Wellington Region climate change extremes and implications

Prepared for Greater Wellington Regional Council

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Executive summary

This report explores projections for a range of extreme climate indices in the Wellington Region (temperature and rainfall), comparing the recent past to modelled future conditions, and considers implications of changes in extremes on different sectors. It is a companion report to the climate change projections for Wellington Region produced by NIWA for the Greater Wellington Regional Council in 2017.

Historic temperature trends in Wellington and Masterton show that warm night-time extreme temperatures have increased and cold extremes (day and night) have decreased, consistent with increasing atmospheric greenhouse gas concentrations globally. Changes to extreme rainfall are less pronounced across the region, but the amount of extreme rainfall recorded in short periods has increased at Kelburn over the past 90 years. Wellington and Masterton were chosen for historic analysis as both sites have the longest records in the region and are part of the New Zealand Seven Station Temperature Series.

In the future, more warm extremes are expected in the Wellington Region (e.g. hot days, heatwave days, warm nights) and fewer cold extremes will occur (e.g. frosts, cold days, cold nights). These trends are amplified under higher greenhouse gas emission scenarios. These temperature changes are likely to affect the productivity of Wellington’s primary sectors, through impacts on stock heat stress, plant water use, pests, and changing plant growth cycles and harvest times. Species in the natural environment may be pushed to their thermal limits and pests may become more prevalent. Urban environments will also be affected through heat stress on people and infrastructure.

For rainfall, the future trajectories are less straightforward, with some areas projected to experience increases in the numbers of rain days and others decreases in rain day totals. However, there is a clear trend towards increasing lengths of dry spells and decreasing lengths of wet spells at both Wellington and Masterton. Increasing prevalence of drought across the region, particularly in the Wairarapa, is likely to impact plant growth, water supply (for both urban and rural uses), and low river flows affecting instream habitat availability.

Extreme, rare rainfall events are likely to increase in intensity due to more moisture being held in a warmer atmosphere. The amount of rain that falls during short duration extreme events (e.g. 1-hour, 100-year return period) is likely to increase disproportionately compared with longer events (e.g. 120-hour). Increasing extreme rainfall is likely to have impacts on slips and landslides, transport networks (important for primary sectors getting products to market), soil saturation, urban drainage systems, and natural environments through sedimentation and reduction in instream habitat quality.

Wellington’s coastal zone is at risk from ongoing sea-level rise and extreme storm tide events. Considerable areas of built up areas, as well as important transport infrastructure, are exposed to rising seas. At present sea levels, 4084 buildings and 36.2 km of roads in the Wellington region are exposed to a 1% annual exceedance probability storm-tide event, which rises to 14,336 buildings and 173 km of roads under 1 m of sea-level rise and 21,755 buildings and 319 km of roads under 2 m of sea-level rise.

1 Introduction

Climate change is already affecting New Zealand with downstream effects on our natural environment and communities. In the coming decades, climate change will increasingly pose challenges to New Zealanders' way of life. NIWA provided climate change projections and impacts information to Greater Wellington Regional Council in 2017 (Pearce et al., 2017), which can be accessed from www.gw.govt.nz/climate-change. That report concentrated on projected changes to average annual and seasonal climate conditions (e.g. average temperature, rainfall, wind speed, and so on). Changes to climatic extremes (e.g. heatwaves, extreme rainfall, and drought) may have a more significant impact on people, economies and the natural environment than changes to the average climatic conditions. In light of this, Greater Wellington Regional Council has commissioned this report, which provides projections of future changes for climatic extremes and their implications for the Wellington Region.

This report contains information about extreme temperature and rainfall changes for the Wellington Region between the historic period (1986-2005) and the mid and late 21st Century. Projections have been extracted from NIWA's Regional Climate Model; output of which has been downscaled to a resolution of 5km x 5km. Recent updates to the High Intensity Rainfall Design System (HIRDS v4) have produced information on extreme rainfall events. Other work on extreme climate indices has been carried out using the weather@home climate model, and results are presented here for extreme temperature changes. Additional analyses of temperature extremes are covered (summer 2017/2018 temperature records and historical trends in station temperatures in the Wellington Region). An extreme index of drought and implications of extreme storm tide events are also considered. An updated section on sea-level rise projections following the publishing of coastal hazards guidance from the Ministry for the Environment is included in the Appendix. Finally, three sections on implications of changes in extremes are presented (based on literature) – for insurance, agriculture and horticulture, ecosystems, and the urban environment.

2 Methodology

Downscaled climate model data from NIWA's Regional Climate Model was used to calculate climate indices presented in section 3 and section 4. The data and downscaling methodology are consistent with those stated in Pearce et al. (2017) for the climate change assessment for Greater Wellington Regional Council.

Scenarios from the Intergovernmental Panel on Climate Change (IPCC) were used to understand potential climate futures based on economic, political and social developments during the 21st century.

2.1 Representative Concentration Pathways

Key messages

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

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

This range of uncertainty has been dealt with by the IPCC through consideration of 'scenarios' that describe possible future concentrations of greenhouse gases in the atmosphere. The wide range of scenarios are associated with possible economic, political, and social developments during the 21st century, and via consideration of results from several different climate models for any given scenario. In the 2013 IPCC Fifth Assessment Report, the atmospheric greenhouse gas concentration components of these scenarios are called Representative Concentrations Pathways (RCPs). These are abbreviated as RCP2.6, RCP4.5, RP6.0, and RCP8.5, in order of increasing radiative forcing by greenhouse gases (i.e. the change in energy in the atmosphere due to greenhouse gas emissions). RCP2.6 leads to low anthropogenic greenhouse gas concentrations (requiring removal of CO_2 from the atmosphere, also called the 'mitigation' scenario), RCP4.5 and RCP6.0 are two 'stabilisation' scenarios (where greenhouse gas emissions and therefore radiative forcing stabilises by 2100) and RCP8.5 has very high greenhouse gas concentrations (the 'high emissions' scenario). Therefore, the RCPs represent a range of 21st century climate policies. Table 2-1 shows the projected global mean surface air temperature for each RCP.

Table 2-1: Projected change in global mean surface air temperature for the mid- and late- 21st century relative to the reference period of 1986-2005 for different RCPs. After IPCC (2013).

Scenario	Alternative name	2046-2065 (mid-century)		2081-2100 (end-century)	
		Mean	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	High emissions 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 2-1). 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 spatially uniform across New Zealand.

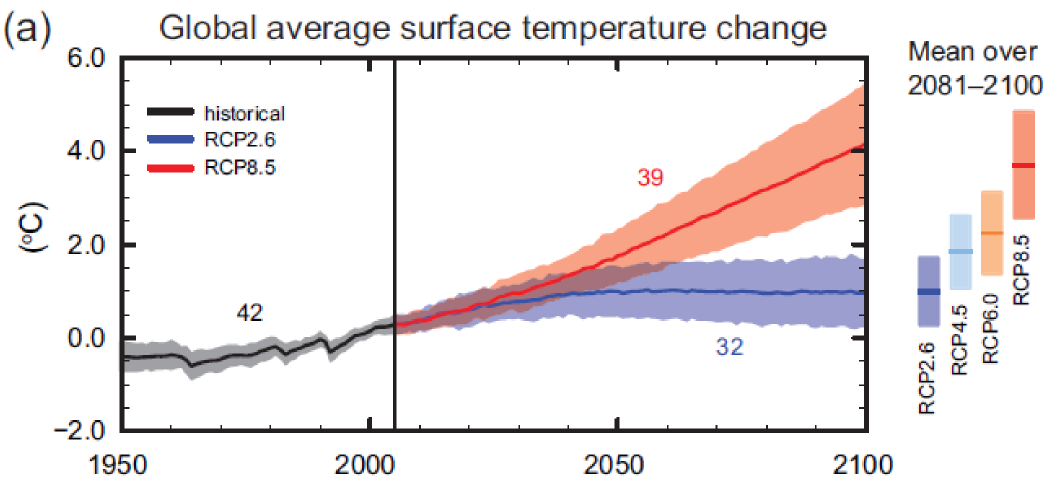


Figure 2-1: CMIP5 multi-model simulated time series from 1950-2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled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

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. Regions that are typically considered "climatically stable", characterised by infrequent extremes or benign impacts from episodic droughts or deluge, may also experience conditions that have not been observed during the instrumental record. The global ocean will continue to warm during the 21st century, influencing ocean circulation and sea ice extent.

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

In this report, global climate model outputs based on three RCPs (RCP2.6, RCP4.5 and RCP8.5) have been downscaled to produce future climate projections for the Wellington Region. The rationale for choosing these three scenarios was to present a high emissions scenario if greenhouse gas emissions continue at current rates (RCP8.5), a scenario which could be realistic if global action is taken towards mitigating climate change, for example the Paris Climate Change agreement (RCP4.5), and a 'best case' scenario if strong mitigation action takes place (RCP2.6).

2.2 NIWA's Regional Climate Model

Key messages

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

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

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

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

The RCM output is then downscaled statistically (by interpolation from the model 27 km grid) to a ~5 km x ~5 km resolution with a daily time-step. The ~5 km grid corresponds to the VCSN grid[1]. Figure 2-2 shows a schematic for the dynamical downscaling method used in this report.

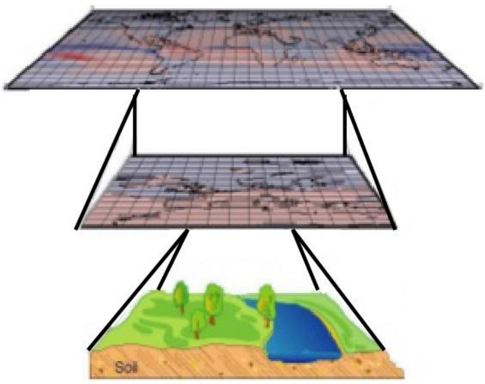


Figure 2-2: Schematic showing dynamical downscaling method used in this report.

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

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

[1] Virtual Climate Station Network, a set of New Zealand climate data based on a 5 km by 5 km grid across the country. Data have been interpolated from 'real' climate station records (TAIT, 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.)

3 Historic and future temperature extreme indices

Key messages

- Increasing numbers of warm extremes and decreasing numbers of cold extremes are projected for the Wellington Region.
- The changes are more pronounced through time and with increased greenhouse forcing.
- For warm nights (T_{min} >15°C), a 50-day increase is projected for Wellington and a 36-day increase for Masterton, under RCP8.5 by 2090.
- For cold nights (T_{min} <5°C), a 24-day decrease is projected for Wellington and a 54-day decrease for Masterton, under RCP8.5 by 2090.
- For cold days (T_{max} <10°C), a 20-day decrease is projected for Wellington and a 12-day decrease for Masterton, under RCP8.5 by 2090.
- For hot days (T_{max} >25°C), a 29-day increase is projected for Wellington and a 70-day increase for Masterton, under RCP8.5 by 2090.
- For extreme hot days (T_{max} >30°C), a 20-day increase for Masterton, under RCP8.5 by 2090. For Wellington, there is a climate shift from the absence of extreme hot days in the historic period to 3 per year by 2090 under RCP8.5.
- For heatwave days (≥3 consecutive days with T_{max} >25°C), a 15-day increase is projected for Wellington and a 67-day increase for Masterton, under RCP8.5 by 2090.
- For extreme heatwave days (≥3 consecutive days with T_{max} >30°C), there is a climate shift from the absence of extreme heatwave days in the historic period for Masterton to 11 per year by 2090 under RCP8.5. There are still no extreme heatwave days projected for in Wellington in the future.

Indices of temperature extremes are considered in this section. These indices are the average number of days per year with temperatures above or below certain thresholds (Table 3-1). Averages are taken over 20-year time spans: 1986-2005 for the historic period, 2031-2050 for the mid-century “2040” period, and 2081-2100 for the late-century “2090” period. Projections for each index are shown as maps for these three time periods, and for the future time periods projections for four IPCC Representative Concentration Pathways (Section 2.1) are given. In addition, projections for Wellington and Masterton are given for these same time periods and RCPs.

Table 3-1: Temperature extreme indices and thresholds.

Temperature extreme indices	Threshold
Warm nights	Daily minimum temperature > 15°C
Cold nights	Daily minimum temperature < 5°C
Cold days	Daily maximum temperature < 10°C
Hot days	Daily maximum temperature > 25°C
Extreme hot days	Daily maximum temperature > 30°C
Heatwave days	Days in a period ≥ 3 days with maximum temperature > 25°C
Extreme heatwave days	Days in a period ≥ 3 days with maximum temperature > 30°C

3.1 Warm nights (minimum temperature > 15°C)

The area around Wellington City experiences the largest number of warm nights in the Wellington Region in the historic period (40-45 warm nights per year) (Figure 3-1). The high elevations of the Tararua Ranges experience the least warm nights (<1 per year).

In the future, the number of warm nights is projected to increase throughout the region (Figure 3-2), with the largest increases in coastal areas and particularly the northeast of the region. Under the lowest concentration scenario (RCP2.6), about 4-10 more warm nights are projected for most of the region. By 2090 under the highest concentration scenario (RCP8.5), at least 30 more warm nights are projected for most parts of the region (excluding high elevation areas). The increase in the number of warm nights is larger with time and greenhouse forcing (i.e. larger increases under higher RCPs and at the end of the century). Table 3-2 shows projected changes in warm nights for Wellington and Masterton. A doubling in the number of warm nights is projected for Wellington by 2090 under RCP8.5, and a tripling is projected for Masterton. This notable change over the coming several decades, even under moderate concentration scenarios, represents a climatic shift in terms of temperature experienced at these two locations.

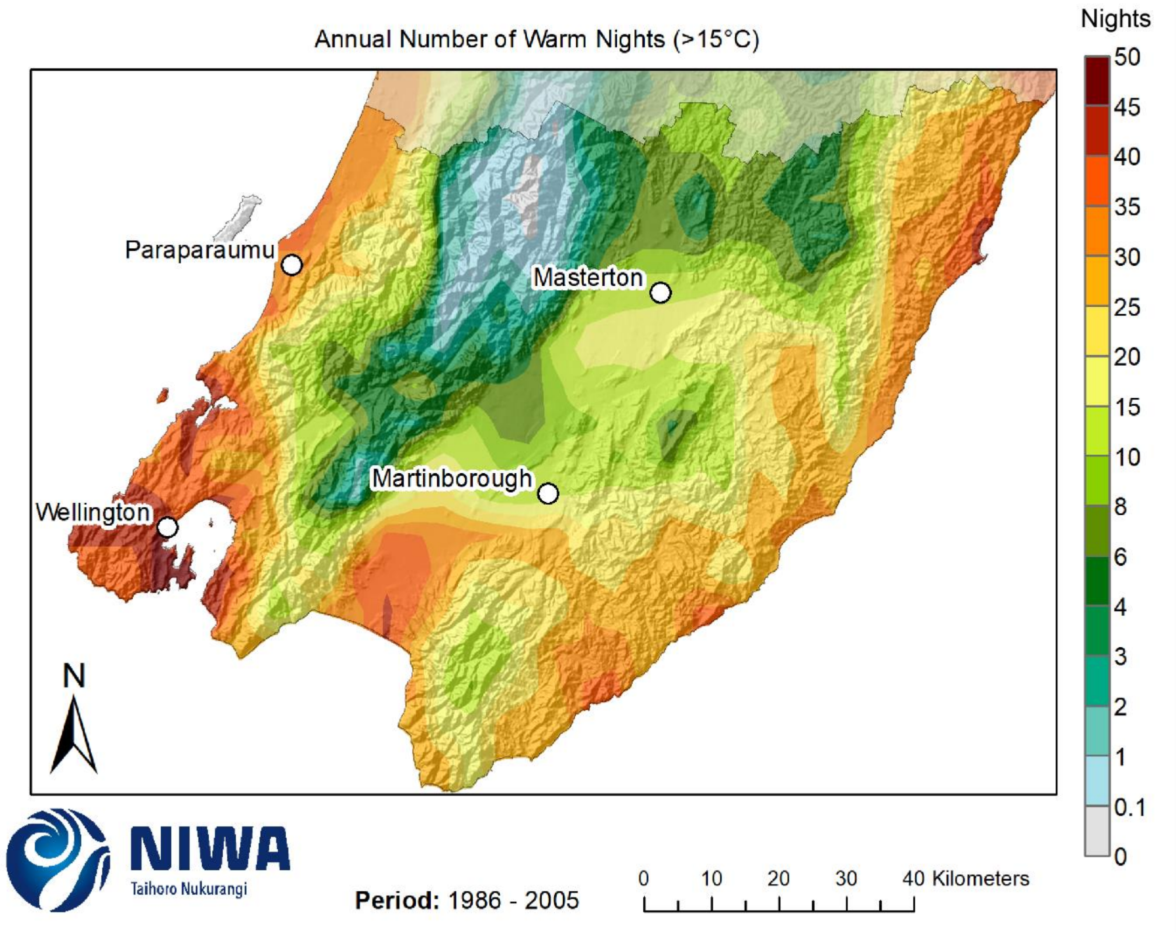


Figure 3-1: Modelled annual number of warm nights (minimum temperature > 15°C), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

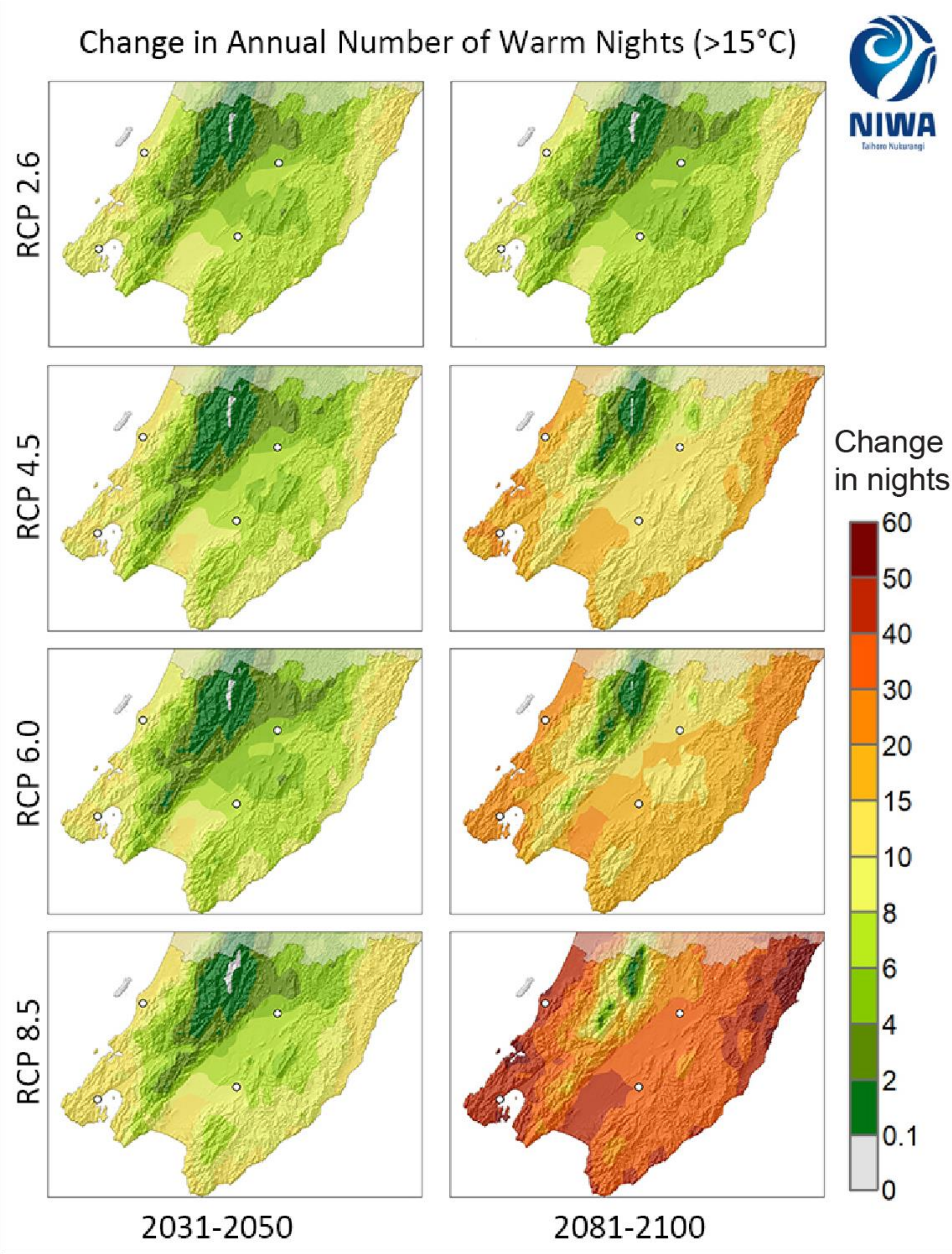


Figure 3-2: Projected annual warm night changes (minimum temperature > 15°C) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 3-2: Modelled annual warm nights (minimum temperature > 15°C) at Wellington and Masterton for the historic period and future changes for four climate change scenarios (RCP2.6, 4.5, 6.0 and 8.5) at two future time periods. Time periods: historic: 1986-2005, mid-century: 2031-2050 "2040", end-century: 2081-2100 "2090"; based on the average of six global climate models.

		Wellington	**Masterton**
Historic		46	16
2040	RCP2.6	56 (+10)	22 (+6)
	RCP4.5	57 (+11)	22 (+6)
	RCP6.0	57 (+11)	22 (+6)
	RCP8.5	59 (+13)	23 (+7)
2090	RCP2.6	55 (+9)	22 (+6)
	RCP4.5	67 (+21)	29 (+13)
	RCP6.0	70 (+24)	31 (+15)
	RCP8.5	96 (+50)	52 (+36)

3.2 Cold nights (minimum temperature < 5°C)

The highest elevations of the Tararua Ranges experience the largest number of cold nights in the historic period, which is about 160 cold nights per year on average (Figure 3-3). The northeast coast of the region experiences the lowest number of cold nights (<50 per year).

In the future, the number of cold nights is projected to decrease throughout the region (Figure 3-4), with the largest reductions in the high elevations of the Tararua Ranges (at least 60 fewer cold nights by 2090 under RCP8.5). The reduction in the number of cold nights is larger with time and greenhouse forcing (i.e. larger decreases under higher RCPs and at the end of the century). Many locations are projected to experience about half the number of cold nights by 2090 under RCP8.5 as they experience in the historic period. Table 3-3 shows projected changes in cold nights for Wellington and Masterton. This notable change over the coming several decades, even under moderate concentration scenarios, represents a climatic shift in terms of temperature experienced at these two locations.

