at Tahiti and the other at Darwin, Australia. Extreme states of this index are indicative of El Niño or La Niña events in the equatorial Pacific. Typically, El Niño events produce more south-westerly flow than usual over New Zealand and associated cooler conditions, with more rainfall in western parts and frequently drought conditions in the east. La Niña events produce more high pressures over the South Island and warmer north-easterly airflow over the North Island, sometimes with drought conditions in the South Island.
Soil moisture	Water stored in the soil in liquid or frozen form.
Soil moisture deficit (SMD)	A day of soil moisture deficit is considered in this report to be when soil moisture is below 75 mm of available soil water capacity. SMD is calculated based on incoming daily rainfall (mm), outgoing daily potential evapotranspiration (PET, mm), and a fixed available water capacity (the amount of water in the soil 'reservoir' that plants can use) of 150 mm. Evapotranspiration (ET) 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. ET is assumed to cease if all the available water is used up.
Soil moisture reliability	The fraction of time that unirrigated soil moisture is at or below the soil moisture threshold used for the low soil moisture timing. This is a measure of time spent under water-short or drought conditions.
Solar radiation	Electromagnetic radiation emitted by the Sun with a spectrum close to the one of a black body with a temperature of 5770 K. The radiation peaks in visible wavelengths. When compared to the terrestrial radiation it is often referred to as shortwave radiation.
Spatial and temporal scales	Climate may vary on a large range of spatial and temporal scales. Spatial scales may range from local (less than 100,000 km^2), through regional (100,000 to 10 million km^2) to continental (10 to 100 million km^2). Temporal scales may range from seasonal to geological (up to hundreds of millions of years).
SRES	Special Report on Emissions Scenarios (SRES) was published by the IPCC in 2000. The greenhouse gas emissions scenarios described in this report were used in the IPCC Third Assessment Report (2001) and IPCC Fourth Assessment Report (2007).
Storm surge	The rise in sea level due to storm meteorological effects. Low-atmospheric pressure relaxes the pressure on the ocean surface causing the sea-level to rise, and wind stress on the ocean surface pushes water down-wind (onshore winds) and to the left up against any adjacent coast (alongshore winds). Storm surge has timescales of sea-level response that coincide with typical synoptic weather motions; typically 1–3 days.

Storm tracks	Originally, a term referring to the tracks of individual cyclonic weather systems, but now often generalized to refer to the main regions where the tracks of extratropical disturbances occur as sequences of low (cyclonic) and high (anticyclonic) pressure systems
Storm-tide	Storm tide refers to the total observed sea level during a storm, which is the combination of storm surge (caused by low atmospheric pressure and by high winds pushing water onshore) and normal high tide
Stormwater	The runoff of water from urban surfaces generated by rainfall or melting snow.
Strahler order	Strahler order describes river size based on tributary hierarchy. Headwater streams with no tributaries are order 1; 2nd order streams develop at the confluence of two 1st order tributaries; stream order increases by 1 where two tributaries of the same order converge.
Surface temperature	Air temperatures measured near or 'at' the surface (usually 1.5 m above the ground).
Synoptic	Weather patterns viewed at a scale of 1000 km or more to be able to see features such as high and low pressure systems.
Tide gauge	A device at a coastal or deep-sea location that continuously measures the level of the sea with respect to the adjacent land. Time averaging of the sea level so recorded gives the observed secular changes of the relative sea level
TopNet	A semi-distributed hydrological model for simulating catchment water balance and river flow, developed by NIWA.
Trend	In this report, the word trend designates a change, generally monotonic in time, in the value of a variable.
Trophic interactions	Interactions between organisms at different levels of the food chain.
Tropical cyclone	A strong, cyclonic-scale disturbance that originates over tropical oceans. Distinguished from weaker systems (often named tropical disturbances or depressions) by exceeding a threshold wind speed. A tropical storm is a tropical cyclone with 1-minute average surface winds between 18 and 32 m s^{-1}. Beyond 32 m s^{-1}, a tropical cyclone is called a hurricane, typhoon, or cyclone, depending on geographic location.
Uncertainty	A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts).
VCSN	Virtual Climate Station Network. Made up of observational datasets of a range of climate variables: maximum and minimum temperature, rainfall, relative humidity, solar radiation, and wind. Daily data are interpolated onto a 0.05° longitude by 0.05° latitude grid (approximately 4 kilometres longitude by 5 kilometres

	latitude), covering all New Zealand (11,491 points). Primary reference to the spline interpolation methodology is Tait et al (2006).
VOCs	Volatile Organic Compounds. These are gases emitted from various solids or liquids such as paint, wood, aerosol sprays, etc. They can lead to irritation to eyes and throat, severe headaches, nausea or dizziness.
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.
W/m^2	Watts per square meter (a measure of radiation intensity).
Wastewater	Used water from any combination of domestic, industrial, commercial or agricultural activities.
Wind erosion	Damage of land as a result of wind removing soil from an area.

12 Appendix I

12.1 The physical science basis of climate change (IPCC Working Group I)

The Summary for Policymakers of the IPCC AR5 Working Group I Report (IPCC, 2013b) 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 globally-averaged combined land and ocean surface temperature data as calculated by a linear trend, show a warming of 0.85 [0.65-1.06] °C, over the period 1880 to 2012.
- The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia. Over the period 1901-2010, global mean sea level rose by 0.19 [0.17 to 0.21] m.
- 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.

By the middle of the 21st century, the magnitudes of the projected climate changes are substantially affected by the choice of emissions 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). 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. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform.

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. 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 mid-latitudes (i.e. New Zealand).

The full range of projected globally averaged temperature increases for all scenarios for 2081-2100 (relative to 1986-2005) is 0.3 to 4.8°C (Figure 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 rainfall 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 rainfall events by the end of the 21st century.

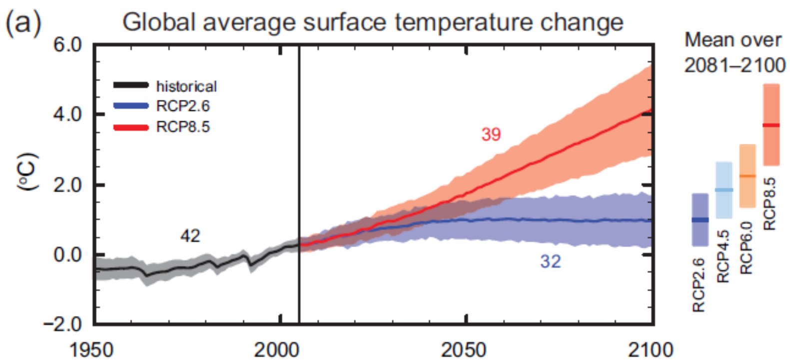

Figure 12-1: CMIP5 multi-model simulated time series from 1950-2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled 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. From 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 0.26-0.98m.** 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. More information about sea level rise projections is given in Section 8.3.

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. This represents a substantial multi-century climate change commitment created by past, present, and future emissions of CO_2.

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

The IPCC AR5 Working Group II Summary for Policymakers (IPCC, 2014b) 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 rainfall patterns and resulting river flow and drought, as well as the distribution and migration patterns of terrestrial and marine ecosystems, the incidence of wildfire, food production, livelihoods, and economies.

Changes in rainfall 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 of 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 rainfall, 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.

At present, the worldwide burden of human ill-health from climate change is relatively small compared with effects of other stressors and is not well quantified. However, there has been increased heat-related mortality and decreased cold-related mortality in some regions because of warming. Local changes in temperature and rainfall have altered the distribution of some water-borne illnesses and disease vectors.

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 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. Engineered and technological options are commonly implemented adaptive responses, often integrated within existing programs such as disaster risk management and water management. There is increasing recognition of the value of social, institutional, and ecosystem-based measures and of the extent of constraints to adaptation. Adaptation options adopted to date continue to emphasise incremental adjustments and co-benefits and are starting to emphasise flexibility and learning. Most assessments of adaptation have been restricted to impacts, vulnerability and adaptation planning, with very few assessing the processes of implementation or the effects of adaptation actions.

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

12.3 Mitigation of Climate Change (IPCC Working Group III)

The IPCC AR5 Working Group III Summary for Policymakers (IPCC, 2014c) 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.

To reach atmospheric greenhouse gas concentration levels of about 450 ppm CO_2-eq by 2100 (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).

13 Appendix II

Extreme value theory

Extreme value theory (EVT) can be used to estimate the magnitude of rare rainfall events from observed time series when the observed series is too short to contain the event directly. This is typically done by fitting an extreme value distribution to an annual maxima series for a given rainfall duration derived from the available data. This modelled distribution can then be used to extrapolate beyond the available data to estimate the rainfall intensity for any event frequency. For this study the Generalised Extreme Value distribution (GEV) has been selected as it has been shown to provide the best fit for New Zealand annual maximum rainfalls (Thompson, 2011).

Generalised Extreme Value distribution

The GEV is a flexible, three-parameter distribution that combines three extreme-value distributions within a single framework: the Gumbel, Frechet and Weibull (Jenkinson, 1955). The parameters of the distribution are $\sigma > 0$, μ and k (the scale, location and shape respectively) with a cumulative frequency distribution function given by

$$F(z) = \begin{cases} e^{-(1+kz)^{-1/k}}, & k \neq 0 \\ e^{-e^{-z}}, & k = 0 \end{cases} \quad (1)$$

where $z = (x - \mu)/\sigma$ and k is the shape parameter. When $k = 0$, the three parameter GEV distribution reduces to the 2 parameter Gumbel; $k < 0$ corresponds to a lower bound, heavy-tail Frechet distribution; and $k > 0$ to an upper bound light-tail Weibull distribution.

Two common methods of estimating the GEV parameters are method of maximum likelihood and the method of L-moments. (Morrison and Smith, 2002) proposed methods for estimating the GEV parameters that combine both maximum likelihood and L-moment methods. Subsequently, Ailliot et al. (2011) extended their method to include the asymptotic covariance structure of the estimates. The parameter estimation method denoted M1 by Ailliot et al. (2011) is used here, where the shape parameter is determined using maximum likelihood, the scale and location parameters are estimated by L-moments. This is like the MIX2 method in (Morrison and Smith, 2002), but subject to an additional constraint of $-0.5 < k < 0.5$.

Depth-duration-frequency calculation

Once parameters for the GEV distribution are found, a depth-duration-frequency table (DDF), or equivalently an intensity-duration-frequency table (IDF), can be easily computed using the inverse of the cumulative density functions given in the equation below, the quantile function

$$z(F) = \begin{cases} \mu + \dfrac{\sigma\left((\log(1-F))^{-k} - 1\right)}{k}, & k \neq 0 \\ \mu + \sigma \log\left(\dfrac{1}{\log(1/F)}\right), & k = 0 \end{cases}.$$

The covariance matrix of the parameters of the GEV distribution for the method of mixed L-moments and maximum likelihood is given by Ailliot et al. (2011). Standard errors for quantile estimates used in this study were found by taking the square root of the variances estimated from the GEV parameter covariance matrix.