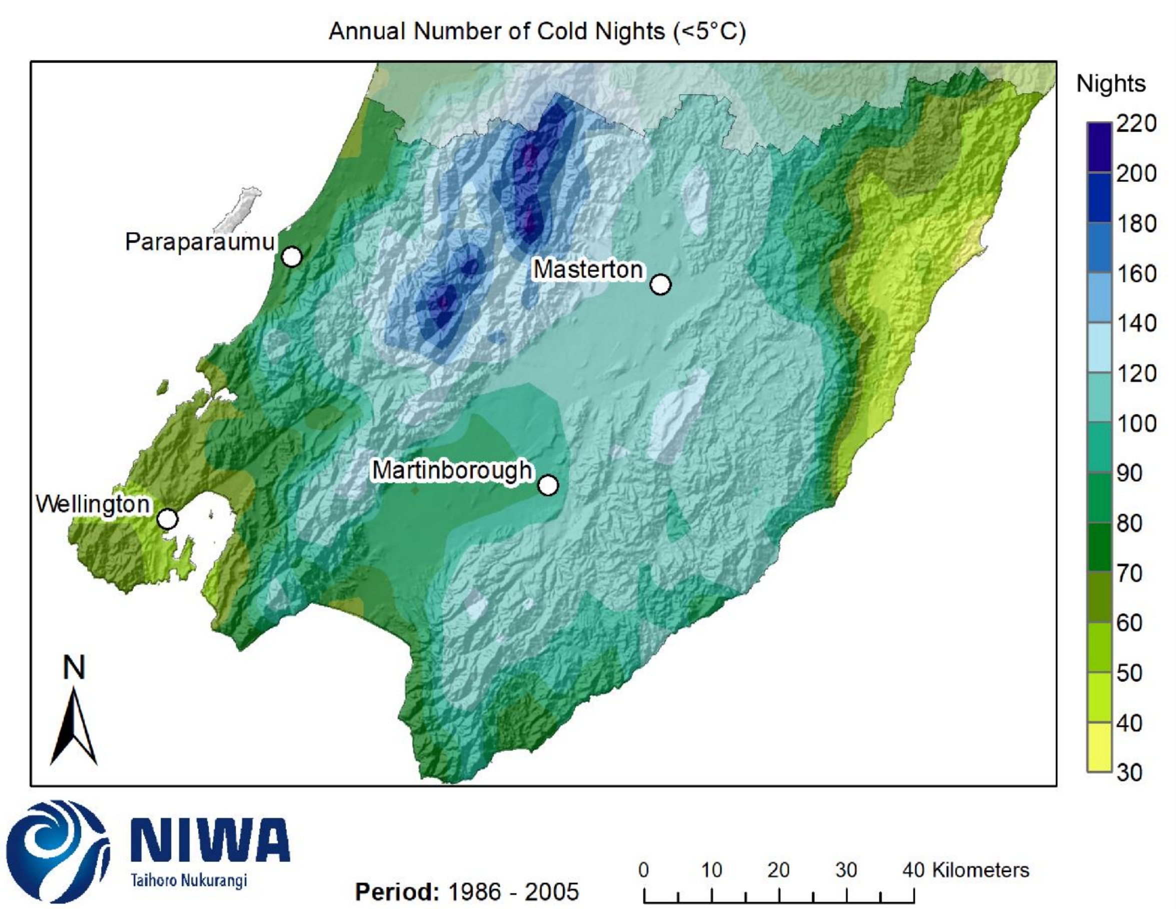


Figure 3-3: Modelled annual number of cold nights (minimum temperature < 5°C), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

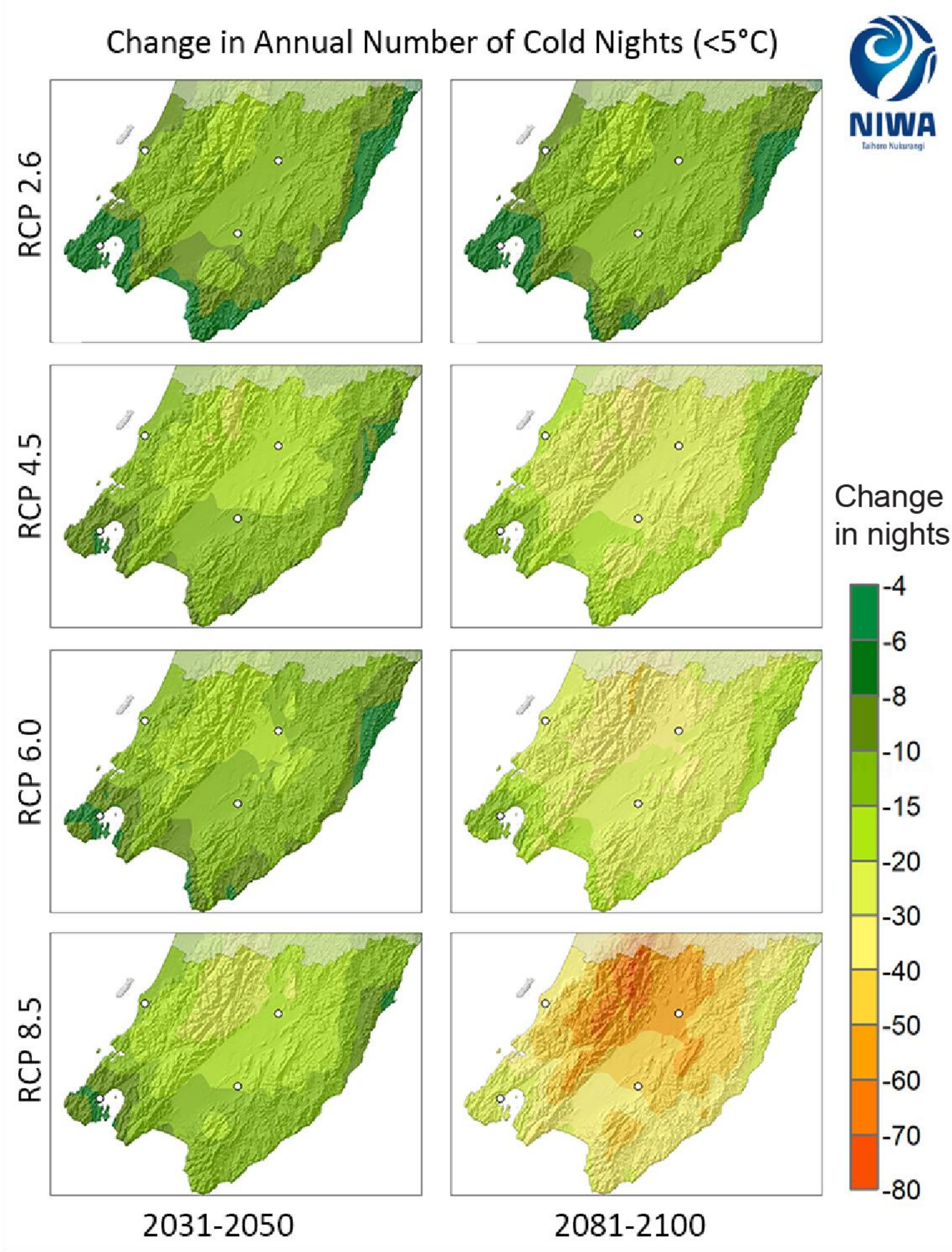


Figure 3-4: Projected annual cold night changes (minimum temperature < 5°C) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 3-3: Modelled annual cold nights (minimum temperature < 5°C) at Wellington and Masterton for the historic period and future changes for four climate change scenarios (RCP2.6, 4.5, 6.0 and 8.5) at two future time periods. Time periods: historic: 1986-2005, mid-century: 2031-2050 "2040", end-century: 2081-2100 "2090"; based on the average of six global climate models.

		Wellington	**Masterton**
Historic		55	115
2040	RCP2.6	49 (-6)	102 (-13)
	RCP4.5	47 (-8)	99 (-16)
	RCP6.0	48 (-7)	100 (-15)
	RCP8.5	48 (-7)	97 (-18)
2090	RCP2.6	49 (-6)	103 (-12)
	RCP4.5	44 (-11)	91 (-24)
	RCP6.0	42 (-13)	85 (-30)
	RCP8.5	31 (-24)	65 (-50)

3.3 Cold days (maximum temperature < 10°C)

The highest elevations of the Tararua Ranges experience the largest number of cold days in the historic period, which is at least 90 cold days per year (Figure 3-5). The Wairarapa Plains and the coastal area north of Paraparaumu experience the lowest number of cold days (<15 per year).

In the future, the number of cold days is projected to decrease throughout the region (Figure 3-6), with the largest reductions in the high elevations of the Tararua Ranges (at least 50 fewer cold days by 2090 under RCP8.5). The number of cold days reduces in frequency with time and greenhouse forcing (i.e. stronger reductions under higher RCPs and at the end of the century). Many locations are projected to experience almost no cold days by 2090 under RCP8.5. Table 3-4 shows projected changes in cold days for Wellington and Masterton. This notable change over the coming several decades, even under moderate concentration scenarios, represents a climatic shift in terms of temperature experienced at these two locations.

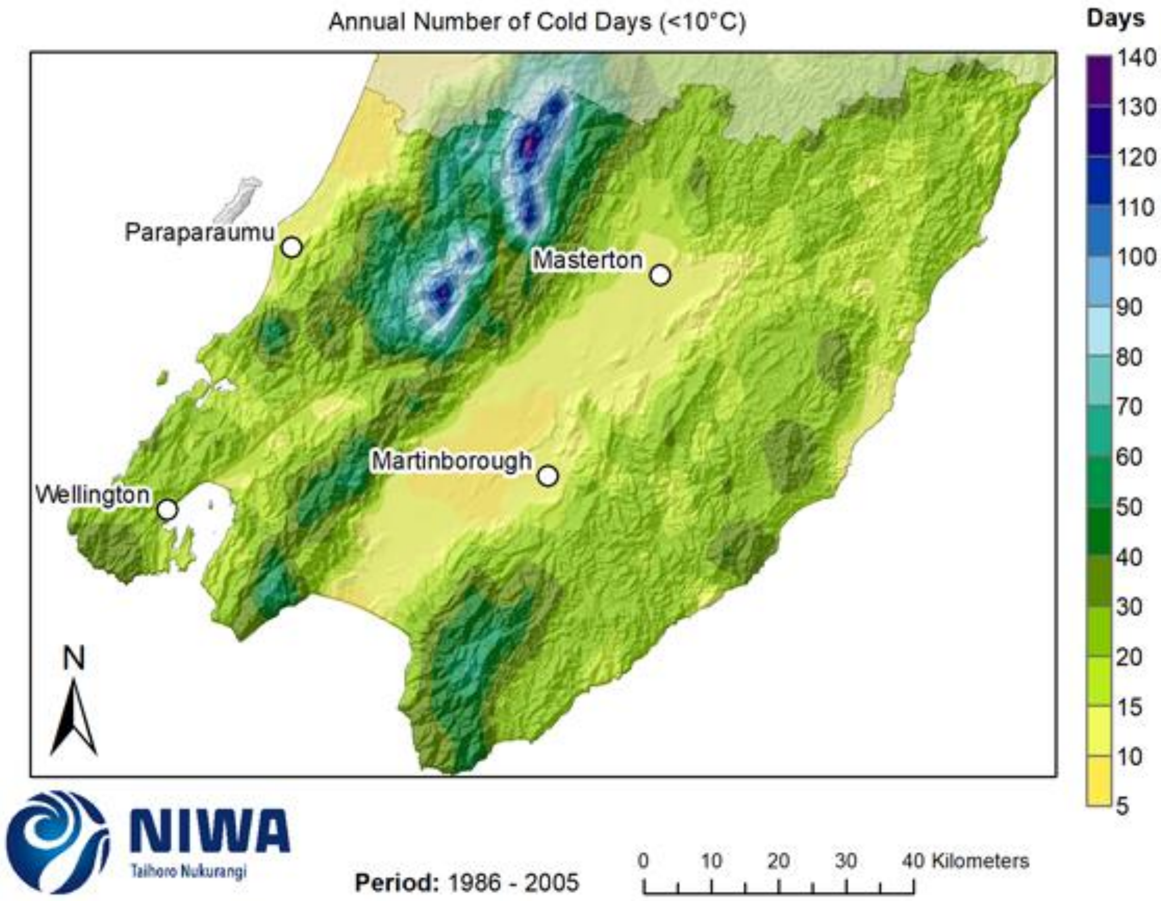


Figure 3-5: Modelled annual number of cold days (maximum temperature < 10°C), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

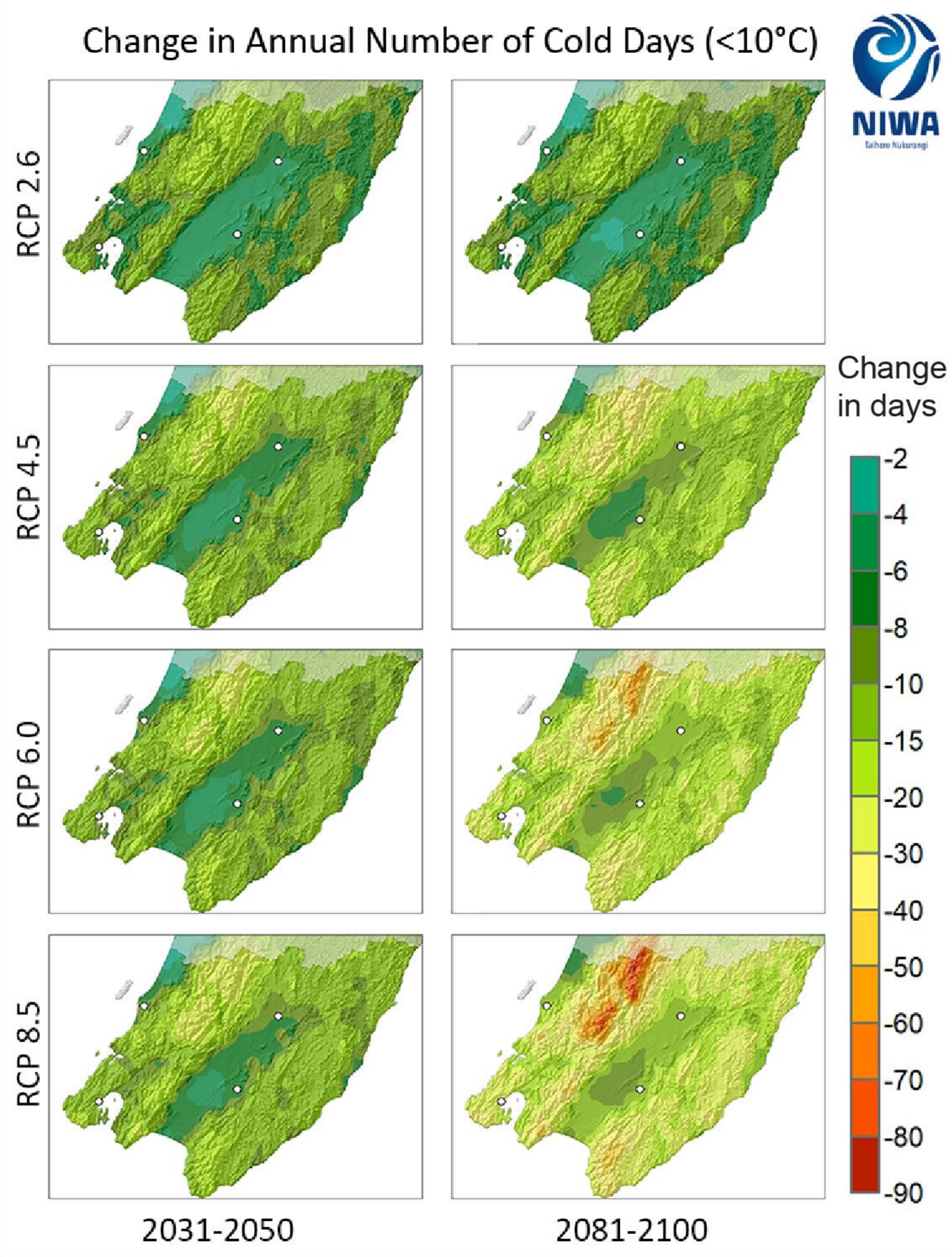


Figure 3-6: Projected annual cold day changes (max temperature < 10°C) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 3-4: Modelled annual cold days (maximum temperature < 10°C) at Wellington and Masterton for the historic period and future changes for four climate change scenarios (RCP2.6, 4.5, 6.0 and 8.5) at two future time periods. Time periods: historic: 1986-2005, mid-century: 2031-2050 "2040", end-century: 2081-2100 "2090"; based on the average of six global climate models.

		Wellington	**Masterton**
Historic		20	13
2040	RCP2.6	12 (-8)	7 (-6)
	RCP4.5	11 (-9)	6 (-7)
	RCP6.0	10 (-10)	6 (-7)
	RCP8.5	9 (-11)	6 (-7)
2090	RCP2.6	12 (-8)	8 (-5)
	RCP4.5	6 (-14)	4 (-9)
	RCP6.0	3 (-17)	3 (-10)
	RCP8.5	0 (-20)	1 (-12)

3.4 Hot days (maximum temperature > 25°C)

In the historic period, the largest number of annual hot days is experienced in the Wairarapa, particularly the area between Masterton and Martinborough as well as the hill country to the east and southeast of Martinborough (Figure 3-7), where 30-35 hot days per year are experienced. The remainder of the Wairarapa generally experiences 15-30 hot days per year. In contrast, the western part of the region experiences far fewer hot days, with Wellington and Paraparaumu experiencing an average of 6-8 hot days per year. The high elevations of the Tararua and Remutaka Ranges experience less than two hot days per year.

In the future (Figure 3-8), the number of hot days is projected to increase throughout the Wellington Region, with larger increases with time and greenhouse forcing (i.e. larger increases under higher RCPs and at the end of the century). Under RCP2.6 at both 2040 and 2090, 10-15 more hot days per year are projected for the Wairarapa and 2-4 more hot days per year are projected for much of the western Wellington Region. Under RCP8.5, changes are more marked, with increases of 15-20 hot days per year for the Wairarapa at 2040 and increases of 60-70 hot days per year at 2090. For Wellington, 6-8 more hot days per year are projected by 2040 and 25-30 more days by 2090. Table 3-5 shows projected changes in hot days for Wellington and Masterton. This notable change over the coming several decades, even under moderate concentration scenarios, represents a climatic shift in terms of temperature experienced at these two locations.

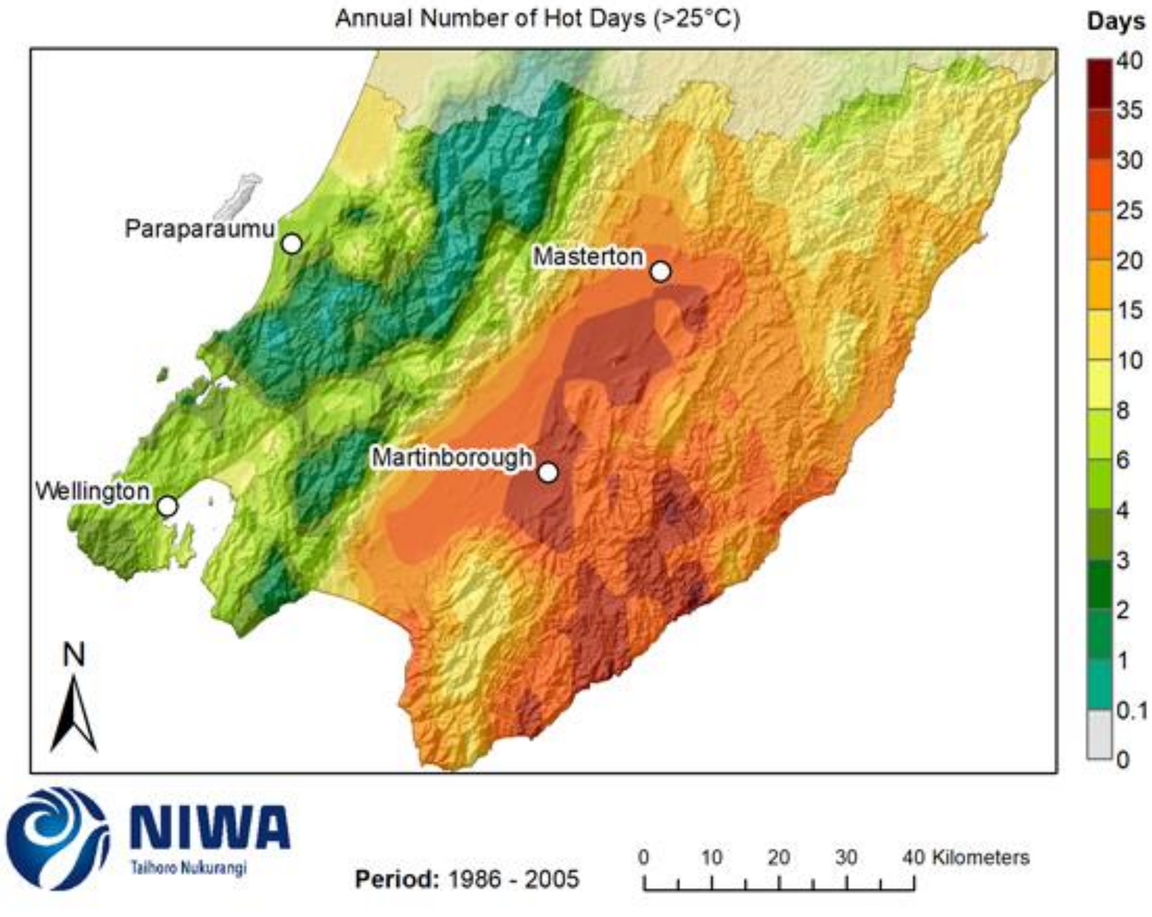


Figure 3-7: Modelled annual number of hot days (maximum temperature > 25°C), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

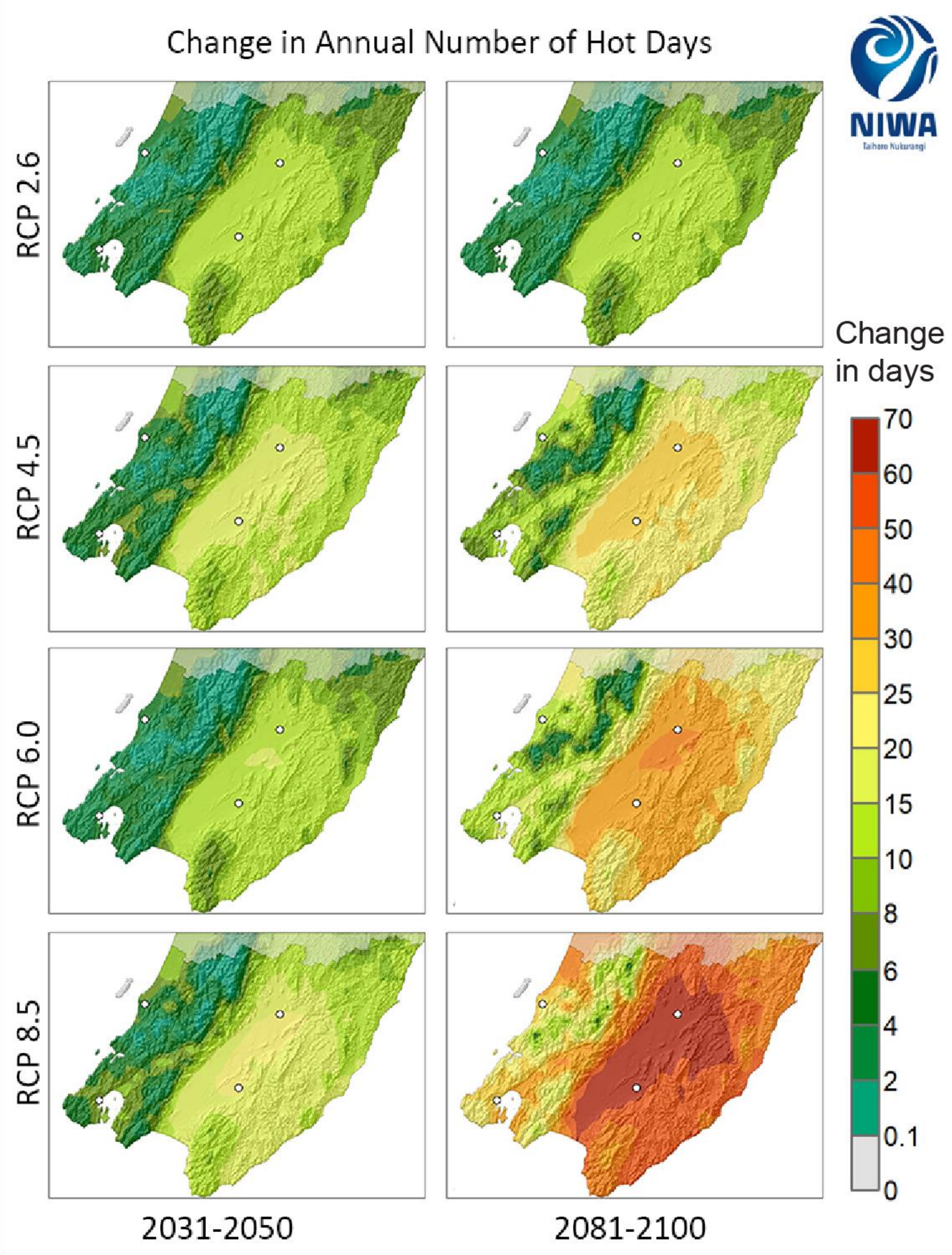


Figure 3-8: Projected annual hot day changes (max temperature > 25°C) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 3-5: Modelled annual hot days (maximum temperature > 25°C) at Wellington and Masterton for the historic period and future changes for four climate change scenarios (RCP2.6, 4.5, 6.0 and 8.5) at two future time periods. Time periods: historic: 1986-2005, mid-century: 2031-2050 "2040", end-century: 2081-2100 "2090"; based on the average of six global climate models.

		Wellington	**Masterton**
Historic		6	31
2040	RCP2.6	11 (+5)	45 (+14)
	RCP4.5	12 (+6)	50 (+19)
	RCP6.0	10 (+4)	46 (+15)
	RCP8.5	13 (+7)	52 (+21)
2090	RCP2.6	11 (+5)	45 (+14)
	RCP4.5	16 (+10)	61 (+30)
	RCP6.0	20 (+14)	72 (+41)
	RCP8.5	35 (+29)	101 (+70)

3.5 Extreme hot days (maximum temperature > 30°C)

In the historic period, extreme hot days mainly occur in the Wairarapa (Figure 3-9), with a maximum of 2-3 days per year in the eastern hill country and 1-2 days per year on the plains between Masterton and Martinborough. Less than one extreme hot day per year is experienced in the area surrounding Wellington Harbour.

In the future (Figure 3-10), the number of extreme hot days per year is projected to increase, particularly for the Wairarapa. Up to four more extreme hot days per year are projected for the Wairarapa at 2040 under all four concentration scenarios, with less than two more extreme hot days per year projected for the area around Wellington Harbour at the same time period. However, by 2090, 15-20 more extreme hot days are projected for much of the Wairarapa under RCP8.5 and 2-4 more hot days per year for the area around Wellington Harbour. The lower concentration scenarios show smaller increases (with RCP2.6 expecting the same increase at 2090 as at 2040; up to two more extreme hot days per year for the Wairarapa). Table 3-6 shows projected changes in extreme hot days for Wellington and Masterton. This notable change by 2090 under RCP8.5 represents a climatic shift in terms of temperature experienced at these two locations.

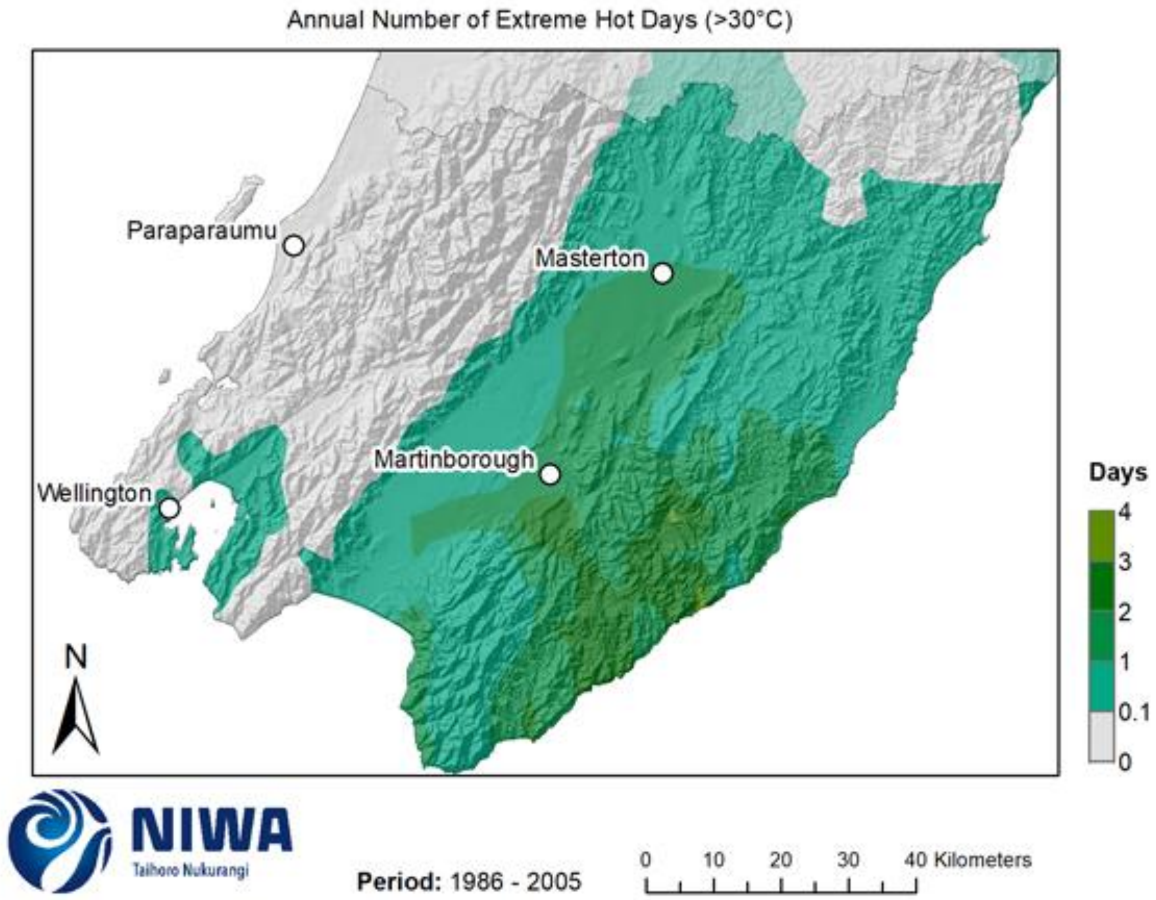


Figure 3-9: Modelled annual number of extreme hot days (maximum temperature > 30°C), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

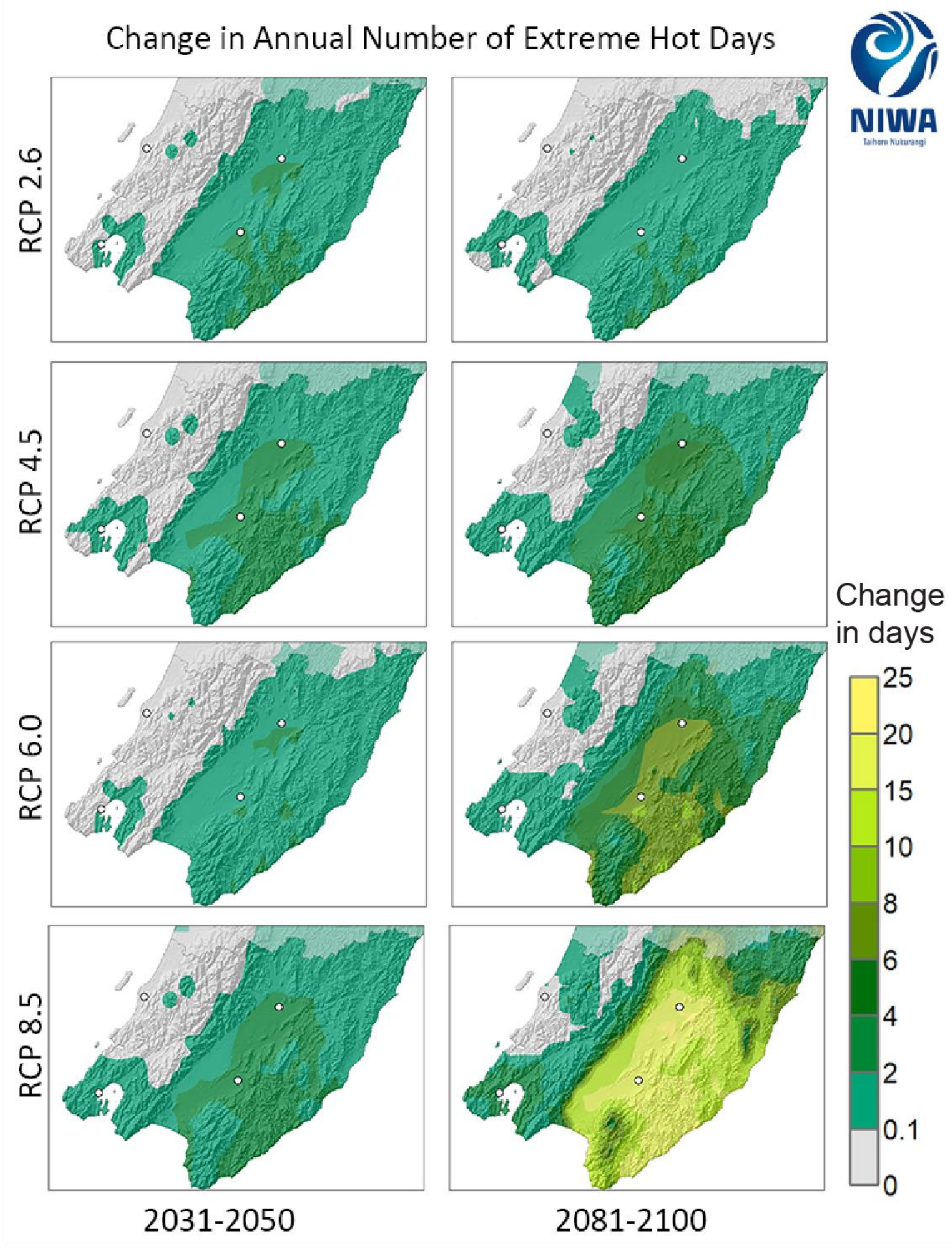


Figure 3-10: Projected annual extreme hot day changes (max temperature > 30°C) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 3-6: Modelled annual extreme hot days (maximum temperature > 30°C) at Wellington and Masterton for the historic period and future changes for four climate change scenarios (RCP2.6, 4.5, 6.0 and 8.5) at two future time periods. Time periods: historic: 1986-2005, mid-century: 2031-2050 "2040", end-century: 2081-2100 "2090"; based on the average of six global climate models.

		Wellington	Masterton
Historic		0	1.5
2040	RCP2.6	0	3.5 (+2)
	RCP4.5	0	4.5 (+3)
	RCP6.0	0	3.5 (+2)
	RCP8.5	0	4.5 (+3)
2090	RCP2.6	0	3 (+1.5)
	RCP4.5	1 (+1)	6.5 (+5)
	RCP6.0	1 (+1)	9.5 (+8)
	RCP8.5	3 (+3)	21.5 (+20)

3.6 Heatwave days and extreme heatwave days

For the purposes of this report, a heatwave is defined as a period of three or more consecutive days where the maximum daily temperature (T_{max}) exceeds a given threshold, either 25°C or 30°C. For the maps in this section, the heatwave climatology and projections are presented as average annual heatwave days (with a T_{max} threshold of 25°C) and extreme heatwave days (with a T_{max} threshold of 30°C). Heatwave days are calculated by aggregating all days per year that are included in a heatwave (e.g., ≥ three consecutive days with T_{max} > 25°C), no matter the length of the heatwave. Thus, a 3-day heatwave contributes 3 days, a 5-day heatwave contributes 5 days, etc. The annual total numbers of heatwave-days are then averaged over the 20-year period of interest (e.g., 2031-2050), and the six global models, to get the ensemble-average annual heatwave-day climatology (past) and future projections. The historic maps show annual average numbers of heatwave days and the future projection maps show the change in the number of heatwave days compared with the historic period.

3.6.1 Heatwave days (≥ 3 consecutive days with maximum temperature > 25°C)

In the historic period, the highest number of annual heatwave days occurs in the Wairarapa, in the area broadly between Masterton and Martinborough (Figure 3-11). Between 15 and 20 heatwave days per year occur in this area in the historic period. Ten to 15 heatwave days per year occur for most of the rest of the Wairarapa. On the western side of the Remutaka Ranges, far fewer heatwave days are observed – less than one three-day heatwave per year is recorded in this part of the region (i.e. one to two heatwave days on average per year (averaged over 20 years), where three is required to be defined as a heatwave).

In the future, the number of heatwave days is projected to increase across the Wellington Region (Figure 3-12), and changes are amplified with time and greenhouse forcing (i.e. higher RCPs exhibit larger increases than lower RCPs in general). Under RCP2.6 at both 2040 and 2090, 10-15 more heatwave days per year are projected for the Wairarapa, whereas under RCP8.5 at 2040 15-20 more heatwave days are projected for the Wairarapa, and at 2090 a large increase of 60-70 more heatwave days are projected. For the western part of the region, the number of heatwave days slightly increases by about two per year under most RCPs and time periods, except for RCP8.5 which sees larger increases in low-lying areas of 10-20 heatwave days per year by 2090. Table 3-7 shows the projected numbers of heatwave days and extreme heatwave days for Wellington and Masterton grid points. This notable change over the coming several decades, even under moderate concentration scenarios, represents a climatic shift in terms of temperature experienced at these two locations.

There are slightly more heatwave days projected for RCP4.5 than RCP6.0 by 2040, which may seem counterintuitive as RCP6.0 has higher CO_2-equivalent concentrations than RCP4.5 by 2100. However, the concentrations of CO_2-equivalent around 2040 are actually lower for RCP6.0 than RCP4.5, so RCP4.5 has a higher greenhouse forcing at that time, resulting in higher numbers of projected heatwave days.

The projections for heatwave days (Figure 3-12) are similar to the projections for hot days (Figure 3-8), particularly for the Wairarapa and for the more extreme scenarios at the end of the century. This implies that most of the increase in hot days is being translated into heatwave days – i.e. most additional days >25°C are going to form in a sequence of least three consecutive days in the future, making heatwaves more frequent.

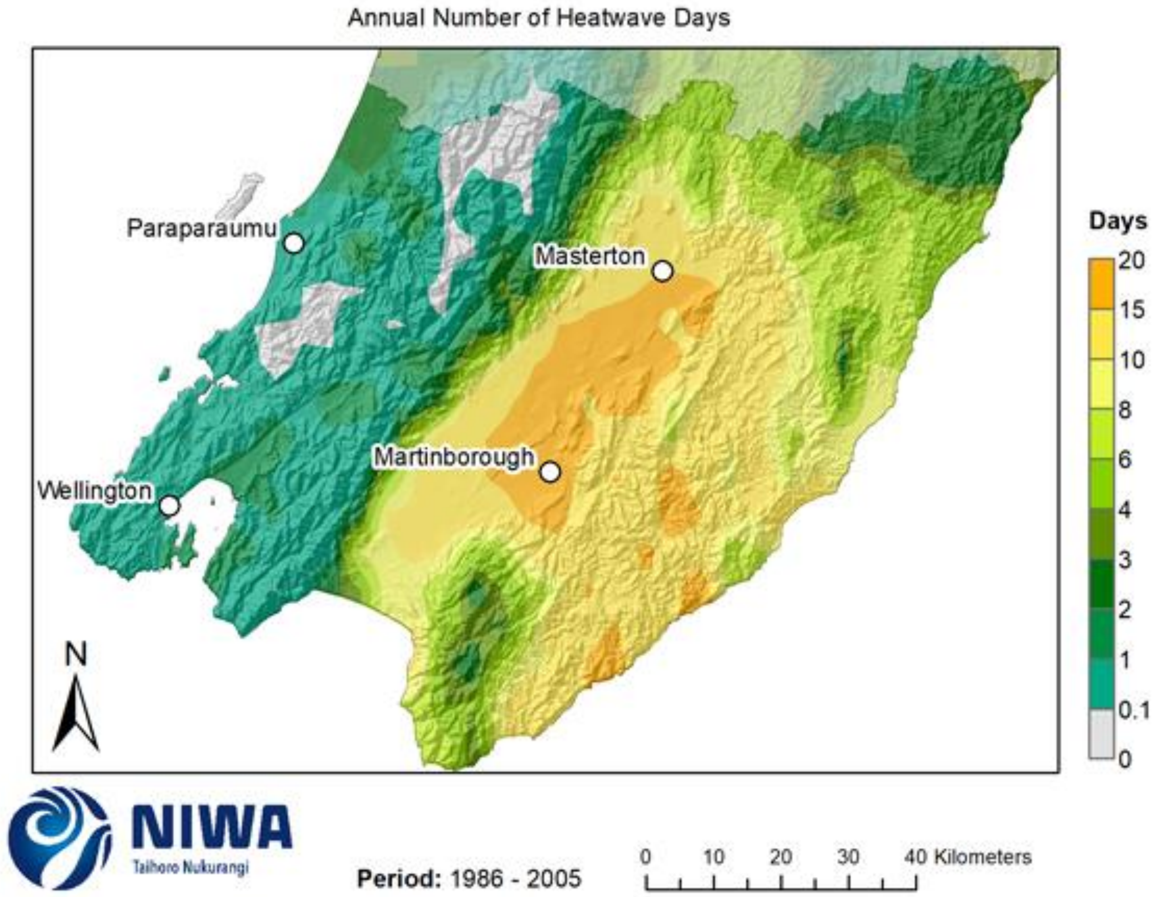


Figure 3-11: Modelled annual number of heatwave days (≥ three consecutive days with maximum temperatures > 25°C), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

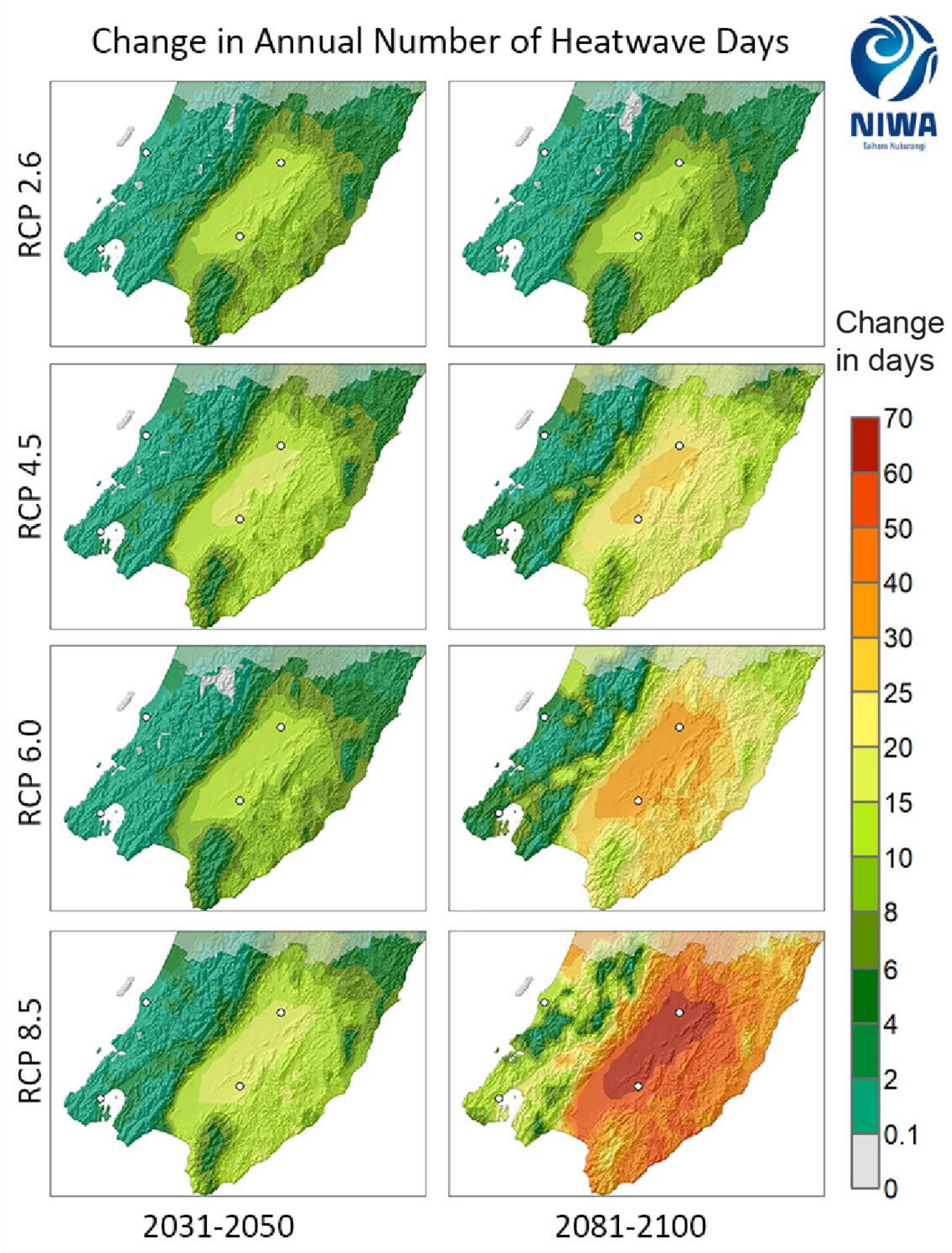


Figure 3-12: Projected annual heatwave day changes (≥ three consecutive days with maximum temperatures > 25°C) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

3.6.2 Extreme heatwave days (maximum temperature > 30°C)

In the historic period, there are few extreme heatwave days modelled for the Wellington Region – less than one extreme heatwave day per year for the Wairarapa, averaged over the 20-year period 1986-2005 (Figure 3-13). No extreme heatwave days occur for the rest of the Wellington Region.

In the future, the number of extreme heatwave days is projected to increase for the Wairarapa (Figure 3-14), and changes are amplified with time and greenhouse forcing (i.e. higher RCPs exhibit larger increases than lower RCPs). Under RCP2.6 and RCP4.5 at both 2040 and 2090, and RCP6.0 and RCP8.5 at 2040, up to two more extreme heatwave days per year are projected for the Wairarapa. However, the most significant change is projected for RCP8.5 at 2090 when 10-15 more extreme heatwave days are projected for an area south of Masterton, and 6-10 more extreme heatwave days are projected for most of the Wairarapa. It is only at 2090 under RCP8.5 that small increases (up to two extreme heatwave days per year) are projected for the western part of the region. Table 3-7 shows the projected numbers of heatwave days and extreme heatwave days for Wellington and Masterton grid points. This notable change over the coming several decades in the number of extreme heatwave days for Masterton represents a climatic shift in terms of extreme temperature experienced at this location.

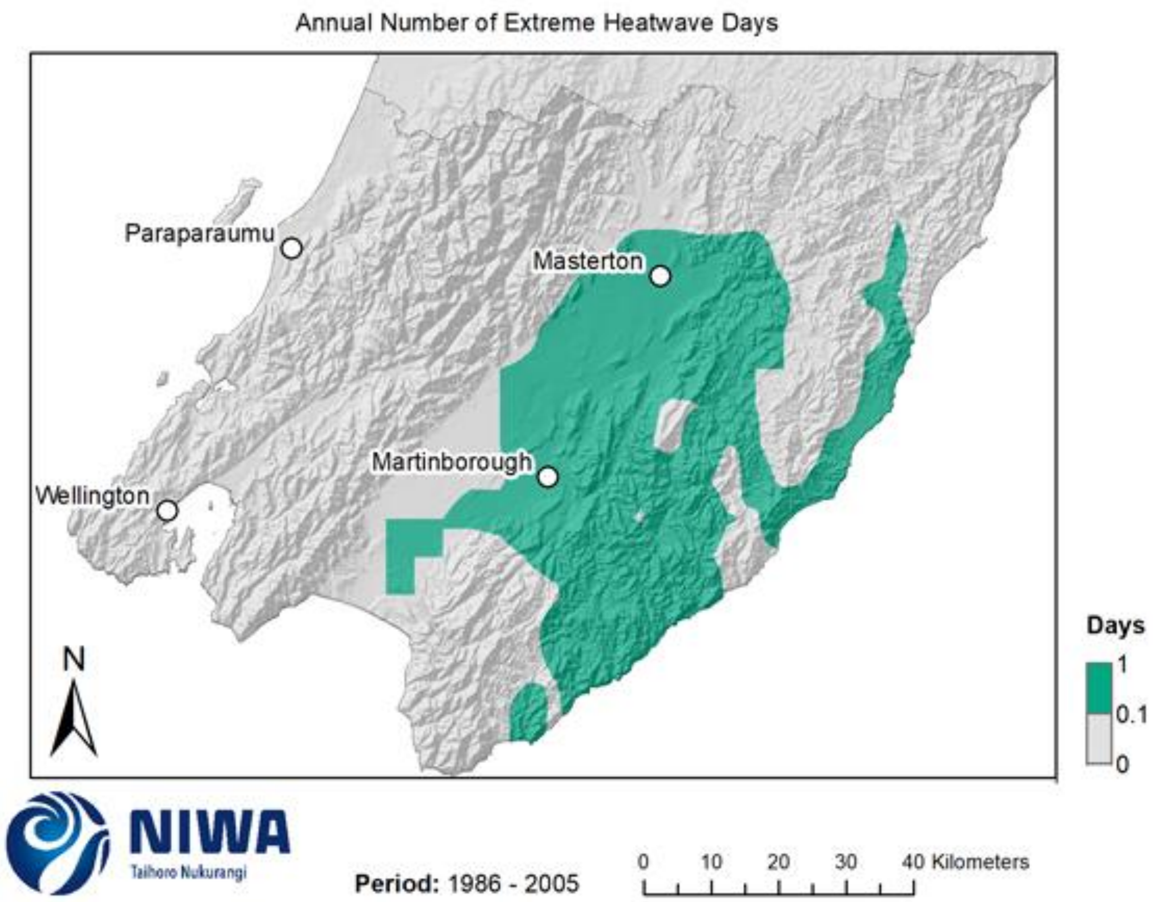


Figure 3-13: Modelled annual number of extreme heatwave days (≥ three consecutive days with maximum temperatures > 30°C), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

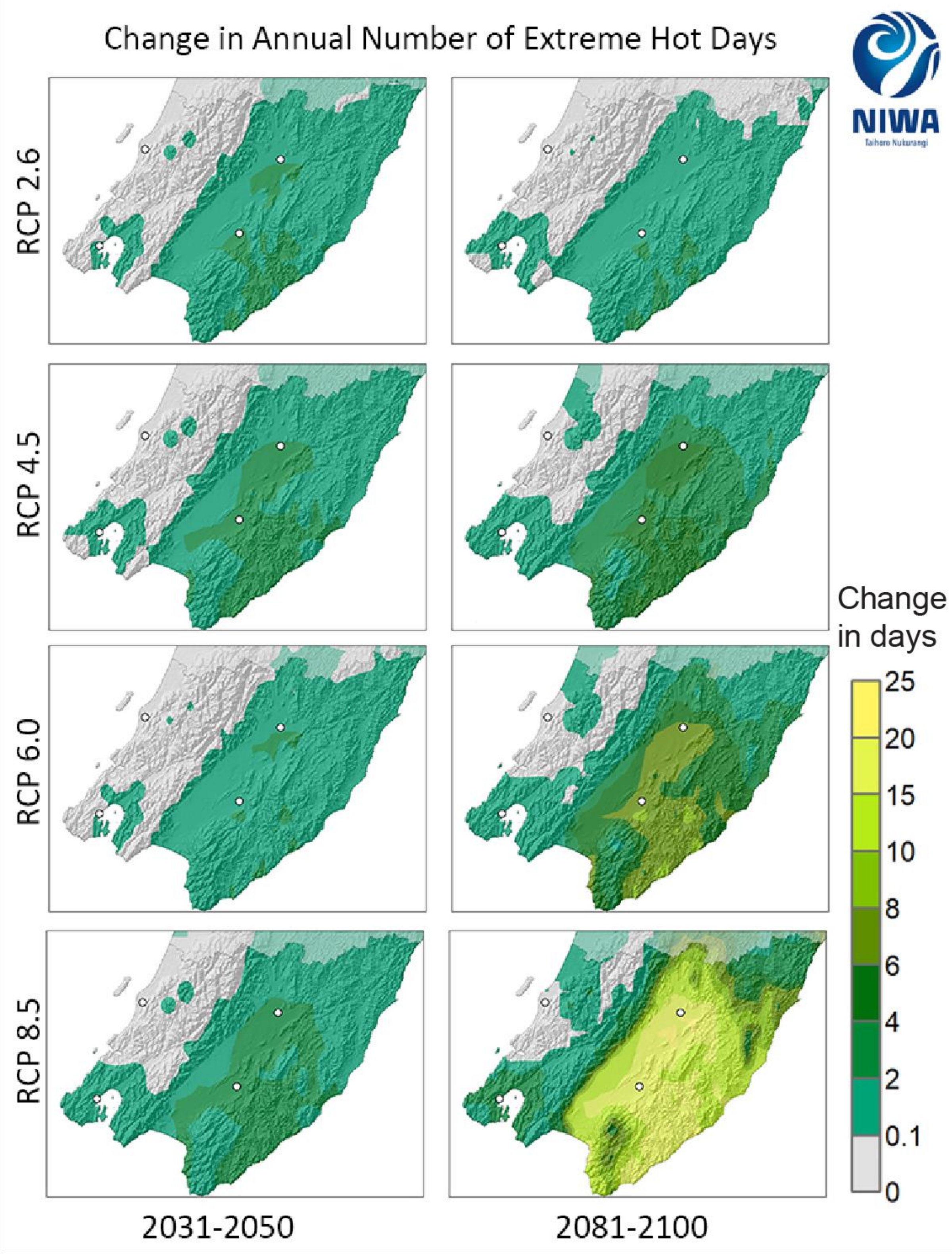


Figure 3-14: Projected annual extreme heatwave day changes (≥ three consecutive days with maximum temperatures > 30°C) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 3-7: Modelled annual heatwave days (≥ three consecutive days with maximum temperatures > 25°C) and extreme heatwave days (≥ three consecutive days with maximum temperatures > 30°C) at Wellington and Masterton for the historic period and future changes for four climate change scenarios (RCP2.6, 4.5, 6.0 and 8.5) at two future time periods. Time periods: historic: 1986-2005, mid-century: 2031-2050 "2040", end-century: 2081-2100 "2090"; based on the average of six global climate models.