14 References

ACKERLEY, D., BELL, R. G., MULLAN, A. B. & MCMILLAN, H. 2013. Estimation of regional departures from global-average sea-level rise around New Zealand from AOGCM simulations. *Weather and Climate,* 33**,** 2-22.

AILLIOT, P., THOMPSON, C. & THOMSON, P. 2011. Mixed methods for fitting the GEV distribution. *Water Resources Research,* 47.

ALLEN, R. J., LANDUYT, W. & RUMBOLD, S. T. 2016. An increase in aerosol burden and radiative effects in a warmer world. *Nature Clim. Change,* 6**,** 269-274.

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.

ANENBERG, S. C., TALGO, K., ARUNACHALAM, S., DOLWICK, P., JANG, C. & WEST, J. J. 2011. Impacts of global, regional, and sectoral black carbon emission reductions on surface air quality and human mortality. *Atmos. Chem. Phys.,* 11**,** 7253-7267.

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.

ASIKAINEN, A., PÄRJÄLÄ, E., JANTUNEN, M., TUOMISTO, J. T., SABEL & E., C. 2017. Effects of Local Greenhouse Gas Abatement Strategies on Air Pollutant Emissions and on Health in Kuopio, Finland. *Climate,* 5**,** 43.

AUCKLAND COUNCIL 2015. The health of Auckland's natural environment in 2015. Te oranga o te taiao o Tamaki Makaurau. State of Environment report 2015. Retrieved from: http://stateofauckland.aucklandcouncil.govt.nz/. 216 pp.

AUGUST, S. M. & HICKS, B. J. 2008. Water temperature and upstream migration of glass eels in New Zealand: implications of climate change. *Environmental Biology of Fishes,* 81**,** 195-205.

BANDARAGODA, C., TARBOTON, D. G. & R.A., W. 2004. Application of TOPNET in the distributed model intercomparison project. *Journal of Hydrology,* 298**,** 178-201.

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.

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.

BASSETT, I. E., COOK, J., BUCHANAN, F. & RUSSELL, J. C. 2016. Treasure Islands: biosecurity in the Hauraki Gulf Marine Park. *New Zealand Journal of Ecology,* 40**,** 250-266.

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.

BEEHIVE. 2011. *Press Release: Kaipara Harbour tidal turbine project approved. Retrieved from:* https://www.beehive.govt.nz/release/kaipara-harbour-tidal-turbine-project-approved [Online]. [Accessed].

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.

BOWEN, M., MARKHAM, J., SUTTON, P. J. H., ZHANG, X., WU, Q., SHEARS, N. T. & FERNANDEZ, D. 2017. Interannual variability of sea surface temperature in the Southwest Pacific and the role of ocean dyanmics. *Journal of Climate,* 30**,** 7481-7492.

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.

BRANZ 2007. Assessment of the need to adapt buildings in New Zealand to the impacts of climate change. Accessed from: https://www.branz.co.nz/cms_show_download.php?id=af3b6b202e83011d176ec5e8f9b58de4ce2ac882.

BROMLEY, A. & GRAY, S. 2017. Carbon monoxide changes in Auckland - the effects of government legislation. *Weather and Climate,* 37**,** 11-22.

BURGESS, T. I., SCOTT, J. K., MCDOUGALL, K. L., STUKELY, M. J. C., CRANE, C., DUNSTAN, W. A., BRIGG, F., ANDJIC, V., WHITE, D., RUDMAN, T., ARENTZ, F., OTA, N. & HARDY, G. 2016. Current and projected global distribution of Phytophthora cinnamomi, one of the world's worst plant pathogens. *Global Change Biology,* 23**,** 1661-1674.

BURRELL, T. K., O'BRIEN, J. M., GRAHAM, S. E., SIMON, K. S., HARDING, J. & MCINTOSH, A. R. 2014. Riparian shading mitigates stream eutrophication in agricultural catchments. *Freshwater Science,* 33**,** 73-84.

BYRNE, M., LAMARE, M., WINTER, D., DWORJANYN, S. A. & UTHICKE, S. 2013. The stunting effect of a high CO2 ocean on calcification and development in sea urchin larvae, a synthesis from the tropics to the poles. *Phil Trans R Soc B* 368.

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.

CAREY-SMITH, T., HENDERSON, R. & SINGH, S. 2017. High Intensity Rainfall Design System, Version 4. NIWA Client Report - in preparation.

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. 2013. The climate and weather of Auckland. NIWA Science & Technology Series, Number 60: 18 pp.

CHAPPELL, P. R. 2014. The weather and climate of Auckland: An expanded view for Watercare Services Ltd, NIWA Client Report AKL-2014-002, 76pp.

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, D., LAMARE, M. & BARKER, M. 2009. Response of sea urchin pluteus larvae (Echinodermata: Echinoidea) to reduced seawater pH: a comparison among a tropical, temperate, and a polar species. *Marine Biology* 156**,** 1125-1137.

CLARK, M. P., RUPP, D. E., WOODS, R. A., ZHENG, X., IBBITT, R. P., SLATER, A. G., SCHMIDT, J. & UDDSTROM, M. J. 2008. Hydrological data assimilation with the ensemble Kalman filter: Use of streamflow observations to update states in a distributed hydrological model. *Adv. Water Resour.,* 31**,** 1309-1324, doi:10.1016/j.advwatres.2008.06.005.

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.

CLEMENT, A. J. H., WHITEHOUSE, P. L. & SLOSS, C. R. 2016. An examination of spatial variability in the timing and magnitude of Holocene relative sea-level changes in the New Zealand archipelago. *Quaternary Science Reviews,* 131**,** 73-101.

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. *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.* Wellington: Department of Conservation.