		Heatwave days (>25°C)		Extreme heatwave days (>30°C)	
		Wellington	Masterton	Wellington	Masterton
Historic		1	16	0	0
2040	RCP2.6	3 (+2)	27 (+11)	0	1 (+1)
	RCP4.5	3 (+2)	32 (+16)	0	1 (+1)
	RCP6.0	2 (+1)	28 (+12)	0	1 (+1)
	RCP8.5	3 (+2)	33 (+17)	0	1 (+1)
2090	RCP2.6	2.5 (+1.5)	26 (+10)	0	0.5 (+0.5)
	RCP4.5	5 (+4)	42 (+26)	0	2 (+2)
	RCP6.0	7 (+6)	53 (+37)	0	3 (+3)
	RCP8.5	16 (+15)	83 (+67)	0	11 (+11)

3.6.3 Changing lengths of heatwaves

The heatwave day and extreme heatwave day maps (Figure 3-11 to Figure 3-14) show cumulative heatwave days, without regard to the length of each event. Figure 3-15 and Figure 3-16 show the length of heatwave-day projections at the VCSN grid-points representing Wellington (Kelburn) and Masterton, and demonstrate the full distribution for these episodes as a function of the duration of each hot spell. Figure 3-15 gives an example for the Masterton grid point at 2090 with the heatwave day threshold of 25°C. Figure 3-16 shows all the combinations for Wellington/Masterton, 2040/2090 and 25/30°C.

In Figure 3-15, heatwave days are shown for the Masterton historical climate ('Present', representing the 6-model average over 1986-2005), and the Masterton late-century climate (2090, representing the 6-model average over 2081-2100). In the historical period, Masterton experiences approximately 16 days per year, on average, of "heatwave" conditions, where at least three consecutive days of temperatures exceed 25°C. For heatwaves lasting 10 days or longer within in a 20-year period, Masterton could expect two such events in the historical climate. Not shown in Figure 3-15 are shorter periods which do not qualify as heatwaves under our three consecutive day criterion: in the historical climate, there are about eight individual days with temperatures >25°C per year, and a further eight days with two-day consecutive temperatures above 25°C.

Figure 3-16 shows that prolonged heatwave events become more frequent as the climate warms, with a marked jump under RCP8.5 relative to the other more modest emission scenarios. For example, under RCP8.5 at 2090, Masterton is projected to experience 82 heatwave days per year of at least three consecutive days duration, of which 37 days will be part of events lasting 10 consecutive days or more.

For a threshold of 30°C, Masterton could experience 11 extreme heatwave days per year of at least three consecutive days duration by 2090 under RCP8.5. Extreme heatwaves lasting 10 days could occur once every 10 years, on average.

For the Wellington grid point, heatwaves are much less common than at Masterton, and heatwaves above the 30°C threshold are almost non-existent, even by the end of the century under the highest emission scenario of RCP8.5. However, for the 25°C threshold, Wellington could expect 16 heatwave-days per year of at least 3 consecutive days duration by 2090 under RCP8.5. Heatwaves lasting 10 days could occur once every 10 years, on average.

For both locations, the projections indicate unprecedented heatwave behaviour compared to what is experienced at present. In particular, the projected length of heatwaves for both locations increases dramatically by 2090 under the higher-end scenarios of RCP6.0 and RCP8.5.

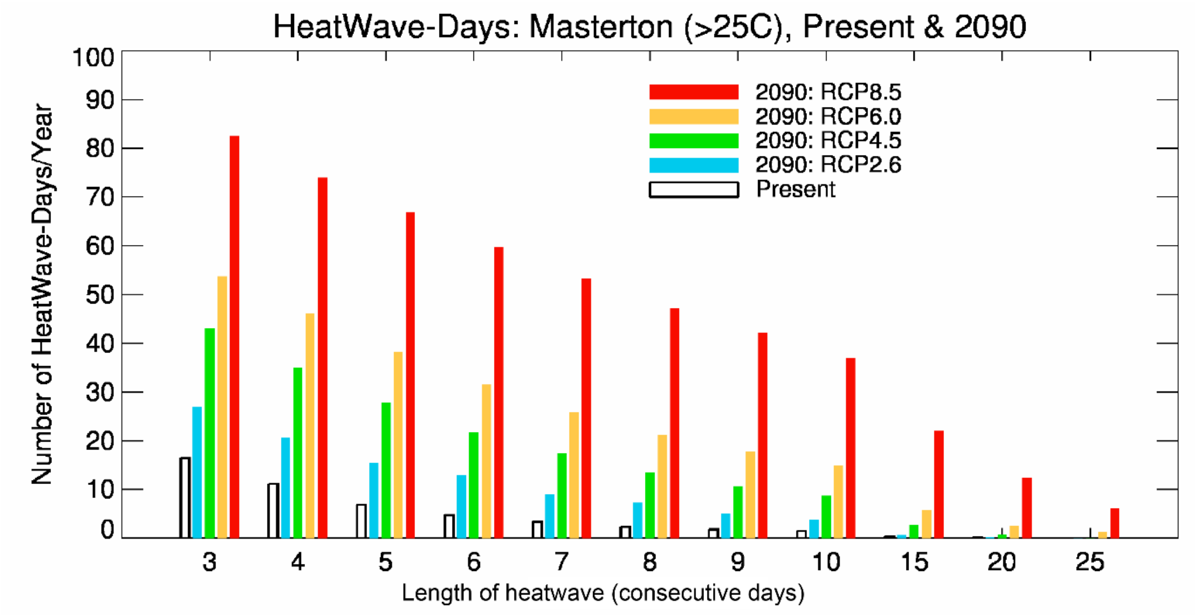


Figure 3-15: Average number of heatwave days per year (>25°C) for the Masterton VCSN grid-point, plotted as a function of the minimum length of the heatwave in consecutive days. Colour bars represent counts under the historical climate (white, far left bar) and for 2090 under RCP2.6 (blue), RCP4.5 (green), RCP6.0 (orange) and RCP8.5 (red). A length of “3” means 3 or more days, “4” means 4 or more days, etc. The histogram bars represent the number of heatwave days for all heatwaves lasting at least as many days as the “length” marked on the horizontal axis.

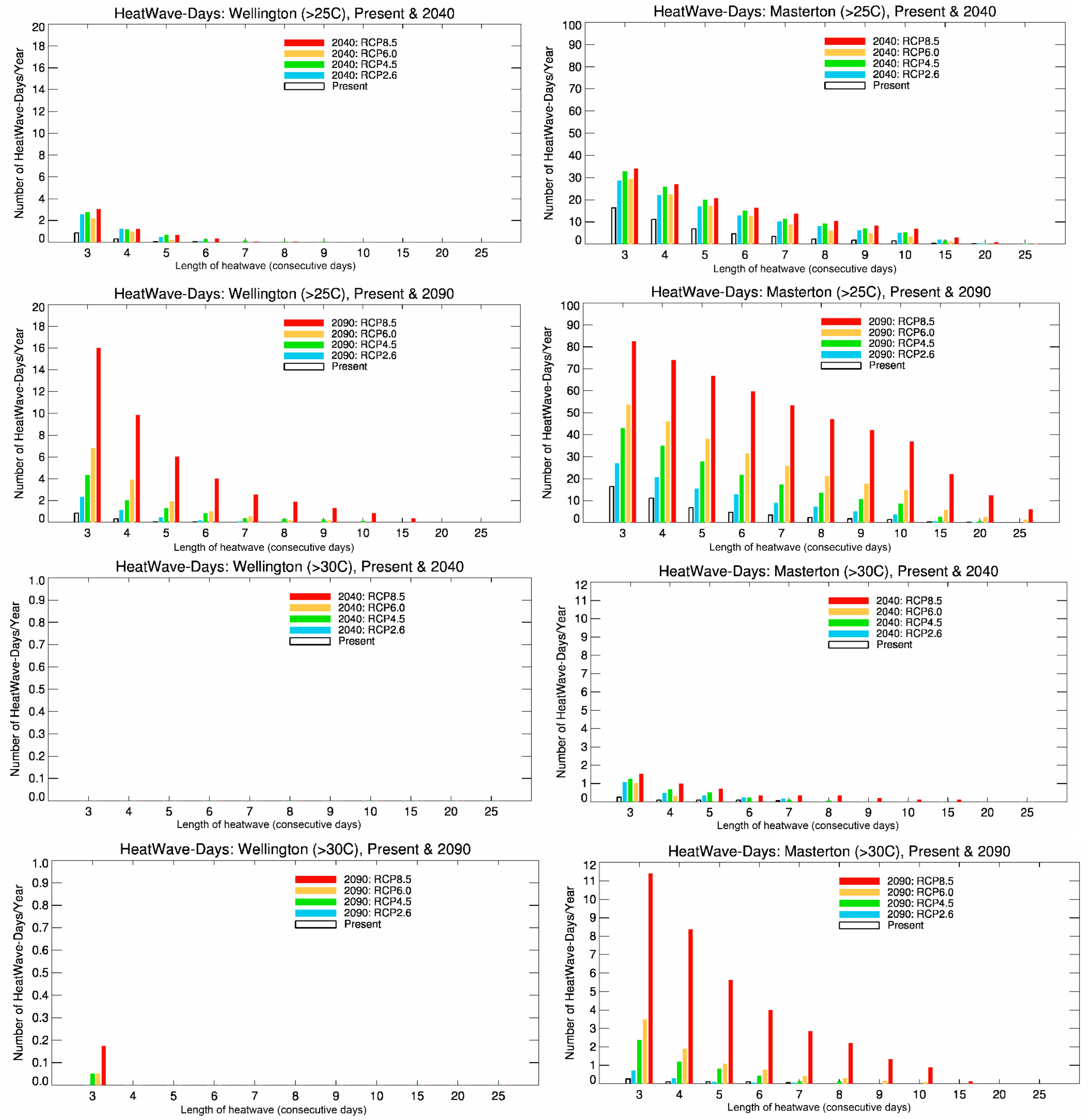


Figure 3-16: Average number of heatwave-days per year for >25°C and >30°C thresholds, for the Wellington (left) and Masterton (right) VCSN grid-points, plotted as a function of the minimum length of the heatwave in days. Colour bars represent counts under the historical climate (white, far left bar) and for either 2040 or 2090 under RCP2.6 (blue), RCP4.5 (green), RCP6.0 (orange) and RCP8.5 (red). A length of "3" means 3 or more days, "4" means 4 or more days, etc. The histogram bars represent the number of heatwave days for all heatwaves lasting at least as many days as the "length" marked on the horizontal axis. Note that the same vertical scale has been used for the 2040 and 2090 plots; otherwise the scale changes between Wellington and Masterton, and between 25°C and 30°C thresholds.

4 Historic and future rainfall extremes

Key messages

- A reduction in the number of rain days (>10, >20 and >30 mm) is projected for high elevations in the Wellington Region (Tararua, Remutaka and Aorangi Ranges).
- The reductions are larger with time and increased greenhouse forcing.
- Some small increases in rain days are projected for the west coast (>10mm), for pockets on both coasts and northern Wairarapa (>20mm) and for most of the Region outside the Tararuas (>30mm) for high greenhouse gas concentrations by the end of the century.
- The number of days over which wet spells occur is projected to decline across most of the region, particularly in the ranges and the Wairarapa. Small increases are projected for the Kapiti Coast.
- Conversely, the number of days over which dry spells occur is projected to increase across the region, particularly in the Wairarapa. Small decreases are projected for the Kapiti Coast and some northern areas.
- A clear trend towards longer dry spells and shorter wet spells is projected for both Wellington and Masterton.

Indices of rainfall extremes are considered in this section. These indices are the average number of days per year with rainfall totals above or below certain thresholds (Table 4-1). Averages are taken over 20-year periods: 1986-2005 for the historic period, 2031-2050 for the mid-century "2040" period, and 2081-2100 for the late-century "2090" period. Projections for each index are shown as maps for these three time periods, and for the future time periods projections for four IPCC Representative Concentration Pathways (Section 2.1) are given. In addition, projections for Wellington and Masterton are given for these same time periods and RCPs.

Table 4-1: Rainfall extreme indices and thresholds.

Rainfall extreme indices	Threshold
Rain days with > 10 mm	> 10 mm
Rain days with > 20 mm	> 20 mm
Rain days with > 30 mm	> 30 mm
Wet spells	> 3, > 5, and > 10 consecutive days with > 1mm of rain on each day
Dry spells	> 3, > 5, and > 10 consecutive days with < 1mm of rain on each day

4.1 Rain days with > 10 mm

In the historic period, the largest number of > 10 mm rain days occurs in the highest elevations of the Tararua Ranges (120-140 days per year), and the lowest number occurs around Martinborough (15-20 days per year) (Figure 4-1). Most of the region experiences 20-50 days with > 10 mm of rain per year.

In the future, the number of > 10 mm rain days is projected to increase for many areas by the middle of the century, but only by a small amount (0-2 days per year for most locations) (Figure 4-2). The highest elevations of the Tararua and Remutaka Ranges experience a decrease in rain days by mid-century of 1-4 days per year (all scenarios). By 2090, most areas are projected to experience a reduction in > 10 mm rain days by 0-2 days per year for most lowland areas and >5 days per year for high elevation locations, under the two higher emission scenarios (RCP6.0 and RCP8.5).

Table 4-2 shows projected changes in > 10 mm rain days for Wellington and Masterton. The magnitude of the projected changes is small compared to the historic numbers of rain days > 10 mm for the two locations.

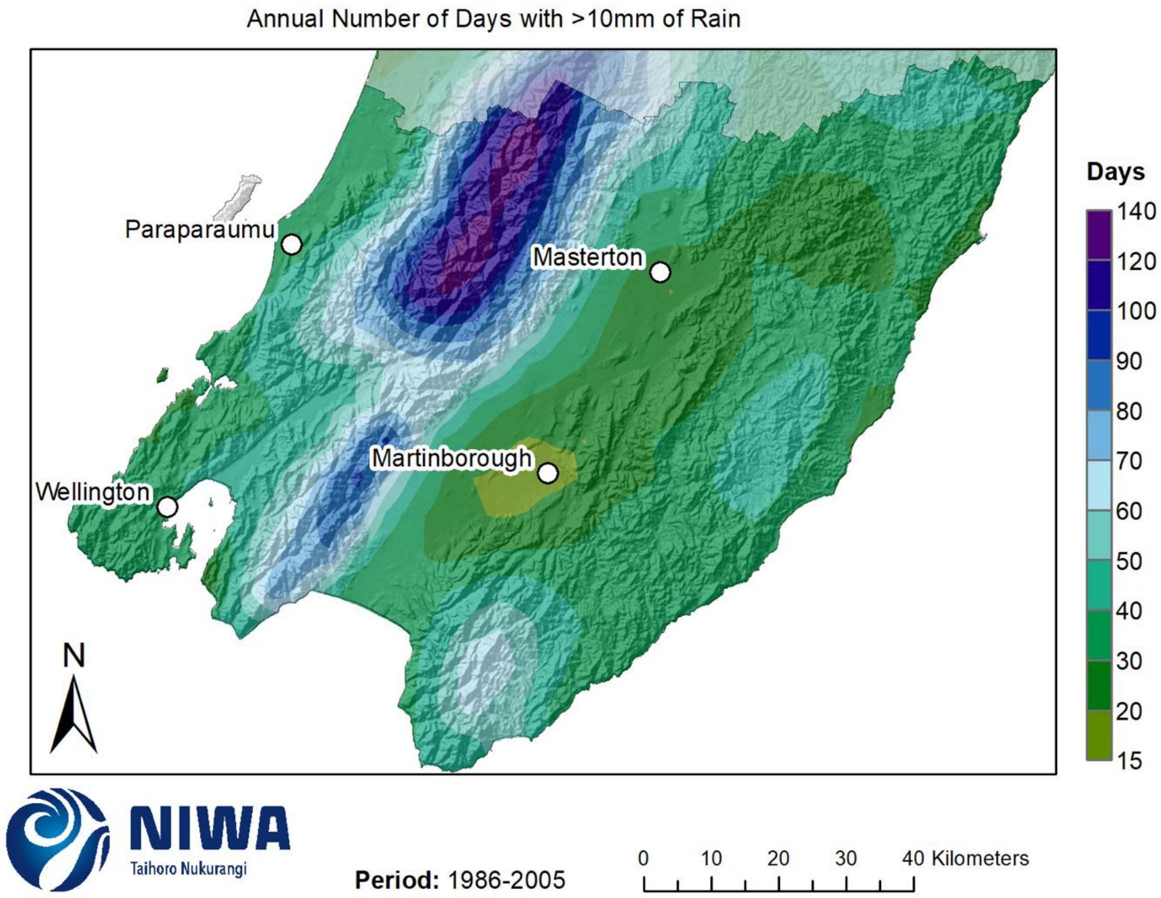


Figure 4-1: Modelled annual number of rain days with > 10 mm, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

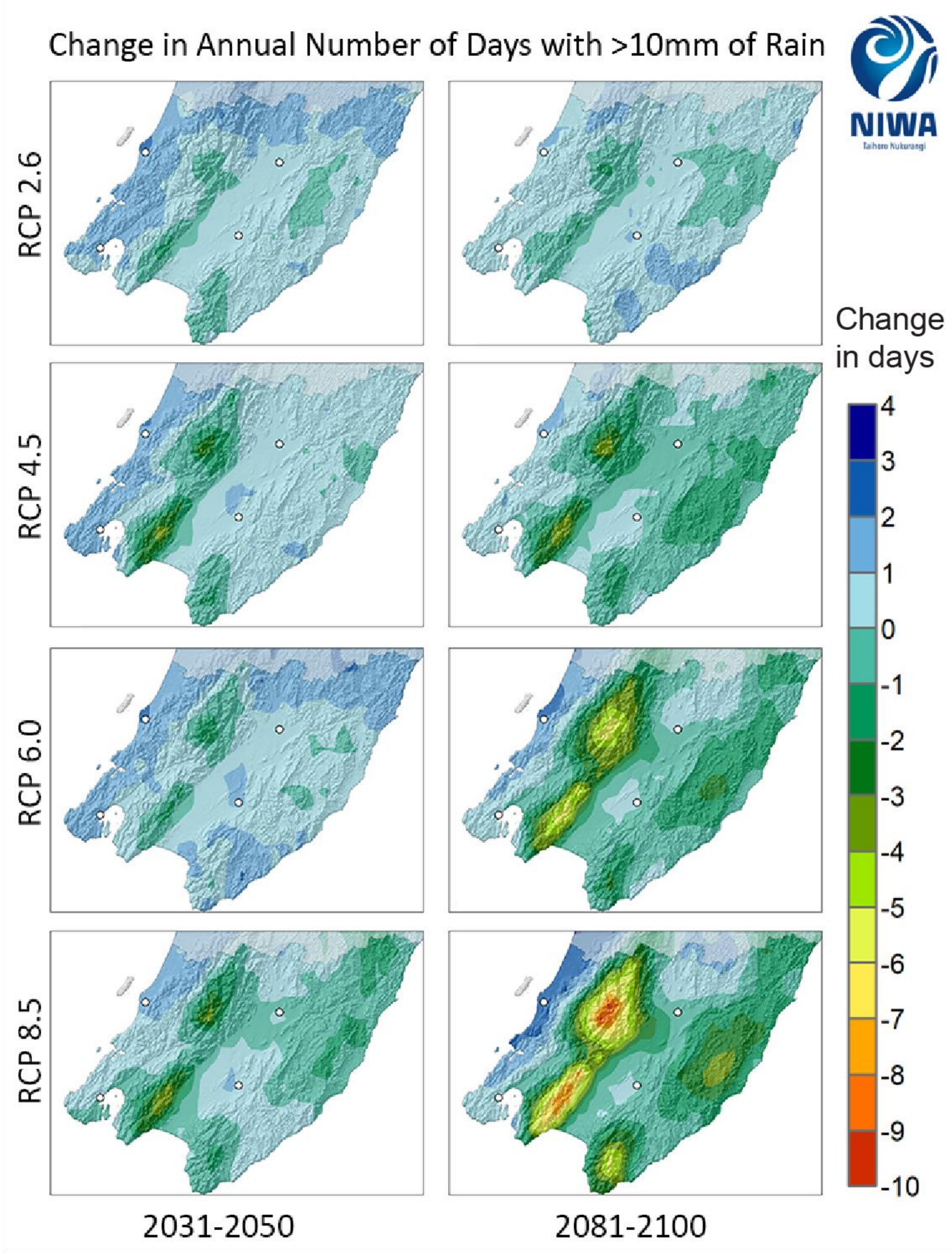


Figure 4-2: Projected annual rain day changes (> 10 mm) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 4-2: Modelled annual rain days (> 10 mm) at Wellington and Masterton for the historic period and future changes for four climate change scenarios (RCP2.6, 4.5, 6.0 and 8.5) at two future time periods. Time periods: historic: 1986-2005, mid-century: 2031-2050 "2040", end-century: 2081-2100 "2090"; based on the average of six global climate models.

		Wellington	**Masterton**
Historic		36	20
2040	RCP2.6	37 (+1)	20.5 (+0.5)
	RCP4.5	37 (+1)	20.6 (+0.6)
	RCP6.0	37 (+1)	20.5 (+0.5)
	RCP8.5	35.9 (-0.1)	20 (+0)
2090	RCP2.6	36.2 (+0.2)	20.6 (+0.6)
	RCP4.5	36.4 (+0.4)	19.8 (-0.2)
	RCP6.0	36.1 (+0.1)	19.9 (-0.1)
	RCP8.5	36.3 (+0.3)	19.2 (-0.8)

4.2 Rain days with > 20 mm

In the historic period, the largest number of > 20 mm rain days occurs in the highest elevations of the Tararua Ranges (60-100 days per year), and the lowest number occurs around Martinborough (2-4 days per year) (Figure 4-3). Most of the Wairarapa experiences 4-8 days with > 20 mm of rain per year, and the western part of the region experiences 10-20 days with > 20 mm of rain per year.

In the future, the number of > 20 mm rain days is projected to increase for most of the region by the middle of the century (2040), but only by a small amount (0-2 days per year for most locations) (Figure 4-4). By 2090, most areas are projected to experience an increase in > 20 mm rain days by 0-2 days per year for most lowland areas, up to an increase of 2-3 days per year for the west coast (under RCP8.5). A decreases of > 2 days per year is projected high elevation locations, under the two higher concentration scenarios (RCP6.0 and RCP8.5).

Table 4-3 shows projected changes in > 20 mm rain days for Wellington and Masterton. The magnitude of the projected changes is small compared to the historic numbers of rain days > 20 mm for the two locations.