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.

COLLINS, D. & ZAMMIT, C. 2017. Climate change impacts on agricultural water resources and flooding. NIWA Client Report for the Ministry of Primary Industries, 2016144CH, 70p.

CROW, S. K., BOOKER, D. J. & SNELDER, T. H. 2013. Contrasting influence of flow regime on freshwater fishes displaying diadromous and nondiadromous life histories. *Ecology of Freshwater Fish,* 22**,** 82-94.

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.

CUMMINGS, V., HEWITT, J., ALLEN, S., MARRIOTT, P., BARR, N. & HEATH, P. 2013. Ocean acidification: impacts on key NZ molluscs, with a focus on flat oysters (Ostrea chiliensis). Final Research Report for the NZ Ministry of Primary Industries on project ZBD200913. 18 p.

CUMMINGS, V., SMITH, A., PEEBLES, B. & MARRIOTT, P. 2015. Shell mineralogy of flat oysters under ocean acidification conditions: preliminary report. Progress report to Ministry of Primary Industries Project ZBD201306. June. 9 p.

CUNNINGHAM, S. C. 2013. *The effects of ocean acidification on juvenile Haliotis iris.* Master of Science, University of Otago.

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., 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.
DECONTO, R. M. & POLLARD, D. 2016. Contribution of Antarctica to past and future sea-level rise. *Nature,* 531**,** 591-597.
DERRAIK, J. G. & SLANEY, D. 2015. Notes on Zika virus – an emerging pathogen now present in the South Pacific. *Australian and New Zealand Journal of Public Health,* 39**,** 5-7.
DERRAIK, J. G. B. & SLANEY, D. 2007. Anthropogenic environmental change, mosquito-borne diseases and human health in New Zealand. *Ecohealth,* 4**,** 72-81.
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.
FANN, N., BRENNAN, T., DOLWICK, P., GAMBLE, J., ILACQUA, V., KOLB, L., NOLTE, C., SPERO, T. & ZISKA, L. 2016. Air Quality Impacts. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* Washington DC, US.: Global Change Research Program.
FENG, Z., LEUNG, L. R., HAGOS, S., HOUZE, R. A., BURLEYSON, C. D. & BALAGURU, K. 2016. More frequent intense and long-lived storms dominate the springtime trend in central US rainfall. *Nature Communications,* 7**,** doi:10.1038/ncomms13429.
FIORE, A. M., NAIK, V. & LEIBENSPERGER, E. M. 2015. Air Quality and Climate Connections. *Journal of the Air & Waste Management Association,* 65**,** 645-685.
FISCHER, E. M. & KNUTTI, R. 2016. Observed heavy precipitation increase confirms theory and early models. *Nature Clim. Change,* 6**,** 986-911, doi:10.1038/nclimate3110.
FISHER, G., KJELLSTROM, T., KINGHAM, S., HALES, S. & SHRESTHA, R. 2007. Health and air pollution in New Zealand (HAPiNZ).
FISHER, G. & SHERMAN, M. 2008. Quantification of Air Quality Co-benefits from Climate Change Mitigation Measures. Report prepared for MfE by EndPoint Consulting Partners. Wellington: Ministry for the Environment. viii + 37 p. Accessed from: http://www.mfe.govt.nz/sites/default/files/quantification-air-quality-co-benefits-apr08.pdf
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.
GARIANO, S. L. & GUZZETTI, F. 2016. Landslides in a changing climate. *Earth-Science Reviews,* 162**,** 227-252.
GILLANDERS, B. M., BLACK, B. A., MEEKAN, M. G. & MORRISON, M. A. 2012. Climatic effects on the growth of a temperate reef fish from the Southern Hemisphere: a biochronological approach. *Marine Biology,* 159**,** 1327-1333.
GOODHUE, N. G., ROUSE, H. L., RAMSAY, D., BELL, R. G., HUME, R. M. & HICKS, D. M. 2012. Coastal adaptation to climate 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.
GRIFFITHS, G. M. 2013. New Zealand six main centre extreme rainfall trends, 1962-2011. *Weather and Climate,* 33**,** 76-88.
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.

HAURAKI GULF FORUM 2014. State of our Gulf 2014. Retrieved from: https://www.aucklandcouncil.govt.nz/about-auckland-council/how-auckland-council-works/harbour-forums/docsstateofgulf/state-gulf-full-report-2014.pdf.

HAY, C. C., MORROW, E. D., KOPP, R. E. & MITROVICA, J. X. 2015. Probabilistic reanalysis of 20th century sea-level rise. *Nature,* 517**,** 481-484.

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.

HEPBURN, C. D., PRITCHARD, D. W. & CORNWALL, C. E., ET AL. 2011. Diversity of carbon use strategies in a kelp forest community: implications for a high CO2 ocean. . *Global Change Biology* 17**,** 2488-2497.

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.

HEWITT, J. & MCCARTAIN, L. D. 2017. Auckland east coast estuarine monitoring programme: report on data collected up until October 2015. Prepared by NIWA for Auckland Council. Auckland Council technical report, TR2017/003. 71pp.

HILL, L., STANLEY, R., HAMMON, C. & WAIPARA, N. 2017. Kauri dieback report 2017: An investigation into the distribution of kauri dieback, and implications for its future management, within the Waitakere Ranges Regional Park. Version 2, update June 2017. Auckland Council report. 40 pp.

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.

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 (ed.) 2013a. *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 2013b. 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:* 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.

IPCC 2014c. 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.

JACOB, D. J. & WINNER, D. A. 2009. Effect of climate change on air quality. *Atmospheric Environment,* 43**,** 51-63.

JAMES, R. K., HEPBURN, C. D. & CORNWALL, C. E., ET AL. 2014. Growth response of an early successional assemblage of coralline algae and benthic diatoms to ocean acidification. . *Marine Biology* 161**,** 1687-1696

JENKINSON, A. F. 1955. The Frequency Distribution of the Annual Maximum (or Minimum) Values of Meteorological Elements. *Quarterly Journal of the Royal Meteorological Society,* 81**,** 158-171, doi:DOI 10.1002/qj.49708134804.

JIANG, N., DIRKS, K. N. & LUO, K. 2014. Effects of local, synoptic and large-scale climate conditions on daily nitrogen dioxide concentrations in Auckland, New Zealand. *International Journal of Climatology,* 34**,** 1883-1897.

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.

KOSSIN, J. P., EMANUEL, K. A. & VECCHI, G. A. 2014. The poleward migration of the location of tropical cyclone maximum intensity. *Nature,* 509**,** 349-352.

KRAMER, L., CHIN, P., CANE, R., KAUFFMAN, E. & MACKERETH, G. 2011. Vector competence of New Zealand mosquitoes for selected arboviruses. *American Journal of Tropical Medicine and Hygiene,* 85**,** 182-189.

KUSCHEL, G., METCALFE, J., WILTON, E., GURIA, J., HALES, S., ROLFE, K. & WOODWARD, A. 2012. Updated health and air pollution in New Zealand study. Volume 1: Summary report. Report to the Health Research Council. Available from www.hapinz.org.nz.

LANDCARE RESEARCH. 2014. *Kauri dieback: Kia touti he kauri. Weed Biocontrol Newsletter, Issue 67, Accessed from:* http://www.landcareresearch.co.nz/publications/newsletters/biological-control-of-weeds/issue-67/kauri-dieback [Online]. [Accessed].

LAW, C. S., BELL, J. J., BOSTOCK, H. C., CORNWALL, C. E., CUMMINGS, V. J., CURRIE, K., DAVY, S. K., GAMMON, M., HEPBURN, C. D., HURD, C. L., LAMARE, M., MIKALOFF-FLETCHER, S. E., NELSON, W. A., PARSONS, D. M., RAGG, N. L. C., SEWELL, M. A., SMITH, A. M. & TRACEY, D. M. 2017. Ocean acidification in New Zealand waters: trends and impacts. *New Zealand Journal of Marine and Freshwater Research***,** 1-41.

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.

LE COZANNET, G., ROHMER, J., CAZENAVE, A., IDIER, D., VAN DE WAL, R., DE WINTER, R., PEDREROS, R., BALOUIN, Y., VINCHON, C. & OLIVEROS, C. 2015. Evaluating uncertainties of future marine flooding occurrence as sea-level rises. *Environmental Modelling and Software,* 73**,** 44-56.
LENDERINK, G. & FOWLER, H. J. 2017. Hydroclimate: understanding rainfall extremes. *Nature Clim. Change,* 7**,** 393-393, doi:10.1038/nclimate3305.
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.
LORREY, A. M., GRIFFITHS, G. M., FAUCHEREAU, N., DIAMOND, H. J., CHAPPELL, P. R. & RENWICK, J. A. 2014. An ex-tropical cyclone climatology for Auckland, New Zealand. *International Journal of Climatology,* 34**,** 1157-1168.
LÜTHI, D., LE FLOCH, M., BEREITER, B., BLUNIER, T., BARNOLA, J.-M., SIEGENTHALER, U., RAYNAUD, D., JOUZEL, J., FISCHER, H., KAWAMURA, K. & STOCKER, T. F. 2008. High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature,* 453**,** 379.
MACINNES-NG, C. & SCHWENDENMANN, L. 2015. Litterfall, carbon and nitrogen cycling in a southern hemisphere conifer forest dominated by kauri (Agathis australis) during drought. *Plant Ecology,* 216**,** 247-262.
MCBRIDE, G., REEVE, G., PRITCHARD, M., LUNDQUIST, C., DAIGENAULT, A., BELL, R. G., BLACKETT, P., SWALES, A., WADWHA, S., TAIT, A. & ZAMMIT, C. 2016. The Firth of Thames and Lower Waihou River. Synthesis Report RA2, Coastal Case Study. Climate Changes, Impacts and Implications for New Zealand to 2100. MBIE contract CO1X1225, 50pp.
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.
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.
MCKERCHAR, A. I. & HENDERSON, R. 2003. Shifts in flood and low-flow regimes in New Zealand due to interdecadal climate variations. *Hydrological Sciences Journal,* 48**,** 637-654.
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.
MCMILLAN, H. K., HREINSSONN, E. O., CLARK, M. P., SINGH, S. K., ZAMMIT, C. & UDDSTROM, M. J. 2013. Operational hydrological data assimilation with the recursive ensemble Kalman Filter. *Hydrol. Earth Syst. Sci.,* 17**,** 21-38.
METCALFE, J. & SRIDHAR, S. 2017. Auckland air emissions inventory 2016 - Transport. Prepared by Emission Impossible Ltd for Auckland Council. Auckland Council [technical report, TR20xx/xxx] (DRAFT ONLY).
METCALFE, J., WICKHAM, L. & SRIDHAR, S. 2017. Auckland air emissions inventory 2016 – home heating. Prepared by Emission Impossible Ltd for Auckland Council. Auckland Council [Technical report, TR2017/xxx] (DRAFT ONLY).
MILDENHALL, D. C. 2001. Middle Holocene mangroves in Hawke's Bay, New Zealand. *New Zealand Journal of Botany,* 39**,** 517-521.
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 & STATS NZ 2014. New Zealand's Environmental Reporting Series: 2014 Air domain report. Available from www.mfe.govt.nz and www.stats.govt.nz.