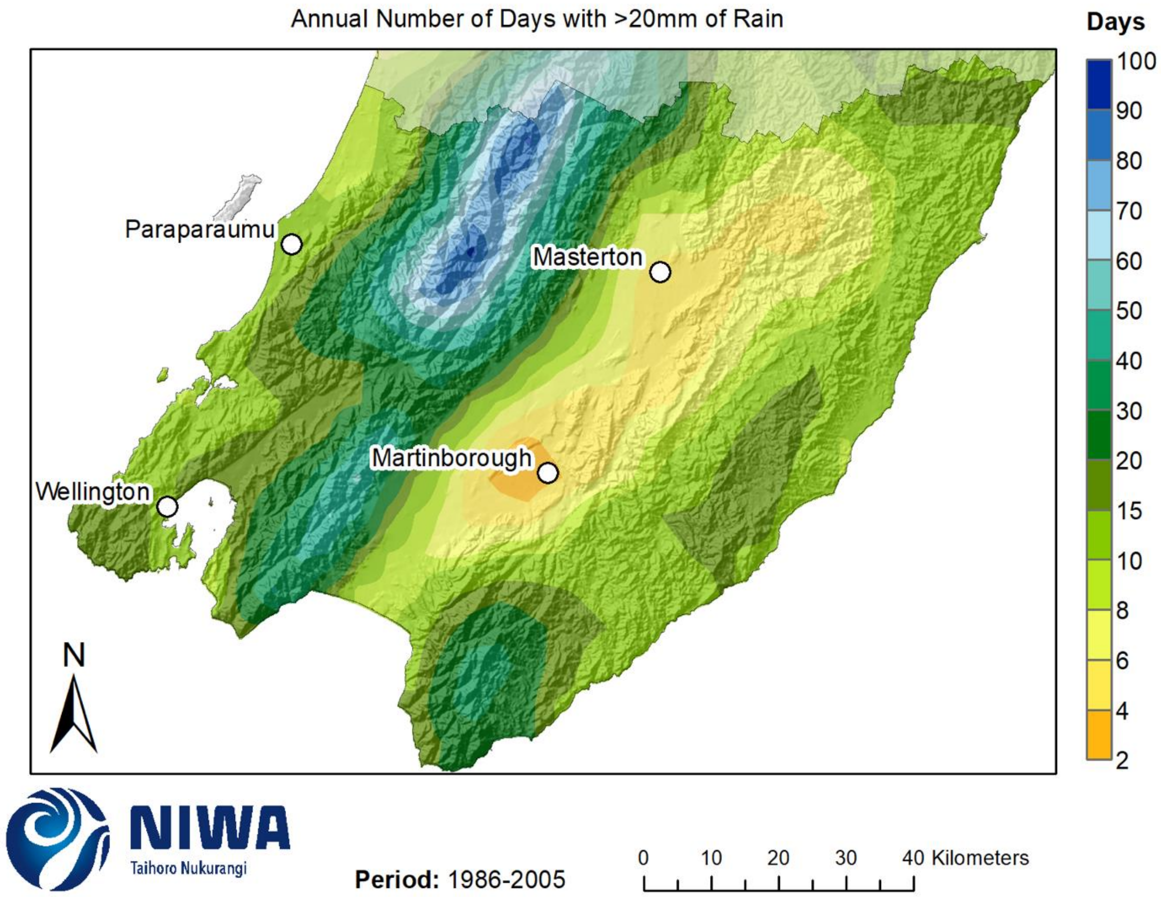


Figure 4-3: Modelled annual number of rain days with > 20 mm, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

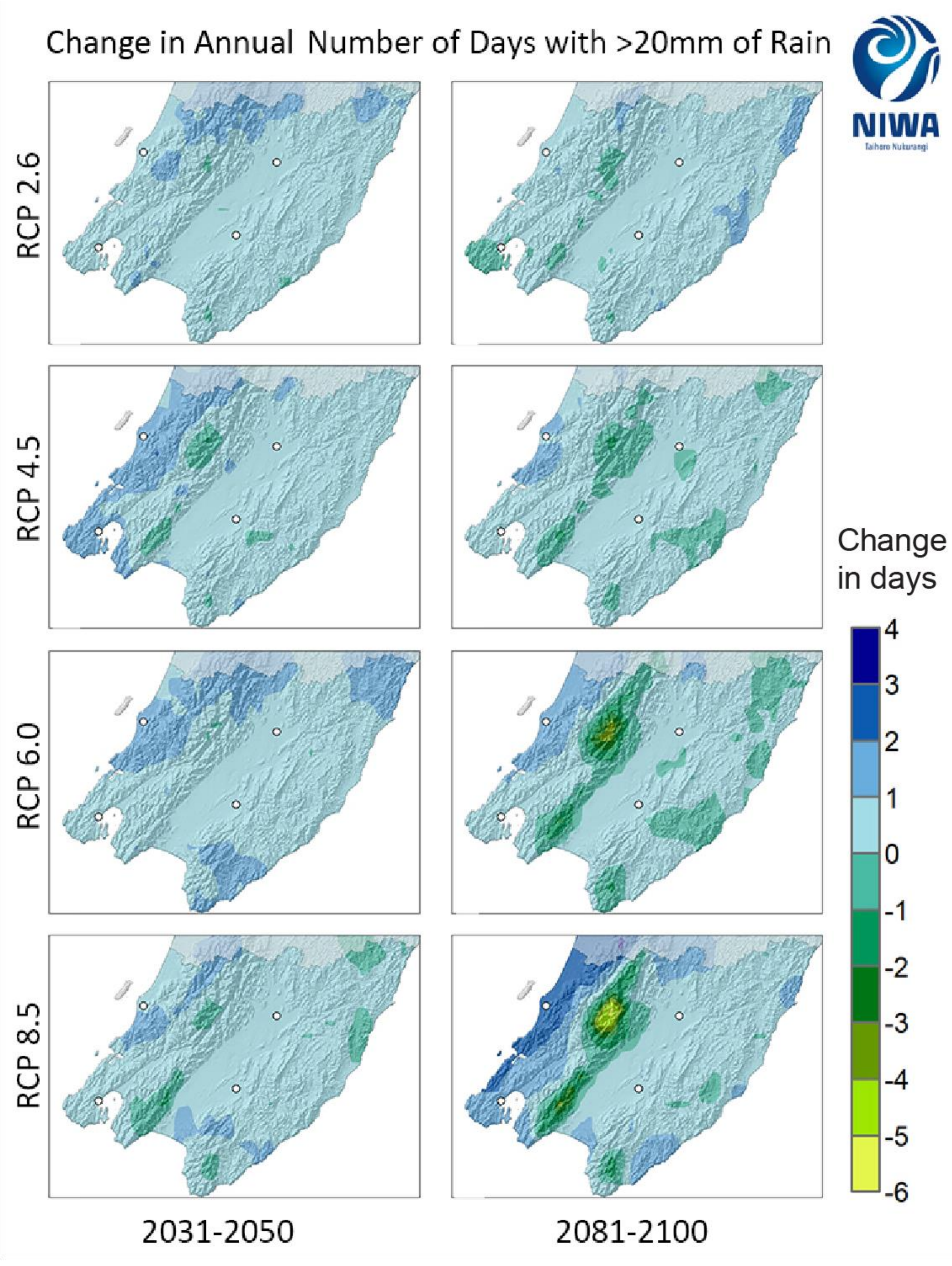


Figure 4-4: Projected annual rain day changes (> 20 mm) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 4-3: Modelled annual rain days (> 20 mm) at Wellington and Masterton for the historic period and future changes for four climate change scenarios (RCP2.6, 4.5, 6.0 and 8.5) at two future time periods. Time periods: historic: 1986-2005, mid-century: 2031-2050 "2040", end-century: 2081-2100 "2090"; based on the average of six global climate models.

		Wellington	**Masterton**
Historic		14	4
2040	RCP2.6	14.5 (+0.5)	4.2 (+0.2)
	RCP4.5	15 (+1)	4.1 (+0.1)
	RCP6.0	15 (+1)	4.1 (+0.1)
	RCP8.5	14.9 (+0.9)	4.2 (+0.2)
2090	RCP2.6	14 (+0)	4.3 (+0.3)
	RCP4.5	14.6 (+0.6)	3.9 (-0.1)
	RCP6.0	14.6 (+0.6)	4.1 (+0.1)
	RCP8.5	16 (+2)	4.2 (+0.2)

4.3 Rain days with > 30 mm

In the historic period, the largest number of > 30 mm rain days occurs in the highest elevations of the Tararua Ranges (50-70 days per year), and the lowest number occurs in the interior Wairarapa (0-2 days per year) (Figure 4-5). The western part of the region experiences 4-10 days with > 30 mm of rain per year.

In the future, the number of > 30 mm rain days is projected to increase for most of the region by the middle of the century (2040), but only by a small amount (0-1 day per year for most locations) (Figure 4-6). By 2090, most areas are projected to experience a slight increase in > 30 mm rain days, especially around the coastal areas (under RCP8.5). A decrease of 1-3 days per year is projected high elevation locations, under the two higher concentration scenarios (RCP6.0 and RCP8.5).

Table 4-4 shows projected changes in > 30 mm rain days for Wellington and Masterton. The magnitude of the projected changes is small compared to the historic numbers of rain days > 30 mm for the two locations.

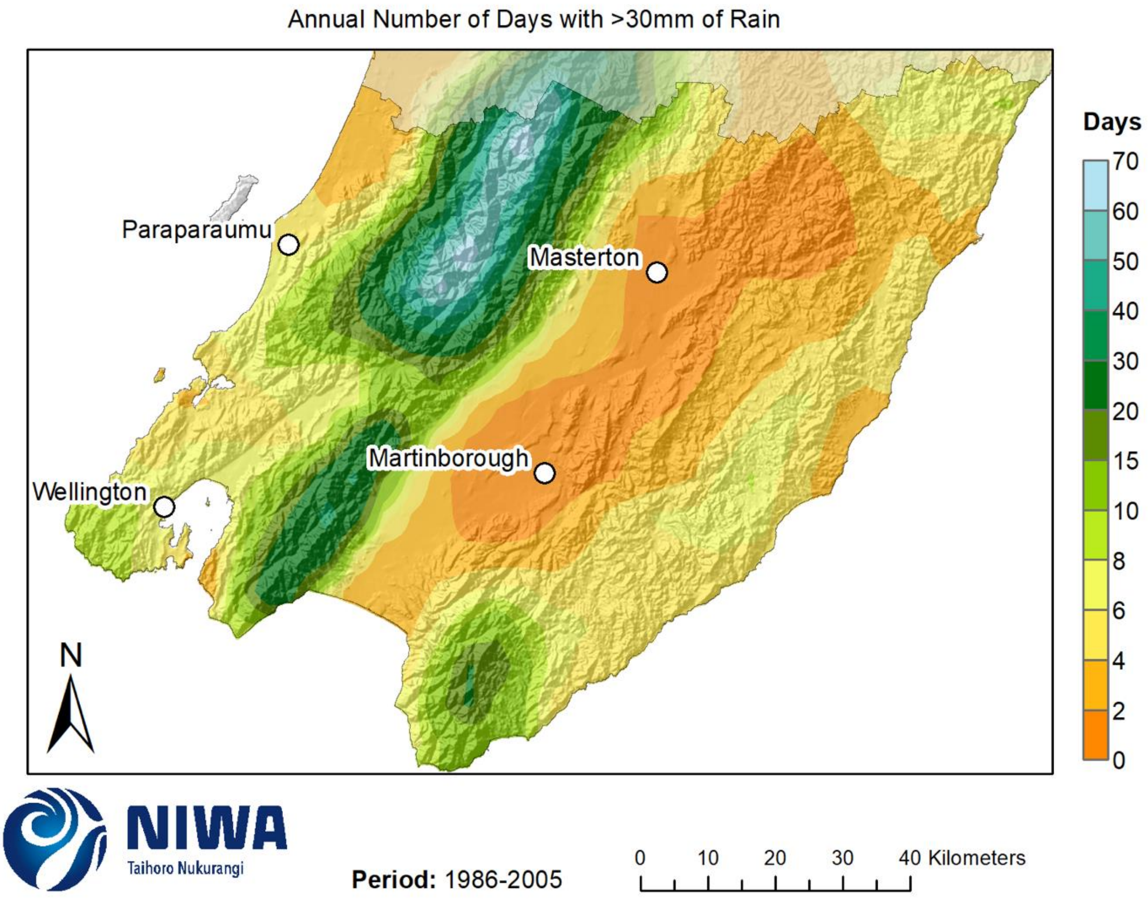


Figure 4-5: Modelled annual number of rain days with > 30 mm, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

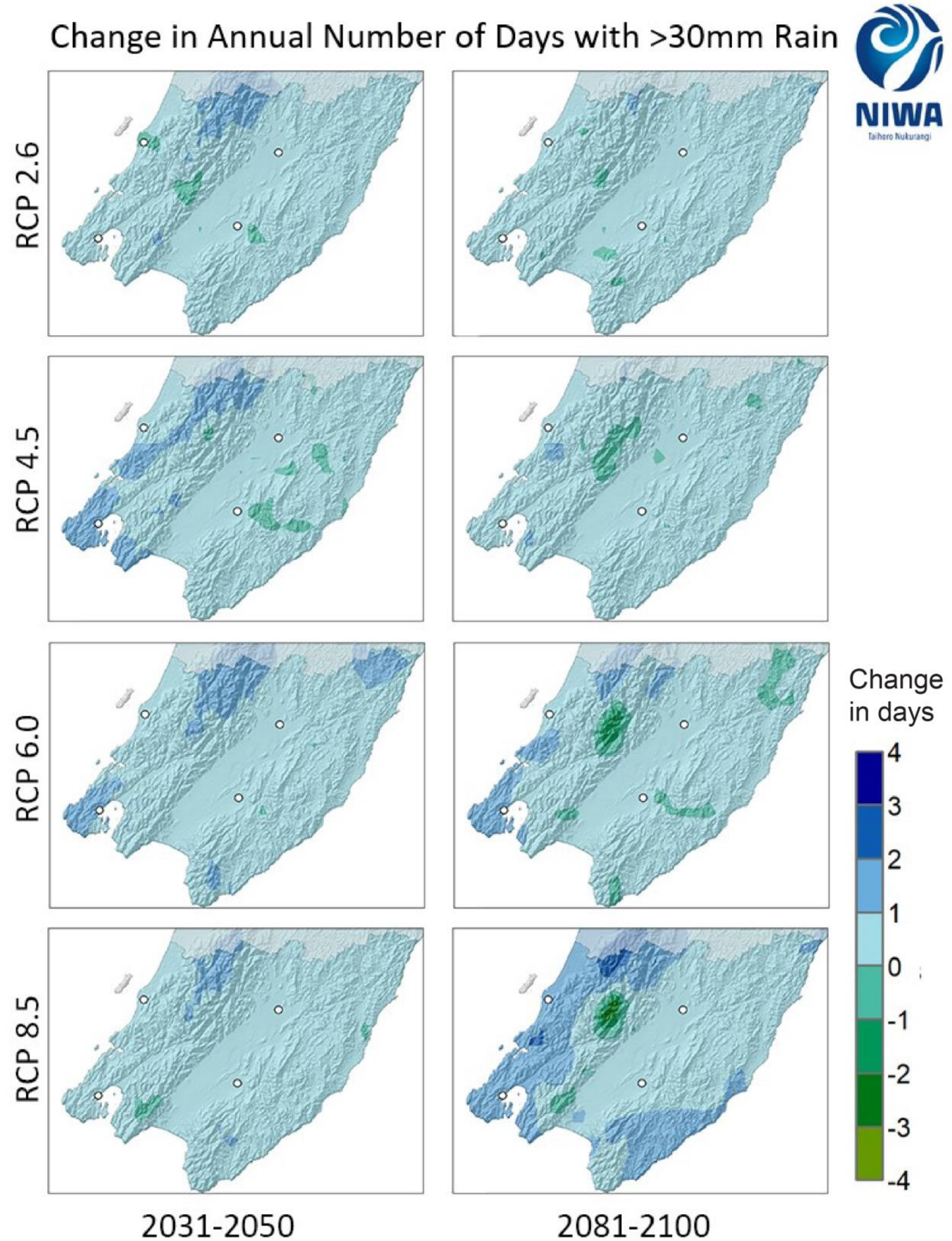


Figure 4-6: Projected annual rain day changes (> 30 mm) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 4-4: Modelled annual rain days (> 30 mm) at Wellington and Masterton for the historic period and future changes for four climate change scenarios (RCP2.6, 4.5, 6.0 and 8.5) at two future time periods. Time periods: historic: 1986-2005, mid-century: 2031-2050 "2040", end-century: 2081-2100 "2090"; based on the average of six global climate models.

		Wellington	**Masterton**
Historic		7	1
2040	RCP2.6	7.6 (+0.6)	1.4 (+0.4)
	RCP4.5	8 (+1)	1.1 (+0.1)
	RCP6.0	8 (+1)	1.2 (+0.2)
	RCP8.5	7.7 (+0.7)	1.3 (+0.3)
2090	RCP2.6	7.3 (+0.3)	1.3 (+0.3)
	RCP4.5	7.7 (+0.7)	1.2 (+0.2)
	RCP6.0	8 (+1)	1.3 (+0.3)
	RCP8.5	9 (+2)	1.2 (+0.2)

4.4 Wet and dry spells

For the purposes of this report, a wet spell or a dry spell is defined as a period of three or more consecutive days where the daily rainfall total exceeds 1 mm (wet spell) or is less than 1 mm (dry spell), respectively. For the maps in this section, the wet and dry spell climatology and projections are presented as average annual number of days that experience each type of event. Wet and dry spell days are calculated by aggregating all days per year that are included in a wet or dry spell (e.g., ≥ three consecutive days with rainfall >1mm or <1mm, respectively), no matter the length of the wet or dry spell. Thus, a 3-day wet or dry spell contributes 3 days, a 5-day wet or dry spell contributes 5 days, etc. The annual total numbers of wet or dry spell days are then averaged over the 20-year period of interest (e.g., 2031-2050), and across the six global models, to determine the ensemble-average annual wet or dry spell day climatology (past) and future projections. The historic maps show annual average numbers of wet or dry spell days and the future projection maps show the change in the number of wet or dry spell days compared with the historic period.

4.4.1 Wet spells

For the historic period, the highest number of days within 3-day wet spells (> 1 mm/day) occurs in the highest elevations of the Tararua Ranges, which has 160-200 days per year (Figure 4-7). The lowest number of days within 3-day wet spells occurs to the east of Martinborough, to the west of Wellington, and on the northeast coast of the region (50-60 days per year). Much of the hill country experiences around 100-120 days per year within 3-day wet spells.

In the future, the number of days within 3-day wet spells is projected to decline across the region (Figure 4-8). This decrease is larger with time and greenhouse forcing (i.e. larger decreases under higher RCPs and at the end of the century). The smallest change is for RCP2.6, which is projecting decreases of 0-6 days within 3-day wet spells by both 2040 and 2090 for most of the region. In contrast, the projections for RCP8.5 suggest decreases of 6-8 days within 3-day wet spells for most of the region by 2040 and decreases of at least 10 days within 3-day wet spells for most of the region by 2090 (20-30 fewer days for some central and eastern areas). The exception to this is the west coast which experiences reductions on the order of 4-8 days within 3-day wet spells by 2090.

Table 4-5 shows projected changes in days within 3-day wet spells for Wellington and Masterton.

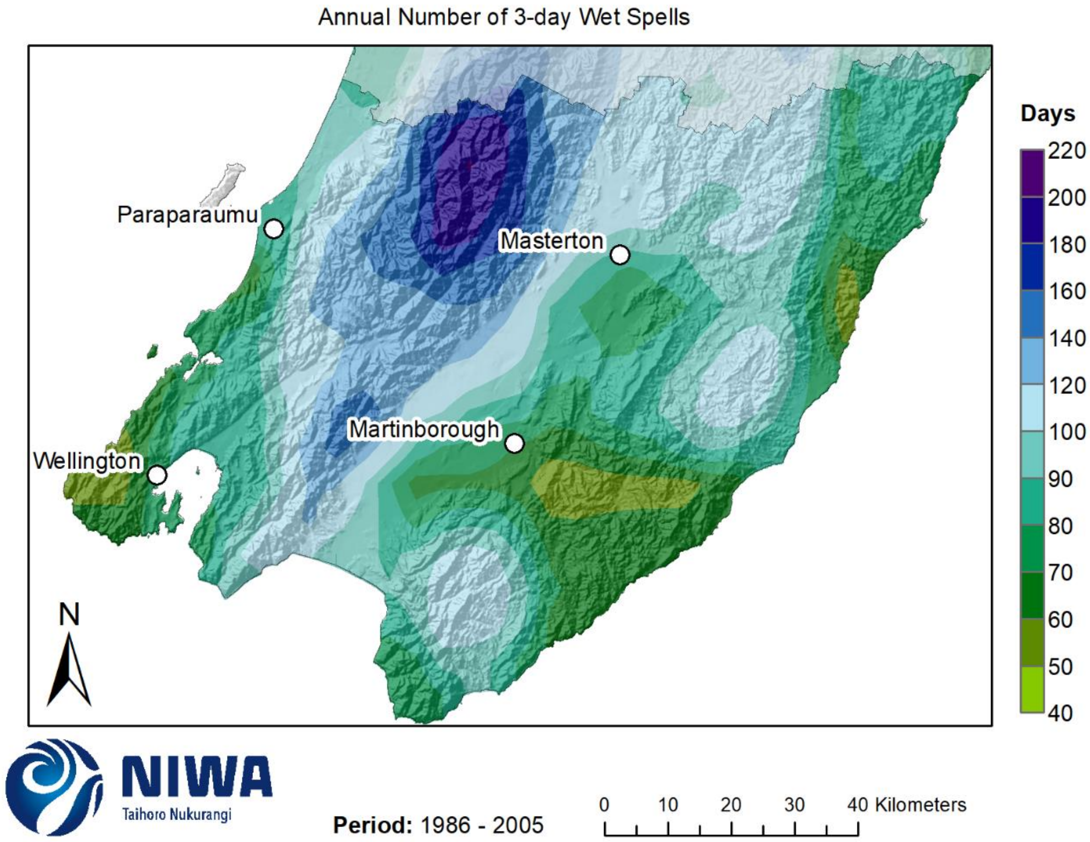


Figure 4-7: Modelled annual number of days within 3-day wet spells (> 1 mm rain per day), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

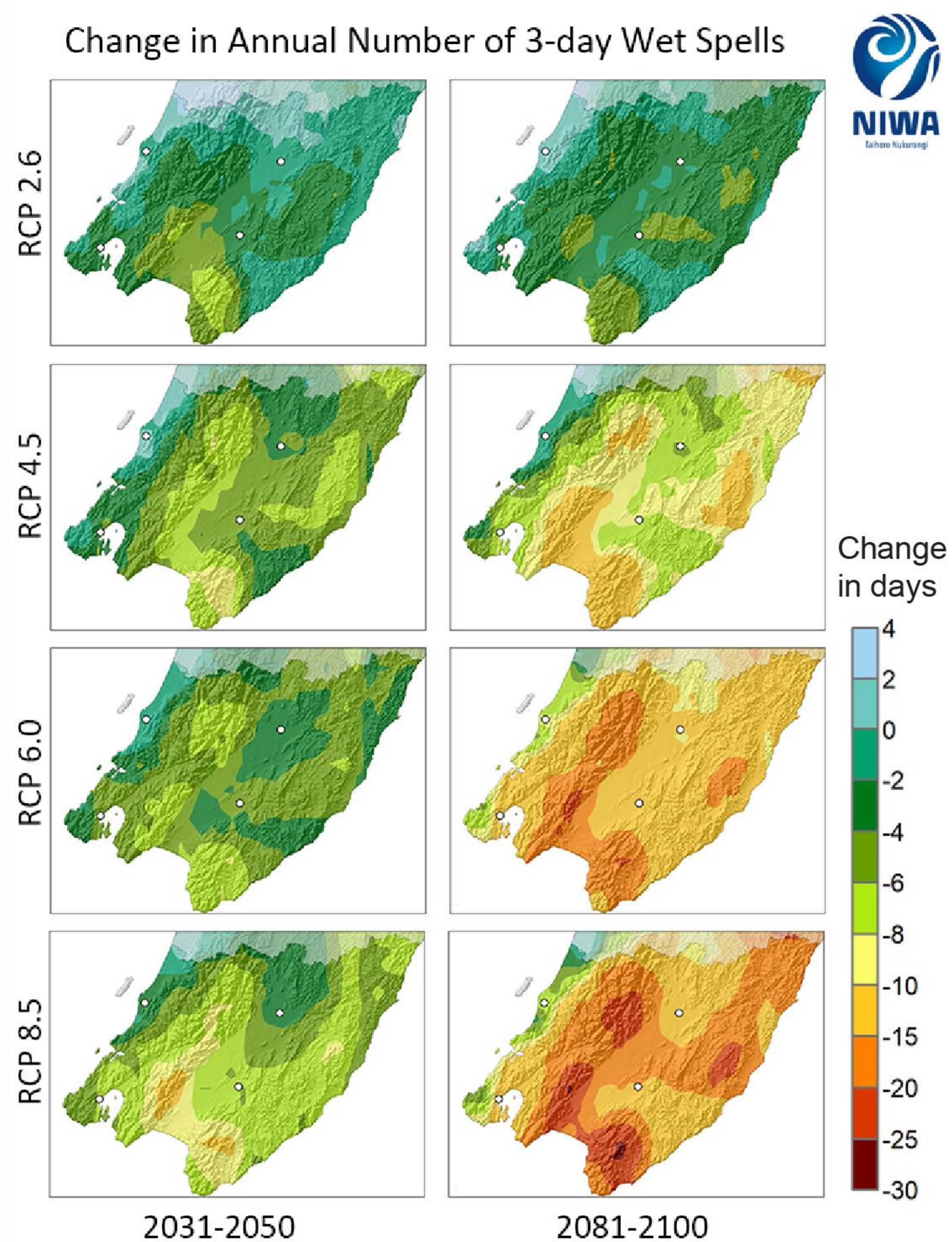


Figure 4-8: Projected change in the annual number of wet days within 3-day wet spells (> 1 mm rain per day) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

The spatial patterns for days within 5-day wet spells are similar to 3-day wet spells. In the historic period, the highest number of days within 5-day wet spells occurs in the highest elevations of the Tararua Ranges, which has 120-160 days per year (Figure 4-9). The lowest number of days within 5-day wet spells occurs to the east of Martinborough, to the west of Wellington, and on the northeast coast of the region (10-20 days per year). Much of the hill country experiences around 30-50 days per year within 5-day wet spells.

In the future, the number of days within 5-day wet spells is projected to decline across the region (Figure 4-10). This decrease is larger with time and greenhouse forcing (i.e. larger decreases under higher RCPs and at the end of the century). The smallest change is for RCP2.6, which is projecting decreases of 0-4 days within 5-day wet spells by both 2040 and 2090 for most of the region. In contrast, the projections for RCP8.5 suggest decreases of 2-8 days within 5-day wet spells for most of the region by 2040 and decreases of at least 8-10 days within 5-day wet spells for most of the region by 2090 (15-30 fewer days for some high elevation areas). The exception to this is the west coast which experiences reductions on the order of 2-6 days within 5-day wet spells by 2090.

Table 4-5 shows projected changes in days within 5-day wet spells for Wellington and Masterton.

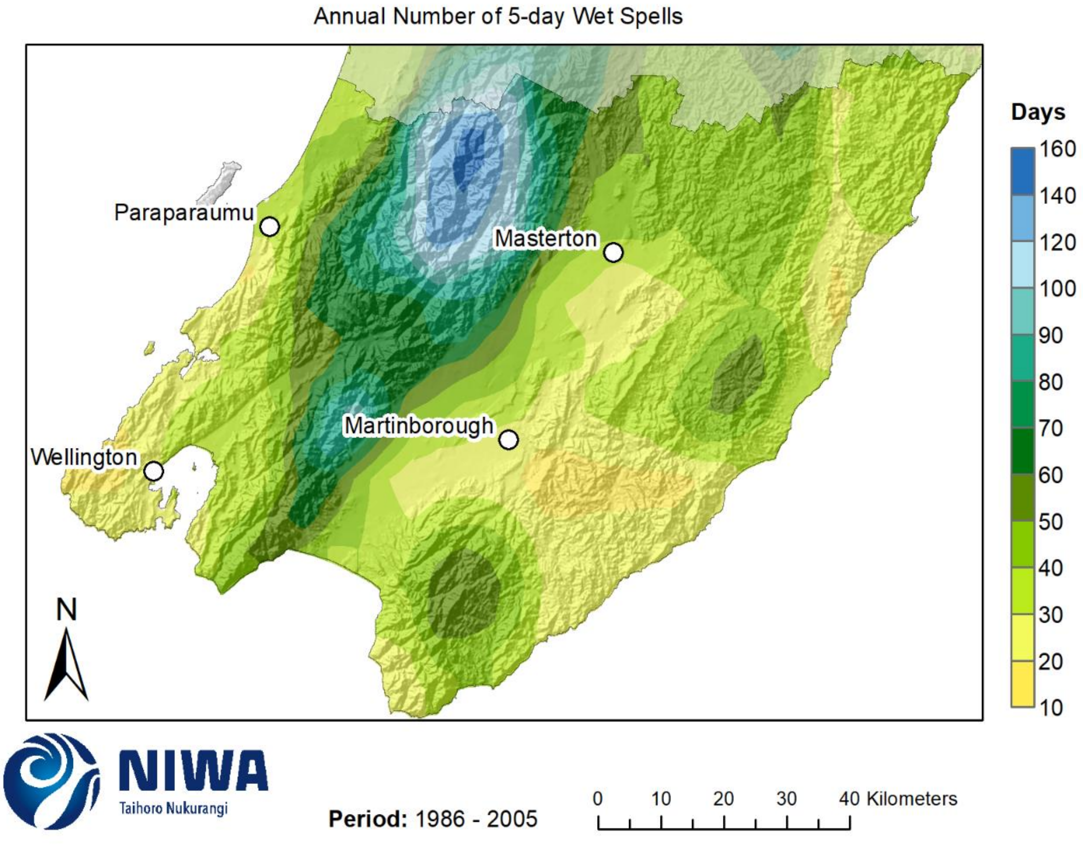


Figure 4-9: Modelled annual number of days within 5-day wet spells (> 1 mm rain per day), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

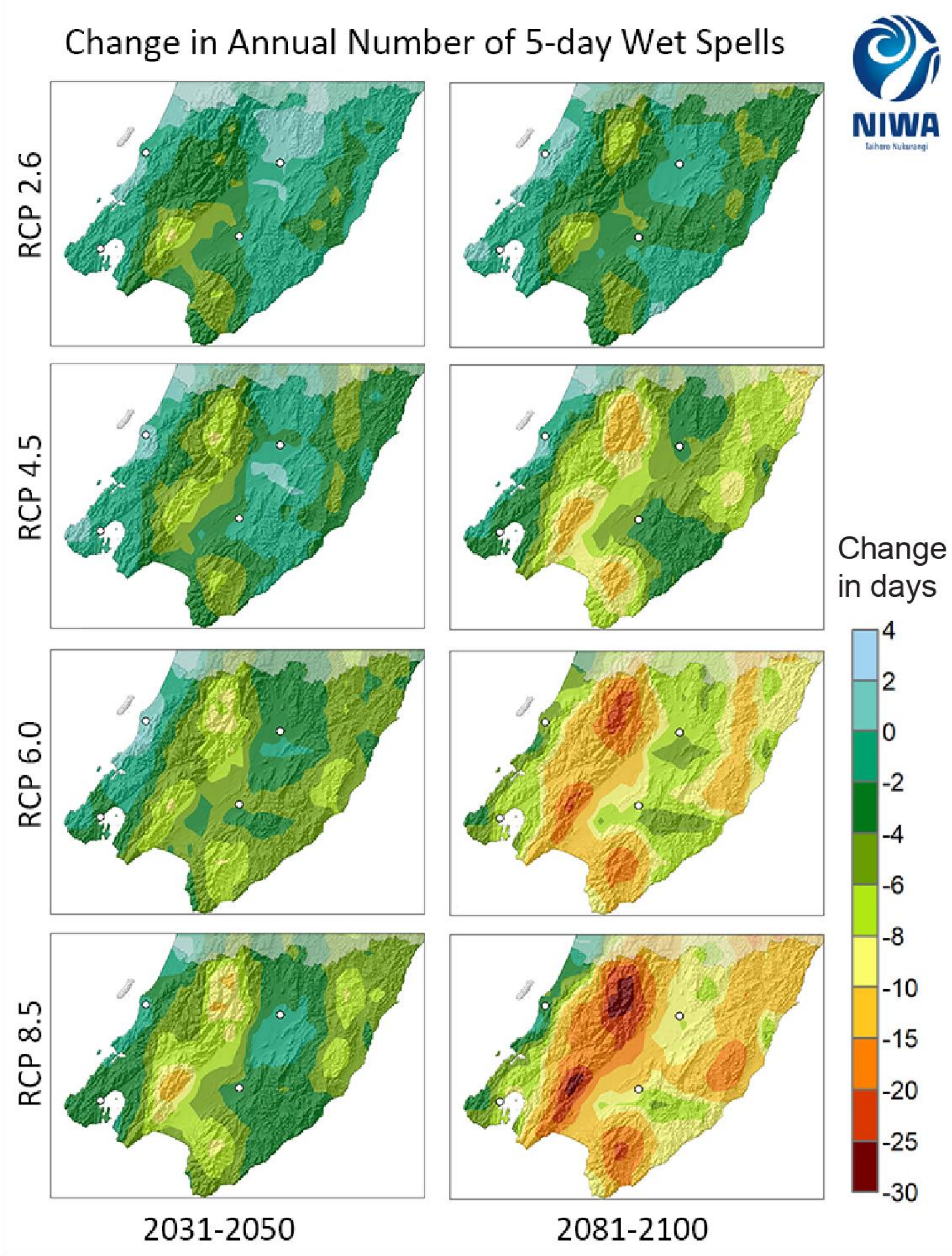


Figure 4-10: Projected change in the annual number of wet days within 5-day wet spells (> 1 mm rain per day) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Again, the spatial patterns for days within 10-day wet spells are similar to 3-day and 5-day wet spells. In the historic period, the highest number of days within 10-day wet spells occurs in the highest elevations of the Tararua Ranges, which has 30-40 days per year (Figure 4-11). The remainder of the region outside the Tararua and Remutaka Ranges experiences 0-5 days within 10-day wet spells per year, on average. Therefore, for most of the region, 10-day wet spells occur once every few years.

In the future, the number of days within 10-day wet spells is projected to decline in high elevation parts of the Tararua and Remutaka Ranges and not change much for the rest of the region (Figure 4-12). This high elevation decrease is larger with time and greenhouse forcing (i.e. larger decreases under higher RCPs and at the end of the century). Small increases and decreases are projected for most of the region of ± 0-2 days within 10-day wet spells per year. High elevations are expected to have decreases of at least 8 days within 10-day wet spells per year by 2090 under RCP4.5, RCP6.0 and RCP8.5, and up to 20 days under RCP8.5.

Table 4-5 shows projected changes in days within 10-day wet spells for Wellington and Masterton.

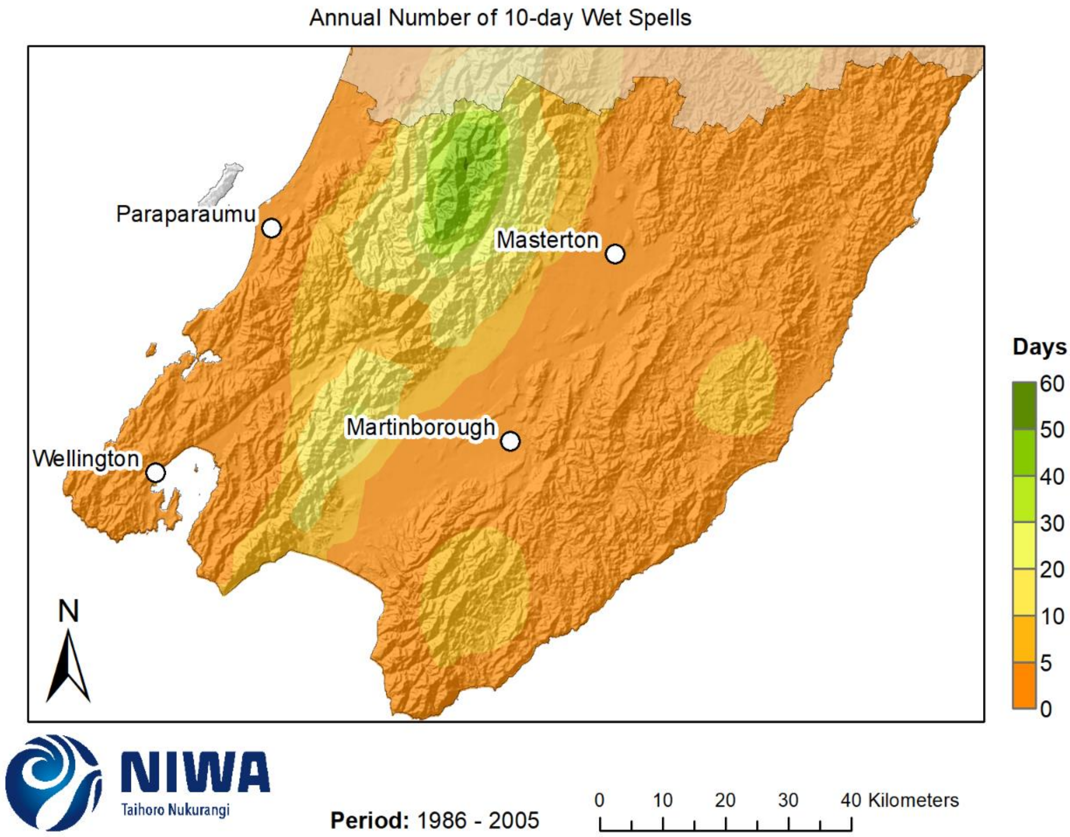


Figure 4-11: Modelled annual number of days within 10-day wet spells (> 1 mm rain per day), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

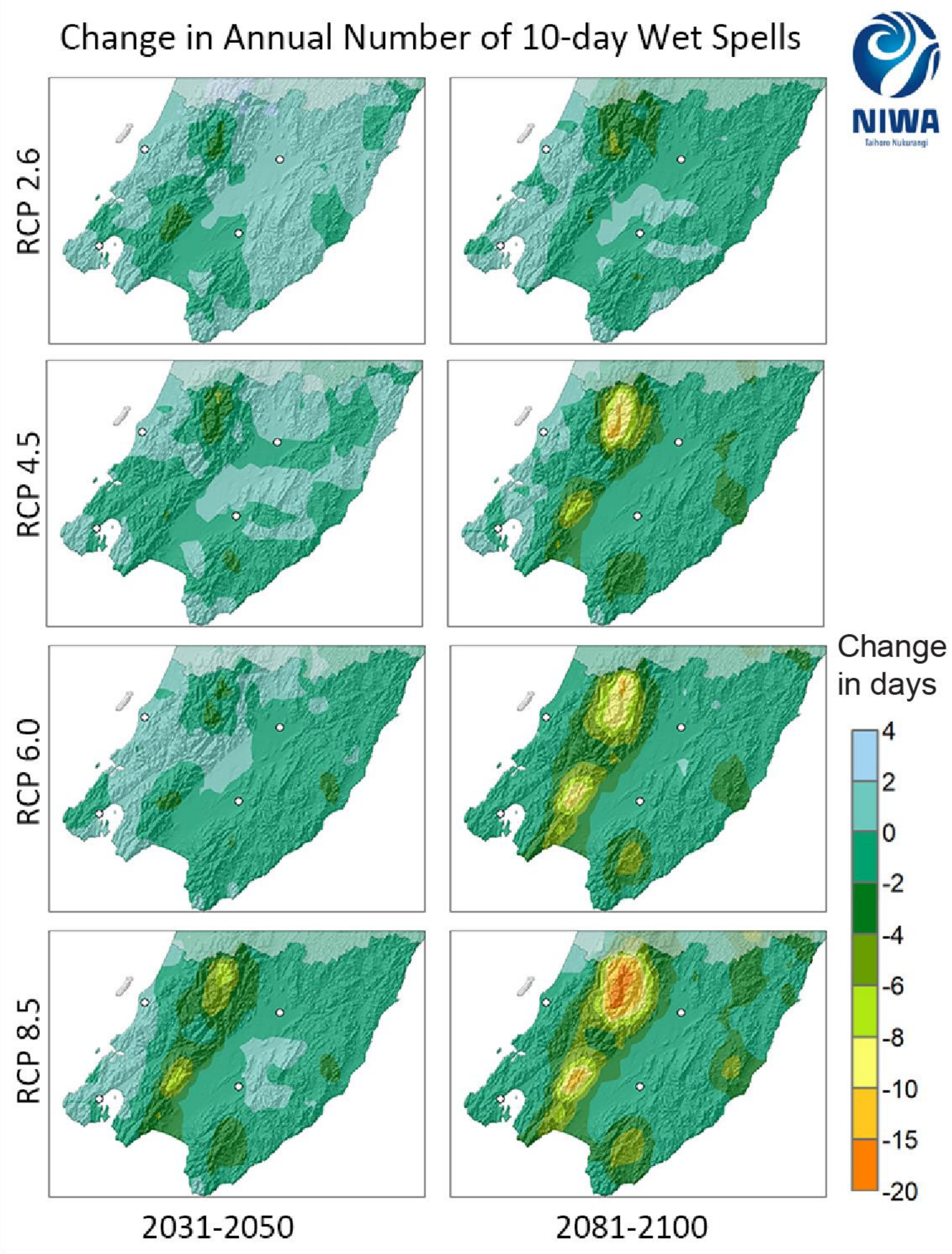


Figure 4-12: Projected change in the annual number of wet days within 10-day wet spells (> 1 mm rain per day) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 4-5: Modelled annual number of days within 3, 5 and 10-day wet spells (> 1mm rain per day) at Wellington and Masterton for the historic period and future changes for four climate change scenarios (RCP2.6, 4.5, 6.0 and 8.5) at two future time periods. Time periods: historic: 1986-2005, mid-century: 2031-2050 "2040", end-century: 2081-2100 "2090"; based on the average of six global climate models.

		3-day wet spells (days)		**5-day wet spells (days)**		**10-day wet spells (days)**	
		Wellington	**Masterton**	**Wellington**	**Masterton**	**Wellington**	**Masterton**
Historic		71	77	26	27	2	1
2040	RCP2.6	67 (-4)	76 (-1)	24 (-2)	27 (+0)	2 (+0)	2 (+1)
	RCP4.5	67 (-4)	74 (-3)	24 (-2)	26 (-1)	2 (+0)	1 (+0)
	RCP6.0	66 (-5)	75 (-2)	23 (-3)	25 (-2)	2 (+0)	0 (-1)
	RCP8.5	65 (-6)	74 (-3)	23 (-3)	26 (-1)	2 (+0)	0 (-1)
2090	RCP2.6	69 (-2)	75 (-2)	25 (-1)	26 (-1)	2 (+0)	1 (+0)
	RCP4.5	64 (-7)	72 (-5)	23 (-3)	24 (-3)	2 (+0)	0 (-1)
	RCP6.0	59 (-12)	67 (-10)	19 (-7)	22 (-5)	1 (-1)	1 (+0)
	RCP8.5	60 (-11)	65 (-12)	20 (-6)	19 (-8)	1 (-1)	0 (-1)

There is a clear trend towards a lower number of days within 3- and 5-day wet spells for both Wellington and Masterton, but there is no clear change in the number of days within 10-day wet spells.

4.4.2 Dry spells

In the historic period, the highest number of days within 3-day dry spells (< 1 mm/day) occurs east of Martinborough, which has 200-220 days per year (Figure 4-13). The lowest number of days within 3-day dry spells occurs in the highest elevations of the Tararua Ranges (70-90 days per year). Most of the region experiences 140-180 days per year within 3-day dry spells.

In the future, the number of days within 3-day dry spells is generally projected to increase across the region (Figure 4-14). Where increases occur, these are larger with time and greenhouse forcing (i.e. larger increases under higher RCPs and at the end of the century). Some small decreases of 0-4 days are projected for the northwest of the region under RCP2.6 at both time periods. By 2040, increases of 2-8 days are widespread across the region for RCP4.5, 6.0 and 8.5. By 2090, the largest increases are projected for RCP8.5, with 15-25 more days within 3-day dry spells per year.

Table 4-6 shows projected changes in days within 3-day dry spells for Wellington and Masterton.

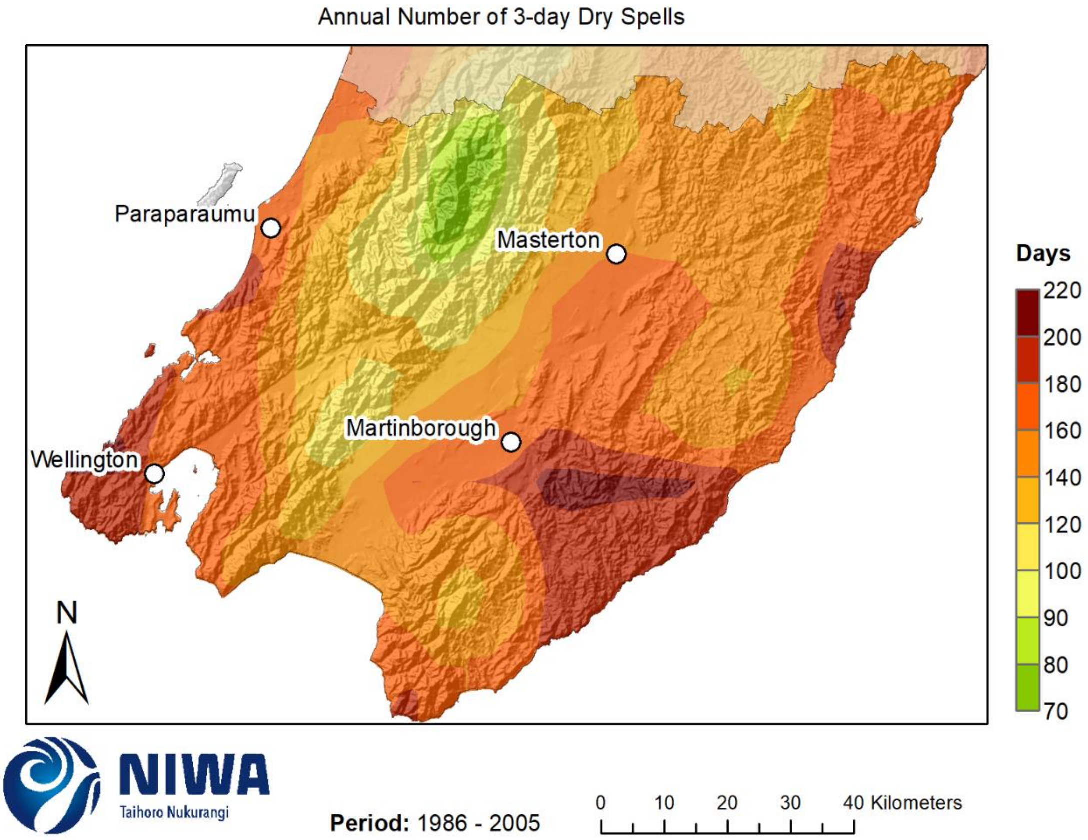


Figure 4-13: Modelled annual number of days within 3-day dry spells (< 1 mm rain per day), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

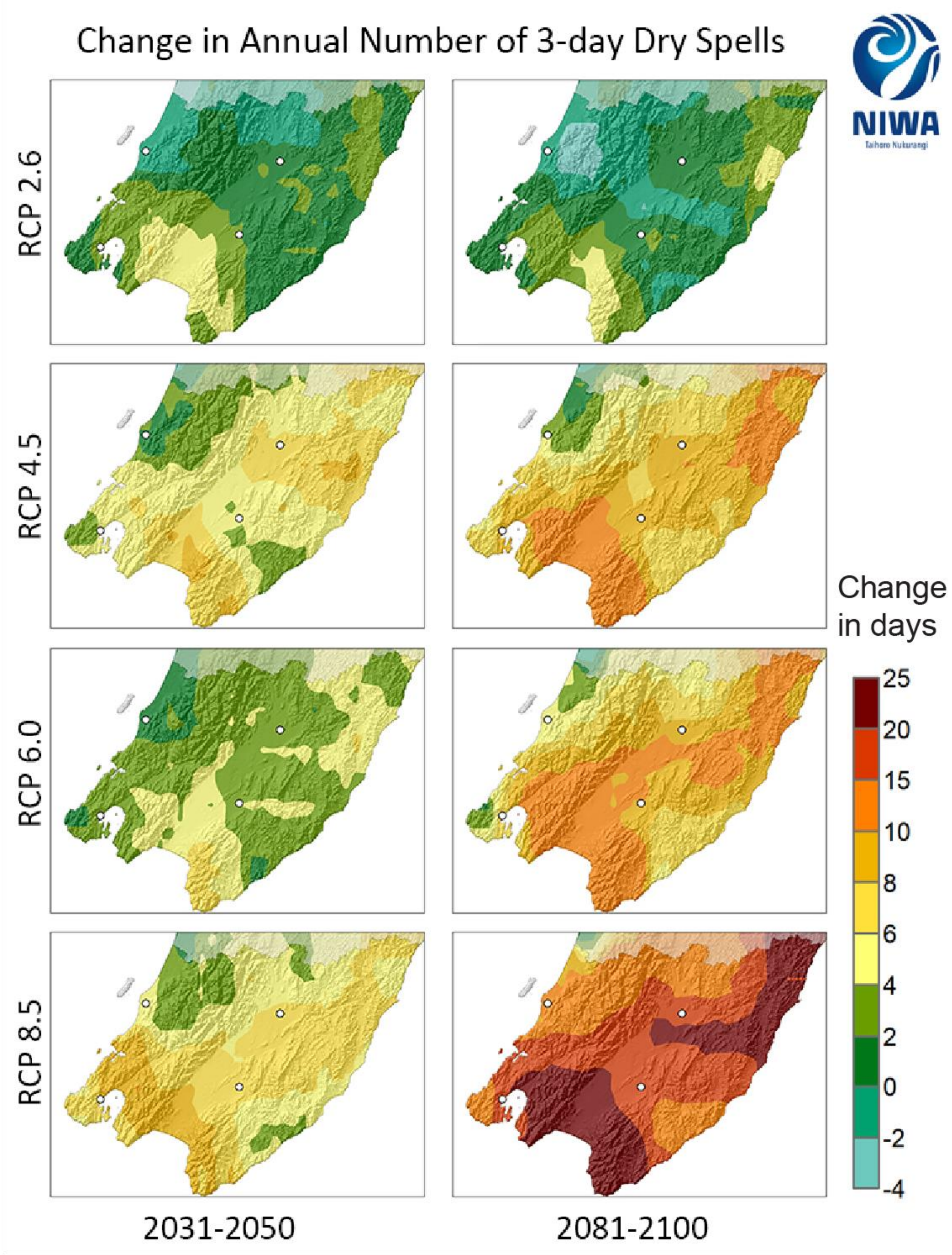


Figure 4-14: Projected change in the annual number of dry days within 3-day dry spells (< 1 mm rain per day) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

The spatial patterns for days within 5-day dry spells are similar to 3-day dry spells. In the historic period, the highest number of days within 5-day dry spells occurs east of Martinborough and west of Wellington, which has 140-160 days per year (Figure 4-15). The lowest number of days within 5-day dry spells occurs in the highest elevations of the Tararua Ranges (30-50 days per year). Most of the region experiences 90-120 days per year within 5-day dry spells.

In the future, the number of days within 5-day dry spells is generally projected to increase across the region (Figure 4-16). Where increases occur, these are larger with time and greenhouse forcing (i.e. larger increases under higher RCPs and at the end of the century). Some decreases of 0-6 days are projected for the northwest and southeast of the region under RCP2.6 at both time periods. By 2040, increases of 4-8 days are widespread across the region for RCP4.5 and RCP8.5. Smaller increases (0-4 days) are projected for RCP6.0 by 2040. By 2090, the largest increases are projected for RCP8.5, with 15-25 more days within 5-day dry spells per year.