MITCHELL, E. J. S., COULSON, G., BUTT, E. W., FORSTER, P. M., JONES, J. M. & WILLIAMS, A. 2017. Heating with Biomass in the United Kingdom: Lessons from New Zealand. *Atmospheric Environment,* 152**,** 431-454.

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.

MORRISON, J. E. & SMITH, J. A. 2002. Stochastic modelling of flood peaks using the generalised extreme value distribution. *Water Resources Research,* 38**,** doi:10.1029/2001wr000502.

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.

MUNDAY, P. L., CHEAL, A. J. & DIXSON, D. L., ET AL. 2014. Behavioural impairment in reef fishes caused by ocean acidification at CO2 seeps. *Nature Climate Change* 4**,** 487-492.

MUNDAY, P. L., WATSON, S.-A., PARSONS, D. M., KING, A., BARR, N., MCLEOD, I., ALLAN, B. J. M. & PETHER, S. M. J. 2015. Effects of elevated CO_2 on early life history development of the yellowtail kingfish, *Seriola lalandi,* a large pelagic fish. *ICES Journal of Marine Science,* doi: 10.1093/icesjms/fsv210.

NEUHEIMER, A. B., THRESHER, R. E., LYLE, J. M. & SEMMENS, J. M. 2011. Tolerance limit for fish growth exceeded by warming waters. *Nature Climate Change,* 1**,** 110-113.

NEW ZEALAND HERALD. 2013. *Kaipara marine turbine plan on hold. Retrieved from:* http://www.nzherald.co.nz/business/news/article.cfm?c_id=3&objectid=11132002 [Online]. [Accessed].

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.

OFFICE OF THE PRIME MINISTER'S CHIEF SCIENCE ADVISOR 2017. New Zealand's fresh waters: Values, state, trends and human impacts. Wellington: Office of the Prime Minister's Chief Science Advisor. Retrieved from: http://www.pmcsa.org.nz/wp-content/uploads/PMCSA-Freshwater-Report.pdf.

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.

OLSEN, D., TREMBLAY, L., CLAPCOTT, J. & HOLMES, R. 2012. Water temperature criteria for native aquatic biota. Auckland Council technical report 2012/036, 80pp.

PARLIAMENTARY COMMISSIONER FOR THE ENVIRONMENT 2012. Hydroelectricity or wild rivers? Climate change versus natural heritage. Wellington: Parliamentary Commissioner for the Environment. Retrieved from: http://www.pce.parliament.nz/media/1277/wild-riversweb.pdf.

PARLIAMENTARY COMMISSIONER FOR THE ENVIRONMENT 2015a. National and regional risk exposure in low-lying coastal areas: Areal extent, population, buildings and infrastructure. Prepared by R.G. Bell, R. Paulik, and S. Wadwha, NIWA Client Report HAM2015-006, 270 pp.

PARLIAMENTARY COMMISSIONER FOR THE ENVIRONMENT 2015b. Preparing New Zealand for rising seas: certainty and uncertainty. Report by NIWA for Parliamentary Commissioner for the Environment, June 2015, 93pp. Sourced from: http://www.pce.parliament.nz/publications/preparing-new-zealand-for-rising-seas-certainty-and-uncertainty.

PARLIAMENTARY COMMISSIONER FOR THE ENVIRONMENT 2015c. 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.

PARLIAMENTARY COMMISSIONER FOR THE ENVIRONMENT 2017. Taonga of an island nation: Saving New Zealand's birds. Wellington: Parliamentary Commissioner for the Environment. Retrieved from: http://www.pce.parliament.nz/media/1695/taonga-of-an-island-nation-web-final-small.pdf. Parliamentary Commissioner for the Environment, Wellington.

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.

PEARCE, J. L., BERINGER, J., NICHOLLS, N., HYNDMAN, R. J., UOTILA, P. & TAPPER, N. J. 2011. Investigating the influence of synoptic-scale meteorology on air quality using self-organizing maps and generalized additive modelling. *Atmospheric Environment,* 45**,** 128-136.

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.

PERRY, G. L. W., WILMSHURST, J. M. & MCGLONE, M. 2014. Ecology and long-term history of fire in New Zealand. *New Zealand Journal of Ecology,* 38**,** 157-176.

PFAHL, S., OGORMAN, P. A. & FISCHER, E. M. 2017. Understanding the regional pattern of projected future changes in extreme precipitation. *Nature Clim. Change,* 7**,** 423-427.

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*.

REINEN-HAMILL, R., HEGAN, B. & SHAND, T. 2006. Regional assessment of areas susceptible to coastal erosion. Report prepared for Auckland Regional Council by Tonkin Taylor. Accessed from: http://temp.aucklandcouncil.govt.nz/EN/planspoliciesprojects/plansstrategies/unitaryplan/Documents/Section32report/Appendices/Appendix%203.32.4.pdf.

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.

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. 2015. Extreme rainfall in early July 2014 in Northland, New Zealand – was there an anthropogenic influence? *Bulletin of the American Meteorological Society,* 96**,** 136-140.

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, 72 pp. Available from: http://www.royalsociety.org.nz/expert-advice/papers/yr2016/climate-change-implications-for-new-zealand/.

ROYAL SOCIETY OF NEW ZEALAND 2017. Human health impacts of climate change for New Zealand: Evidence summary. 18 pp. Available from: https://royalsociety.org.nz/assets/documents/Report-Human-Health-Impacts-of-Climate-Change-for-New-Zealand-Oct-2017.pdf.