Table 4-6 shows projected changes in days within 5-day dry spells for Wellington and Masterton.

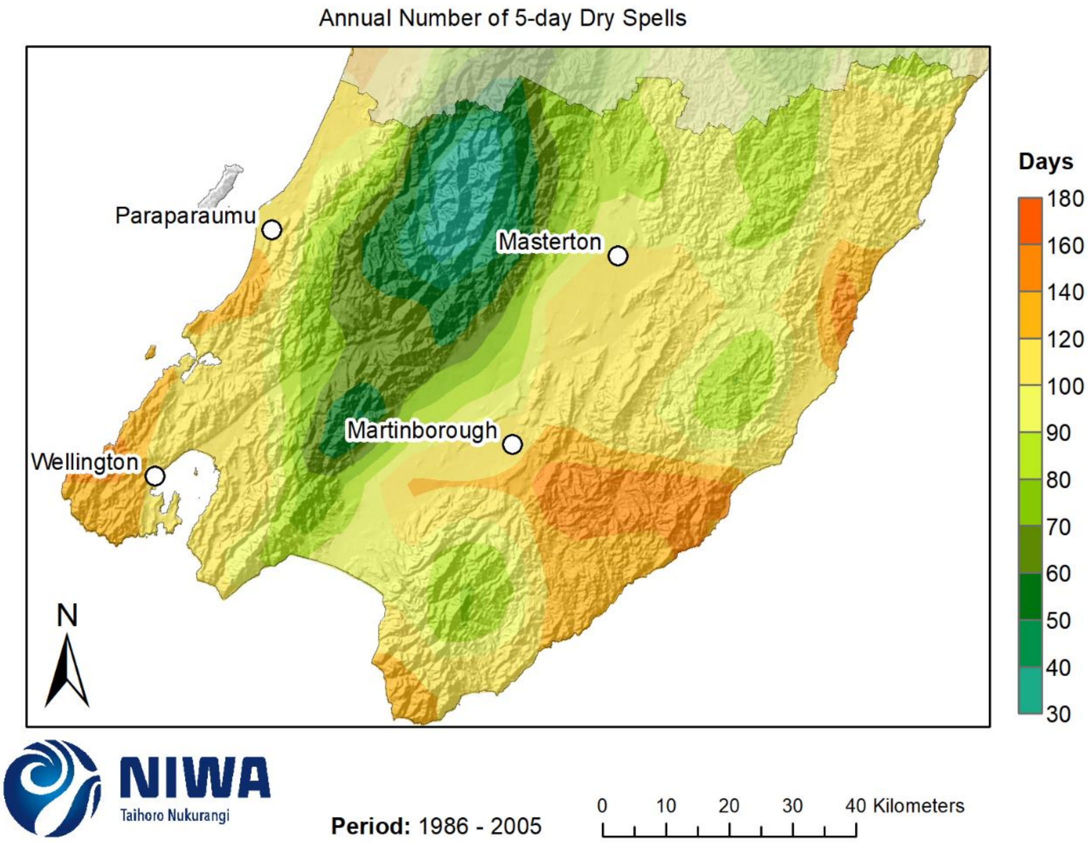


Figure 4-15: Modelled annual number of days within 5-day dry spells (< 1 mm rain per day), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

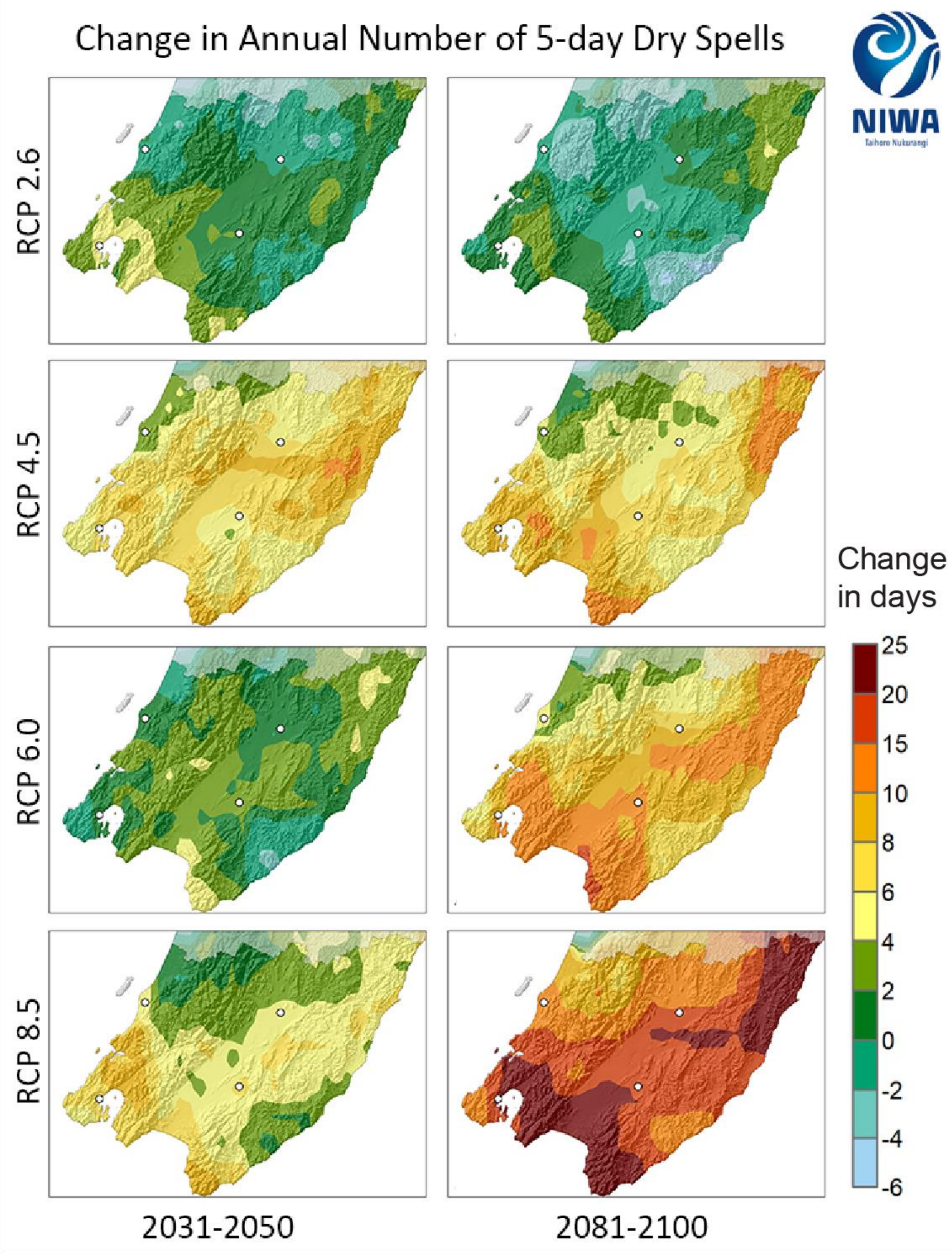


Figure 4-16: Projected change in the annual number of dry days within 5-day dry spells (< 1 mm rain per day) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Again, the spatial patterns for days within 10-day dry spells are similar to 3-day and 5-day dry spells. In the historic period, the highest number of days within 10-day dry spells occurs east of Martinborough, which has 40-60 days per year (Figure 4-17). The lowest number of days within 10-day dry spells occurs in the highest elevations of the Tararua Ranges (0-5 days per year). Most of the region experiences 10-30 days per year within 10-day dry spells.

In the future, the number of days within 10-day dry spells is generally projected to increase across the region (Figure 4-18). Where increases occur, these are larger with time and greenhouse forcing (i.e. larger increases under higher RCPs and at the end of the century). Some decreases of 0-4 days are projected for the north of the region under RCP2.6 at both time periods and RCP4.5 by 2090. By 2040, increases of 2-4 days are widespread across the east of the region for RCP4.5 and RCP8.5. Smaller increases of 0-4 days are projected for the west of the region at this time slice. By 2090, the largest increases are projected for RCP8.5, with 8-15 more days within 10-day dry spells per year for the area around Wellington City as well as most of the Wairarapa.

Table 4-6 shows projected changes in days within 10-day dry spells for Wellington and Masterton.

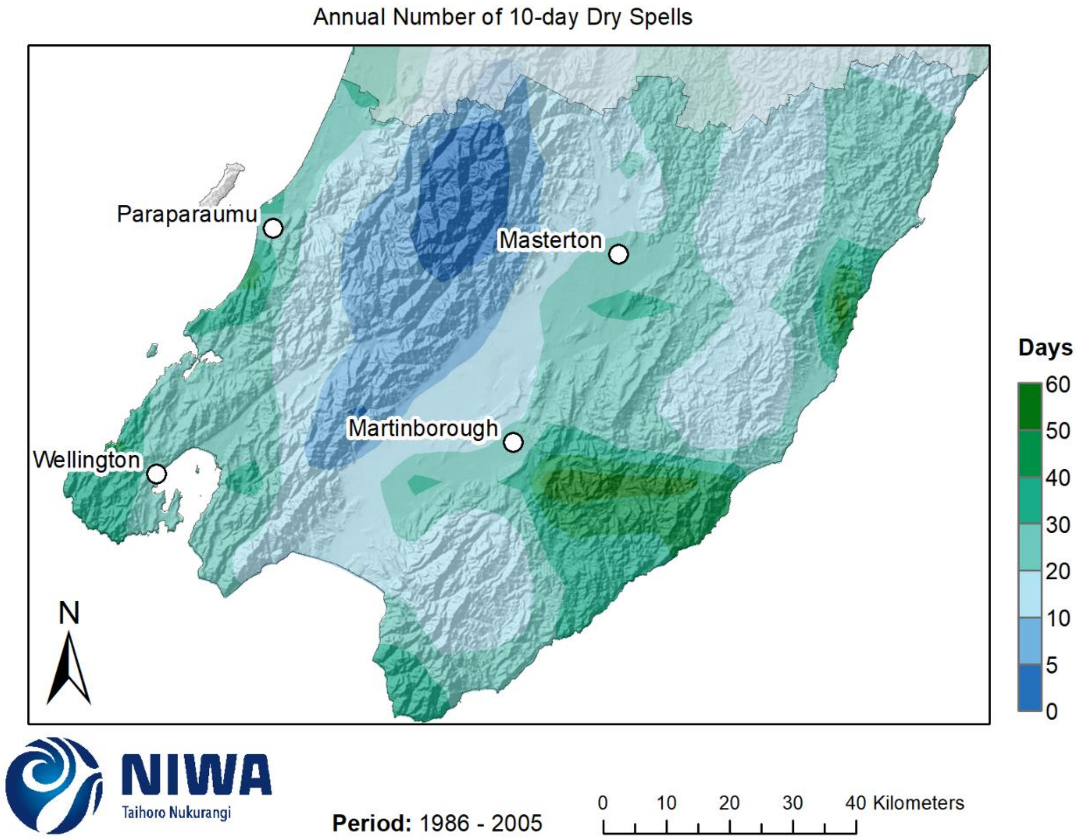


Figure 4-17: Modelled annual number of days within 10-day dry spells (< 1 mm rain per day), average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

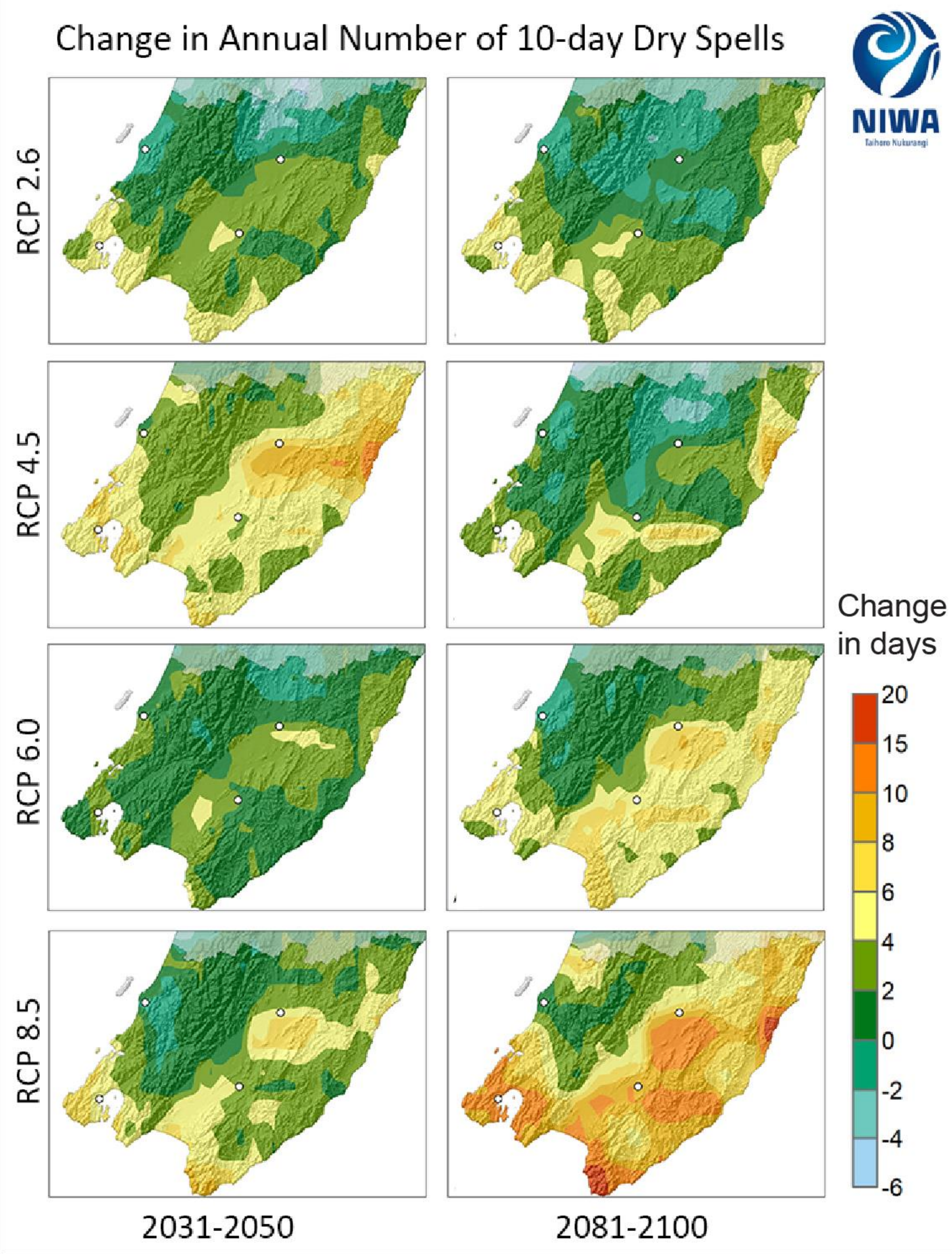


Figure 4-18: Projected change in the annual number of dry days within 10-day dry spells (< 1 mm rain per day) at 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

Table 4-6: Modelled annual number of days within 3, 5 and 10-day dry spells (< 1mm rain per day) at Wellington and Masterton for the historic period and future changes for four climate change scenarios (RCP2.6, 4.5, 6.0 and 8.5) at two future time periods. Time periods: historic: 1986-2005, mid-century: 2031-2050 "2040", end-century: 2081-2100 "2090"; based on the average of six global climate models.

		3-day dry spells (days)		5-day dry spells (days)		10-day dry spells (days)	
		Wellington	**Masterton**	**Wellington**	**Masterton**	**Wellington**	**Masterton**
Historic		181	170	119	114	27	28
2040	RCP2.6	184 (+3)	172 (+2)	124 (+5)	114 (+0)	32 (+5)	31 (+3)
	RCP4.5	185 (+4)	177 (+7)	125 (+6)	121 (+7)	33 (+6)	37 (+9)
	RCP6.0	184 (+3)	173 (+3)	120 (+1)	115 (+1)	30 (+3)	33 (+5)
	RCP8.5	189 (+8)	178 (+8)	126 (+7)	119 (+5)	32 (+5)	34 (+6)
2090	RCP2.6	182 (+1)	172 (+2)	120 (+1)	115 (+1)	32 (+5)	29 (+1)
	RCP4.5	190 (+9)	180 (+10)	129 (+10)	121 (+7)	31 (+4)	30 (+2)
	RCP6.0	187 (+6)	179 (+9)	130 (+11)	123 (+9)	31 (+4)	36 (+8)
	RCP8.5	199 (+18)	190 (+20)	140 (+21)	132 (+18)	39 (+12)	38 (+10)

There is a clear trend towards a higher number of days within 3-day, 5-day and 10-day dry spells in Wellington and Masterton. The changes projected by 2040 and 2090 under all scenarios except RCP8.5 for 3- and 5-day dry spells are relatively small compared to the historic number of days within those dry spells. However, the changes projected by 2090 under RCP8.5 are more notable. For 10-day dry spells, the projected changes are smaller than for 3- and 5-day dry spells but they represent a larger proportion of the historic numbers of days within dry spells of that length. Therefore, these changes may be thought of as being more significant.

4.4.3 Changing lengths of wet and dry spells

The maps above (Figure 4-7 to Figure 4-18) illustrate how the number of consecutive dry or wet days changes for selected spell-lengths in the Wellington Region.

Figure 4-19 and Figure 4-20 show the complete breakdown over all spell lengths at the Wellington (Kelburn) and Masterton VCSN grid points. Figure 4-19 provides an example for discussion, repeated in Figure 4-20 for other combinations of dry and wet days, 2040/2090 and Wellington/Masterton. The focus here is on consecutive days, either dry or wet, so the figures start at 2-day spells. The histogram bars represent the number of days per year that form part of dry day sequences lasting at least as many days as the “length” marked on the horizontal axis. For example, in the historical period, Masterton averages 201 dry days per year, which occur as part of 2-or-more day sequence (i.e., excluding singleton dry days). The corresponding Wellington value is 208 dry-days, according to the model analysis.

For longer-lasting dry spells, Figure 4-19 and Figure 4-20 indicate that Masterton (Wellington) experiences 11 days (5 days) per year, on average, that form part of 10-or-more dry day sequences. Thus, while the total number of dry days is similar at both locations, Masterton gets longer dry spells in contrast to Wellington.

Figure 4-19 and Figure 4-20 indicate a clear trend towards longer dry spells and shorter wet spells over time as the climate warms. By the end of the century (2090) under RCP8.5, Masterton (Wellington) is projected to have 219 (224) dry days per year, which occur as part of a 2-or-more day sequence, and 13 (9) dry days per year, which occur as part of a 10-or-more day sequence. Summing over all dry days, independent of the length of the dry spell, there is an increase in the number of dry days per year as the region warms (Section 4.2.4 of Pearce et al., 2017).

Conversely, wet day spells show a clear trend towards decreasing frequency at both locations as the climate warms. For wet spells of 2 days or more, Masterton (Wellington) experience 113 (107) days per year in the historical period, and is projected to experience 99 (96) days by 2090 under the RCP8.5 scenario. For wet spells of 3 days or more, Masterton (Wellington) experience 75 (71) days per year in the historical period, and is projected to experience 61 (60) days by 2090 under the RCP8.5 scenario. For wet spells of 10 days or more, Masterton (Wellington) experience 1.3 (1.6) days per year in the historical period, and is projected to experience 0.6 (0.5) days by 2090 under the RCP8.5 scenario. Thus, extended wet spells are uncommon but do occur: for example, for an occurrence of 0.5 days per year in a 10-day continuous wet spell implies the region might experience this once in a 20-year period.

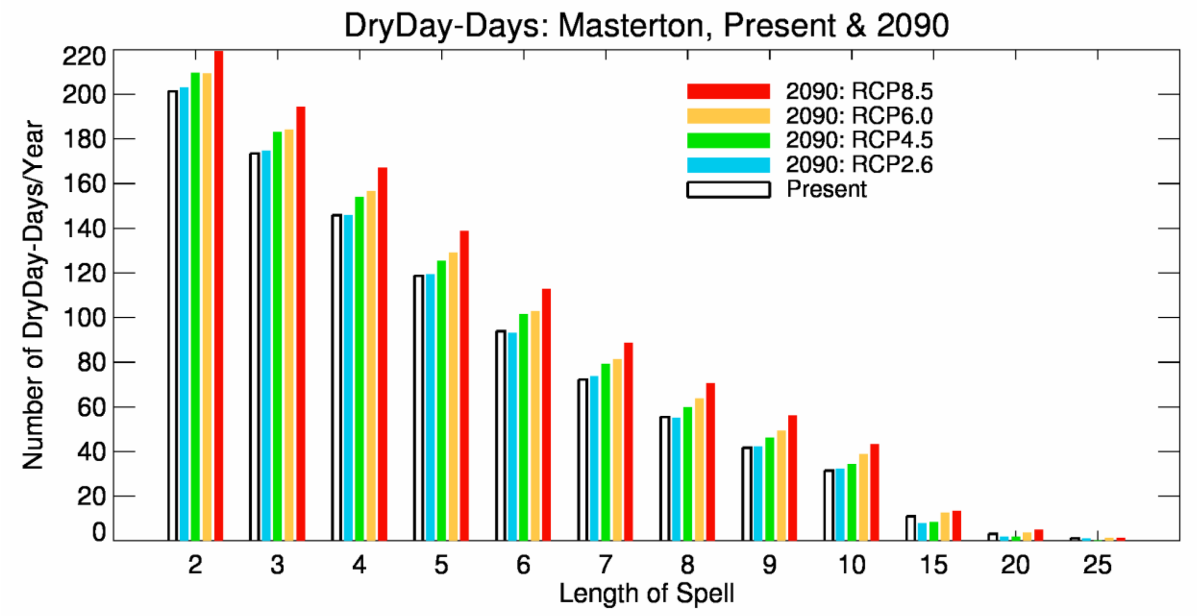


Figure 4-19: Average number of dry-days (in days per year) for the Masterton VCSN grid-point, plotted as a function of the minimum length of the dry spell in days. Colour bars represent counts under the historical climate (white, far left bar) and for 2090 under RCP2.6 (blue), RCP4.5 (green), RCP6.0 (orange) and RCP8.5 (red). A length of "2" means 2 or more days, "3" means 3 or more days, etc.

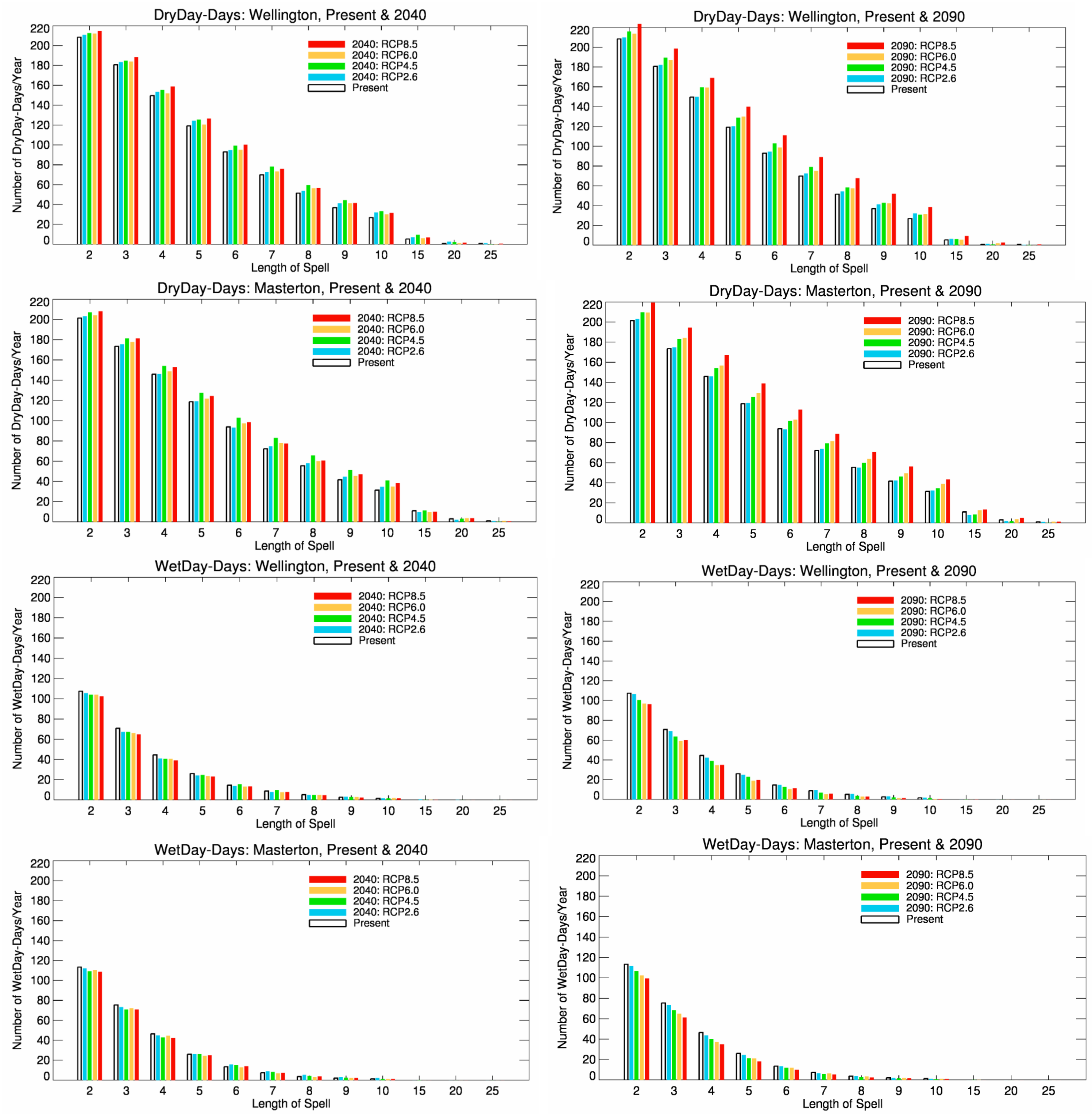


Figure 4-20: Average number of dry-days and wet-days (in days per year) for the Wellington (left) and Masterton (right) VCSN grid-points, plotted as a function of the minimum length of the dry or wet spell in days. Colour bars represent counts under the historical climate (hollow, far left bar) and for either 2040 or 2090 under RCP2.6 (blue), RCP4.5 (green), RCP6.0 (orange) and RCP8.5 (red). A length of “2” means 2 or more days, “3” means 3 or more days, etc.