RUTLEDGE, D., AUSSEIL, A.-G., BAISDEN, T., BODEKER, G., BOOKER, D. J., CAMERON, M., COLLINS, D., DAIGENAULT, A., FERNANDEZ, M., FRAME, B., KELLER, E., KREMSER, S., KIRSCHBAUM, M., LEWIS, J., MULLAN, A. B., REISINGER, A., SOOD, A., STUART, S., TAIT, A., TEIXEIRA, E. I., TIMAR, L. & ZAMMIT, C. 2017. Identifying feedbacks, understanding cumulative impacts and recognising limits: A national integrated assessment. Synthesis Report RA3. Climate Changes, Impacts and Implications for New Zealand to 2100. MBIE contract C01X1225, 84pp.

SALINGER, M. J. & MULLAN, A. B. 1999. New Zealand climate: temperature and precipitation variations and their links with atmospheric circulation 1930–1994. *International Journal of Climatology,* 19**,** 1049-1071.

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

SALMOND, J. A., DIRKS, K. N., FIDDES, S., PEZZA, A., TALBOT, N., SCARFE, J., RENWICK, J. & PETERSEN, J. 2016. A climatological analysis of the incidence of brown haze in Auckland, New Zealand. *International Journal of Climatology,* 36**,** 2516-2526.

SETTELE, J., SCHOLES, R., BETTS, R., BUNN, S., LEADLEY, P., NEPSTAD, D., OVERPECK, J. T. & TABOADA, M. 2014. Terrestrial and inland water 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, United Kingdom and New York, USA: Cambridge University Press.

SHARPLES, J. 1997. Cross-shelf intrusion of subtropical water into the coastal zone of northeast New Zealand. *Continental Shelf Research,* 17**,** 835-897.

SHARPLES, J. & GREIG, M. J. N. 1998. Tidal currents, mean flows and upwelling on the north-east coast of New Zealand. *New Zealand Journal of Marine and Freshwater Research,* 32**,** 215-231.

SHEPPARD, C. S. 2013. Potential spread of recently naturalised plants in New Zealand under climate change. *Climatic Change,* 117**,** 919-931.

SHEPPARD, C. S., BURNS, B. R. & STANLEY, M. C. 2016. Future-proofing weed management for the effects of climate change: is New Zealand underestimating the risk of increased plant invasions? *New Zealand Journal of Ecology,* 40**,** 398-405.

SHINDELL, D., KUYLENSTIERNA, J. C. I., VIGNATI, E., VAN DINGENEN, R., AMANN, M., KLIMONT, Z., ANENBERG, S. C., MULLER, N., JANSSENS-MAENHOUT, G., RAES, F., SCHWARTZ, J., FALUVEGI, G., POZZOLI, L., KUPIAINEN, K., HÖGLUND-ISAKSSON, L., EMBERSON, L., STREETS, D., RAMANATHAN, V., HICKS, K., OANH, N. T. K., MILLY, G., WILLIAMS, M., DEMKINE, V. & FOWLER, D. 2012. Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science,* 335**,** 183.

SILVA, R. A., WEST, J. J., LAMARQUE, J.-F., SHINDELL, D. T., COLLINS, W. J., FALUVEGI, G., FOLBERTH, G. A., HOROWITZ, L. W., NAGASHIMA, T., NAIK, V., RUMBOLD, S. T., SUDO, K., TAKEMURA, T., BERGMANN, D., CAMERON-SMITH, P., DOHERTY, R. M., JOSSE, B., MACKENZIE, I. A., STEVENSON, D. S. & ZENG, G. 2017. Future global mortality from changes in air pollution attributable to climate change. *Nature Clim. Change,* 7**,** 647-651.

SILVA, R. A., WEST, J. J., LAMARQUE, J. F., SHINDELL, D. T., COLLINS, W. J., DALSOREN, S., FALUVEGI, G., FOLBERTH, G., HOROWITZ, L. W., NAGASHIMA, T., NAIK, V., RUMBOLD, S. T., SUDO, K., TAKEMURA, T., BERGMANN, D., CAMERON-SMITH, P., CIONNI, I., DOHERTY, R. M., EYRING, V., JOSSE, B., MACKENZIE, I. A., PLUMMER, D., RIGHI, M., STEVENSON, D. S., STRODE, S., SZOPA, S. & ZENGAST, G. 2016. The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. *Atmos. Chem. Phys.,* 16**,** 9847-9862.

SINGERS, N., OSBORNE, B., LOVEGROVE, T., JAMIESON, A., BOOW, J., SAWYER, J., HILL, K., ANDREWS, J., HILL, S. & WEBB, C. 2017. Indigenous terrestrial and wetland ecosystems of Auckland. Auckland Council report sourced from: http://www.knowledgeauckland.org.nz/assets/publications/Indigenous-terrestrial-and-wetland-ecosystems-of-Auckland-2017.pdf.

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.

SMITH, A. M., BERMAN, J. & KEY JR, M. M., ET AL. 2013. Not all sponges will thrive in a high-CO2 ocean: Review of the mineralogy of calcifying sponges. *Palaeogeography Palaeoclimatology Palaeoecology,* 392**,** 463-472.

STANTON, B. R., SUTTON, P. J. H. & CHISWELL, S. M. 1997. The East Auckland Current, 1994-1995. *New Zealand Journal of Marine and Freshwater Research,* 31**,** 537-549.

STEPHENS, S., BELL, R. G. & LAWRENCE, J. 2017. Applying principles of uncertainty within coastal hazard assessments to better support coastal adaptation. *Journal of Marine Science and Engineering,* 5**,** 40, http://www.mdpi.com/2077-1312/5/3/40.
STEPHENS, S., BELL, R. G., WADWHA, S. & ALLIS, M. 2016a. Coastal hazard and sea-level rise inundation exposure for Auckland Airport, NIWA Client Report for Auckland Airport Ltd, HAM2016-017, 28pp.
STEPHENS, S., WADWHA, S. & BELL, R. G. 2016b. Coastal hazard and sea-level rise inundation exposure for Onehunga, Mangere and Manukau. NIWA Client Report for Panuku Developments Auckland, HAM2016-066, 29 pp.
STEPHENS, S., WADWHA, S. & TUCKEY, B. 2016c. Coastal inundation by storm-tides and waves in the Auckland Region. Prepared by NIWA and DHI Ltd for Auckland Council. Auckland Council technical report TR2016/017, 206 pp.
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.
TAGARIS, E., LIAO, K.-J., DELUCIA, A. J., DECK, L., AMAR, P. & RUSSELL, A. G. 2009. Potential Impact of Climate Change on Air Pollution-Related Human Health Effects. *Environmental Science & Technology,* 43**,** 4979-4988.
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.
TAIT, L. 2014. Impacts of natural and manipulated variations intemperature, pH and light on photosynthetic parameters of coralline–kelp assemblages. *J. Mar Exp Biol. Ecol.,* 454**,** 1-8.
TAYLOR, K. E., STOUFFER, R. J. & MEEHL, G. A. 2012a. An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society,* 93**,** 485-498.
TAYLOR, R. G., SCANLON, B., DÖLL, P., RODELL, M., VAN BEEK, R., WADA, Y., LONGUEVERGNE, L., LEBLANC, M., FAMIGLIETTI, J. S., EDMUNDS, M., KONIKOW, L., GREEN, T. R., CHEN, J., TANIGUCHI, M., BIERKENS, M. F. P., MACDONALD, A., FAN, Y., MAXWELL, R. M., YECHIELI, Y., GURDAK, J. J., ALLEN, D. M., SHAMSUDDUHA, M., HISCOCK, K., YEH, P. J. F., HOLMAN, I. & TREIDEL, H. 2012b. Ground water and climate change. *Nature Climate Change,* 3**,** 322.
THOMPSON, C. 2011. HIRDSV3: High Intensity Rainfall Design System. Wellington: National Institute of Water and Atmosphere.
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.
TRENBERTH, K. E. 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change,* 42**,** 327-339, doi:10.1023/A:1005488920935.
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.
UNEP 2017. The Emissions Gap Report 2017, accessed from https://wedocs.unep.org/bitstream/handle/20.500.11822/22070/EGR_2017.pdf, 116pp.
UNEP & WMO 2011. Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers. Accessed from: https://wedocs.unep.org/rest/bitstreams/12809/retrieve, 36pp.
VILIJEVAC, Z., MURPHY, G., SMAILL, A., CROWCROFT, G. & BOWDEN, D. 2002. South Auckland Groundwater, Kaawa Aquifer Recharge Study and Management of the Volcanic and Kaawa Aquifers. Auckland Regional Council Technical Publication TP133.
WALSH, K. J. E., MCBRIDE, J. L., KLOTZBACH, P. J., BALACHANDRAN, S., CAMARGO, S. J., HOLLAND, G., KNUTSON, T. R., KOSSIN, J. P., LEE, T.-C., SOBEL, A. & SUGI, M. 2016. Tropical cyclones and climate change. *WIREs Climate Change,* 7**,** 75-89.

WANG, Y., XIE, Y., DONG, W., MING, Y., WANG, J. & SHEN, L. 2017. Adverse effects of increasing drought on air quality via natural processes. *Atmos. Chem. Phys.,* 17**,** 12827-12843.
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.
WILHITE, D. A. 2000. Drought as a natural hazard: concepts and definitions. *In:* WILHITE, D. A. (ed.) *Drought: A global assessment.* London: Routledge.
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.
WISE, M. G., DOWDESWELL, J. A., JAKOBSSON, M. & LARTER, R. D. 2017. Evidence of marine ice-cliff instability in Pine Island Bay from iceberg-keel plough marks. *Nature,* 550**,** 506.
WONG, P. P., LOSADA, I. J., GATTUSO, J.-P., HINKEL, J., KHATTABI, A., MCINNES, K. L., SAITO, Y. & SALLENGER, A. 2014. Coastal systems and low-lying areas. *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 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.
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.
WYSE, S., MACINNES-NG, C., BURNS, B. R., CLEARWATER, M. J. & SCHWENDENMANN, L. 2013. Species assemblage patterns around a dominant emergent tree are associated with drought resistance. *Tree Physiology,* 33**,** 1269-1283.
ZAMMIT, C. & WOODS, R. 2011. Projected climate and river flow for the Waimakariri catchment for 2040s and 2090s. NIWA Client Report: CHCH2011-025, 52p.
ZELDIS, J. R. & ET AL. 2015. Firth of Thames water quality and ecosystem health. NIWA Client report No: CHC2014-123. Prepared for the Waikato Regional Council and Dairy New Zealand. .
ZELDIS, J. R., WALTERS, R. A., GREIG, M. J. N. & IMAGE, K. 2004. Circulation over the northeastern New Zealand continental slope, shelf and adjacent Hauraki Gulf, from spring to summer. *Continental Shelf Research,* 24**,** 543-561.

Find out more: phone 09 301 0101, email
rimu@aucklandcouncil.govt.nz or visit
aucklandcouncil.govt.nz and knowledgeauckland.org.nz

Auckland Council
Te Kaunihera o Tāmaki Makaurau