4.5 Extreme rainfall events (HIRDS v4)

Key messages

- Rainfall amounts recorded during short duration extreme events have increased over time at Wellington (Kelburn).
- The amount of rainfall that falls during extreme rainfall events is likely to increase in the future.
- Shorter duration events will experience the largest increases in rainfall intensity.
- The largest rainfall increases are projected for the areas with highest rainfall – the Tararua, Remutaka and Aorangi Ranges. The smallest rainfall increases are projected for the areas with lowest rainfall (the Wairarapa Plains).

Rainfall extremes are expected to increase with climate change due to a warmer atmosphere being able to hold more moisture. The 2018 update to the High Intensity Rainfall Design System (HIRDS) (Carey-Smith et al., 2018) found that percentage increases vary from 6% per degree of warming for 5-day duration events, to about 8% per degree of warming for 24-hour events, to over 13% per degree of warming for hourly duration events (Table 4-7). Given that there has been approximately 1°C of warming in New Zealand over the past century according to NIWA's Seven Station Temperature Series[2], one would expect these increases in extreme rainfall depths to be apparent in the observational record. However, extremes by their nature are rare and highly variable, therefore it is very difficult to reliably estimate trends in extreme events, even from relatively long rain gauge records.

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

Table 4-7: Percentage change factors to estimate the increase in rainfall depth that is expected to result from a 1 degree increase in temperature. Source: Ministry for the Environment (2018). The most likely percentage change is shown on the top of each row and the range provided below it shows the variability that could be expected across New Zealand based on the RCM results. To obtain change factors for a temperature change that is not 1 degree, the values in this table should be multiplied by the projected temperature change.

ARI: Duration	2 yr	5 yr	10 yr	20 yr	30 yr	50 yr	100 yr
1 hour	12.2 9.8 – 17.5	12.8 10.6 – 18.1	13.1 10.7 – 18.5	13.3 10.7 – 18.8	13.4 10.7 – 18.9	13.5 10.7 – 19.1	13.6 10.7 – 19.4
2 hours	11.7 9.2 – 18.0	12.3 9.9 – 18.4	12.6 10.0 – 18.7	12.8 10.1 – 19.0	12.9 10.1 – 19.1	13.0 10.1 – 19.3	13.1 10.1 – 19.6
6 hours	9.8 7.5 – 14.9	10.5 8.0 – 15.4	10.8 8.3 – 15.9	11.1 8.4 – 16.4	11.2 8.5 – 16.6	11.3 8.5 – 17.0	11.5 8.5 – 17.4
12 hours	8.5 5.7 – 13.5	9.2 6.5 – 13.9	9.5 6.8 – 14.2	9.7 7.1 – 14.5	9.8 7.2 – 14.8	9.9 7.3 – 15.1	10.1 7.3 – 15.4
24 hours	7.2 4.0 – 11.9	7.8 4.6 – 12.0	8.1 4.8 – 12.1	8.2 4.9 – 12.2	8.3 5.0 – 12.3	8.4 5.1 – 12.5	8.6 5.2 – 12.8
48 hours	6.1 2.6 – 11.0	6.7 3.1 – 11.1	7.0 3.3 – 11.2	7.2 3.4 – 11.3	7.3 3.4 – 11.3	7.4 3.4 – 11.4	7.5 3.5 – 11.5
72 hours	5.5 2.1 – 10.5	6.2 2.6 – 10.6	6.5 2.7 – 10.8	6.6 2.8 – 10.9	6.7 2.9 – 11.0	6.8 2.9 – 11.1	6.9 2.9 – 11.2
96 hours	5.1 1.7 – 10.0	5.7 2.2 – 10.2	6.0 2.4 – 10.5	6.2 2.5 – 10.7	6.3 2.6 – 10.9	6.4 2.6 – 11.0	6.5 2.7 – 11.2
120 hours	4.8 1.3 – 9.6	5.4 1.9 – 9.7	5.7 2.1 – 10.0	5.8 2.3 – 10.2	5.9 2.3 – 10.4	6.0 2.4 – 10.5	6.1 2.4 – 10.7

4.5.1 Past trends in extreme rainfall for Wellington gauges

Figure 4-21 to Figure 4-24 contain annual maxima series for gauges in the Wellington Region with long records (Kelburn, Wellington Airport, Paraparaumu, and Waingawa, respectively). The nine panels in each figure contain the maxima series for different event durations ranging from 10 minutes to 5 days. Linear trends have been fitted to all these time-series, although very few of these are statistically significant. The only consistently significant trends are in the short duration events at Kelburn. To assess the robustness of these trends in the presence of sporadic very large extremes, trends have also been fitted after removing the largest and smallest outliers.

For Kelburn (Figure 4-21), this is mainly to test whether the two large events around the year 2000 are the main contributor to the positive trend. As can be seen, while the magnitude of the trend reduces when these events are removed, the trends are still significant even when the most extreme 10% of points are removed. After removal of the most extreme points, the 1-hour duration trend comes to approximately 4 ± 2 mm/century. Expressed relative to the mean 1-hour annual maxima this equates to a 20% ± 10% increase per century.

This result still needs to be treated with some scepticism as a similar trend is not observed in other long-term records in the Wellington Region. The record for Wellington Airport (Figure 4-22) actually shows a significant negative trend for the shortest durations and no consistently significant trends for longer durations. However, there does appear to be some unexplained discontinuity in the available sub-hourly records for Wellington Airport, as they show a step decrease for the last ten years of the record which may be distorting any real trend.

For Paraparaumu and Waingawa (near Masterton), no significant trends are found for any event duration, although for short durations at Waingawa the record length is only 40 years.

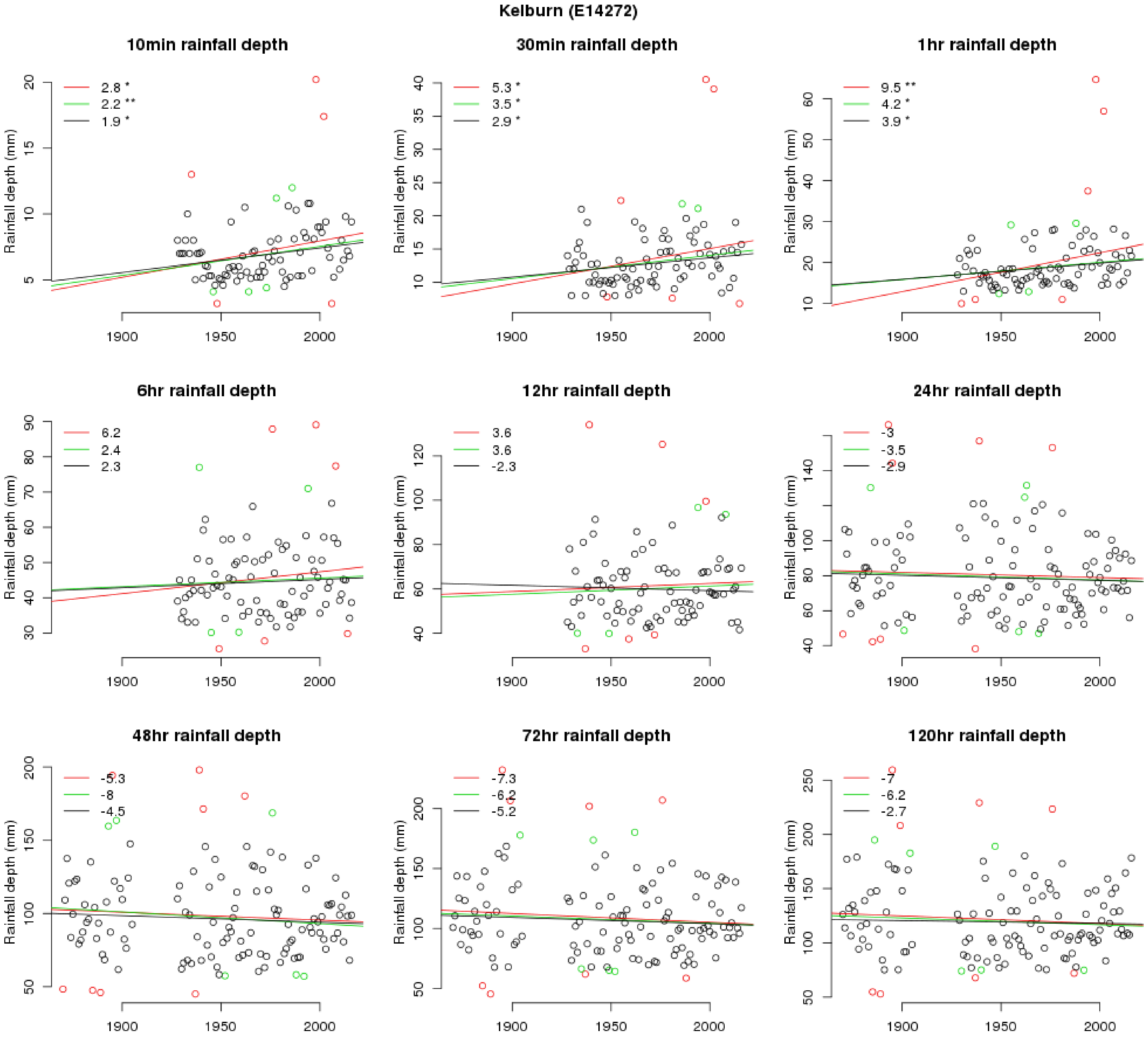


Figure 4-21: Annual maxima rainfall time series from Kelburn for a range of event durations. For each duration, trends have also been estimated with the trend magnitudes (in mm/century) shown in the figure legends. A '*' or '**' indicates significance at the 5% or 1% level, respectively. The red lines are trends fitted to all points in the series. The green lines are fitted after the most extreme 5% of points are removed; i.e. excluding the red points which are the top and bottom 2.5%. The black lines are fitted after both green and red points are removed (the top and bottom 5% of data points). For Kelburn, the sub-daily record spans 1928—2016 and the daily record spans 1870—2016, although there is missing data between 1906 and 1927.

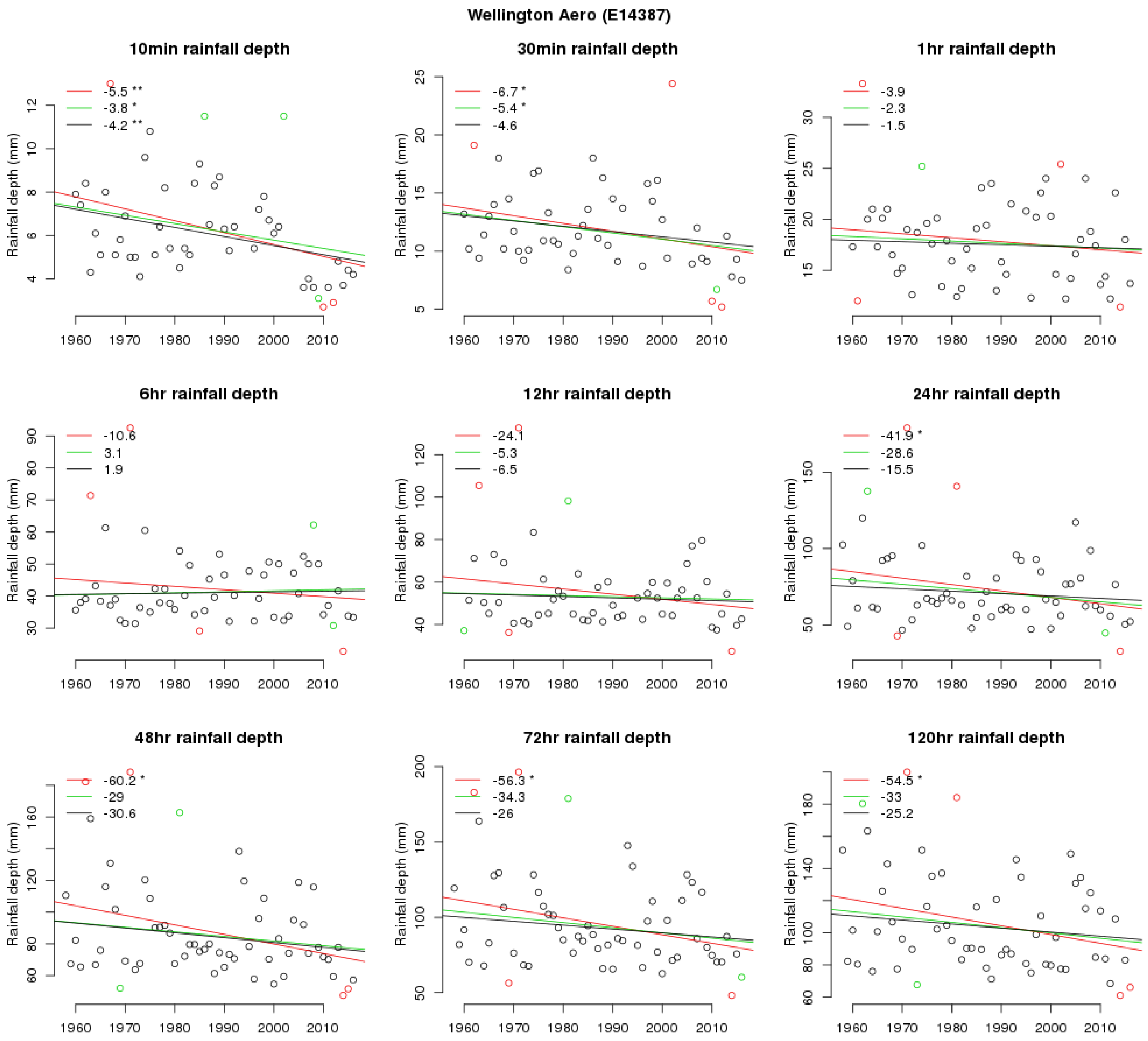


Figure 4-22: As Figure 4-21, except for Wellington Airport. For Wellington Airport, the sub-daily record spans 1960—2016 and the daily record spans 1958—2016.

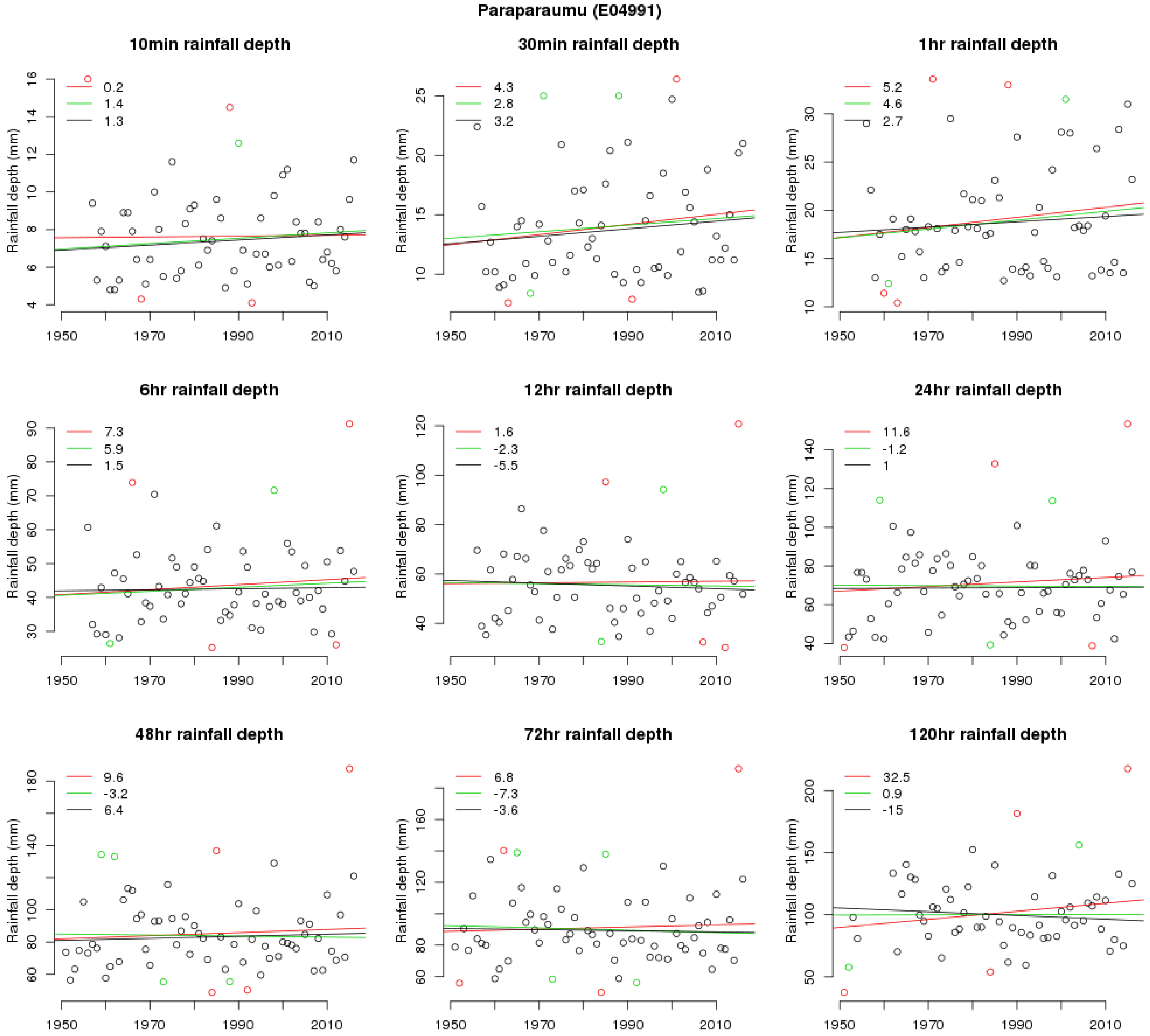


Figure 4-23: As Figure 4-21, except for Paraparaumu. For Paraparaumu, the sub-daily record spans 1956—2016 and the daily record spans 1951—2016.

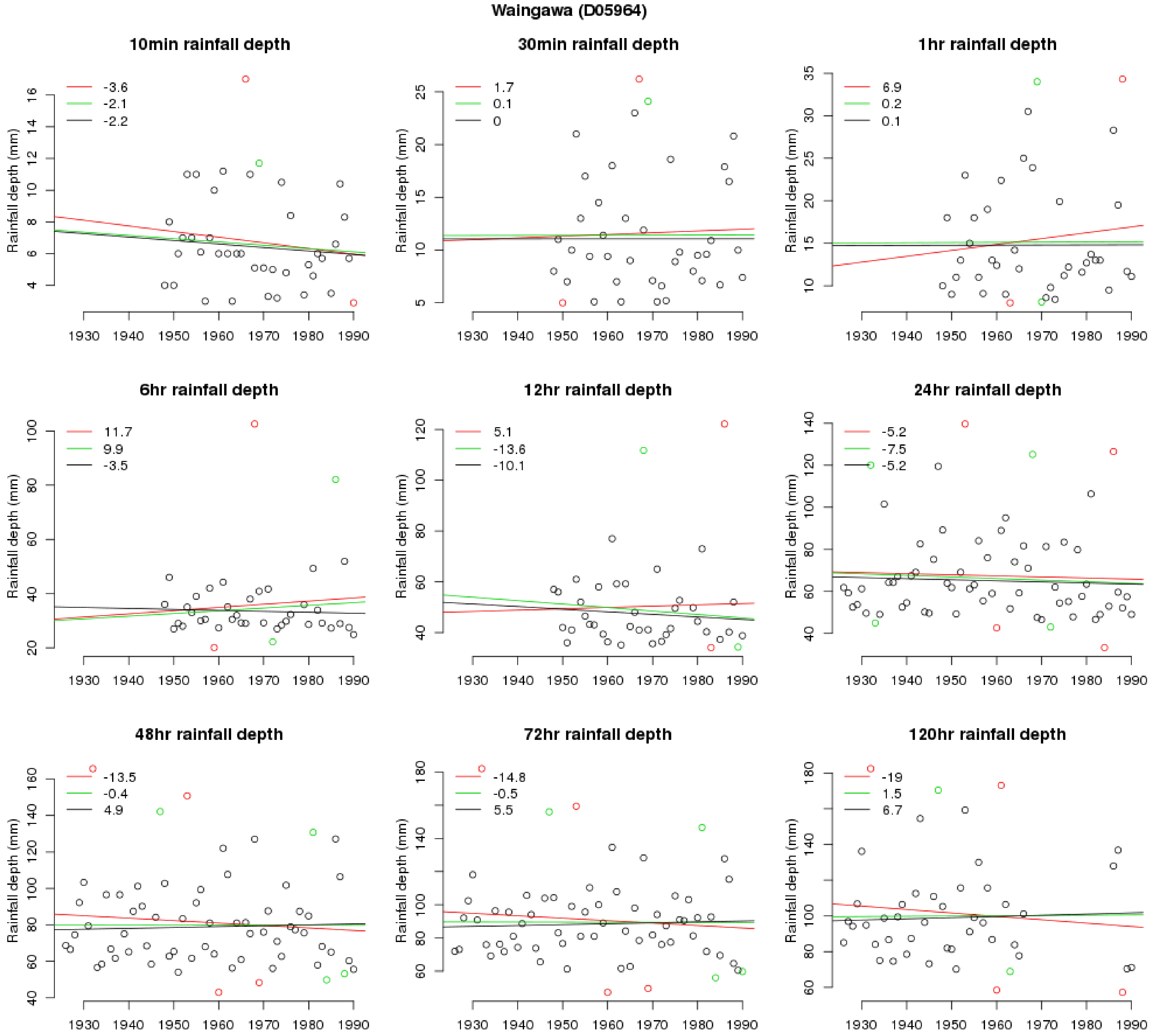


Figure 4-24: As Figure 4-21, except for Waingawa (near Masterton). For Waingawa, the sub-daily record spans 1948—1990 and the daily record spans 1926—1990.

4.5.2 Future projections for extreme rainfall in Wellington

The High Intensity Rainfall Design System provides rainfall depths for a range of event durations and frequencies on a two square kilometre grid covering New Zealand. These historical rainfall surfaces are derived by applying a regional index-frequency extreme value analysis to a large number of rain gauge records. Full details of this procedure can be found in Carey-Smith et al. (2018).

GWRC has been provided with individual maps and GIS data files for all four RCPs, historic and future time periods, for rainfall event durations of 10 minutes, 1 hour, 6 hours, 1 day, 3 days, and 5 days. Maps and GIS files have been provided for the 1-in-50-year rainfall depth and 1-in-100-year rainfall depth. Due to the large number of maps, only a subset of these have been analysed in the report below.

Figure 4-25 to Figure 4-28 show the 1-in-100-year rainfall depth for 10-minute, 1 hour, 1 day and 5-day duration events. As well as the historical surface, scenarios based on RCP4.5 at end-century and RCP8.5 at mid- and end-century are also shown. These are derived by applying the relevant percentage change factor (Table 4-7) to the historical surface, where the temperature anomaly for the given RCP time-slice is based on NIWA's regional climate modelling results (see Table 8 from Carey-Smith, et al. 2018).

Only one mid-century RCP (RCP8.5) is shown as the temperature difference between the RCPs over this time-slice is very small. By the end of century, however, the change in temperature, and therefore extreme rainfall, between the four RCPs is considerable. The differences due to climate change are much more pronounced for the short duration events than for longer durations.

There is a consistent spatial pattern of the largest rainfall depths occurring in the high elevation parts of the Wellington Region: the Tararua Ranges, the Remutaka Ranges, and the Aorangi Ranges. The smallest rainfall depths generally occur on the Wairarapa Plains. Although the rainfall depths for the longer duration events are much larger than for the shorter duration events, the proportional increase of rainfall depth within event durations is much larger for shorter events than longer events, per Table 4-7: 13.6% per degree of warming for 1-hour duration, 100-year return period events vs. 6.1% for 120-hour (5-day) duration, 100-year return period events.

Understanding changes in short duration extreme rainfall events is still an active area of research and the exact mechanisms that lead to the relatively larger increases are not fully understood. However, it is clear that as well as the expected thermodynamic changes resulting from a warmer atmosphere (i.e. the Clausius-Clapeyron relationship), changes in dynamic processes can also contribute to increased extremes. For instance, changes in vertical velocity (Pfahl et al., 2017) which can lead to the intensification of short duration convective activity (Prein et al., 2017).

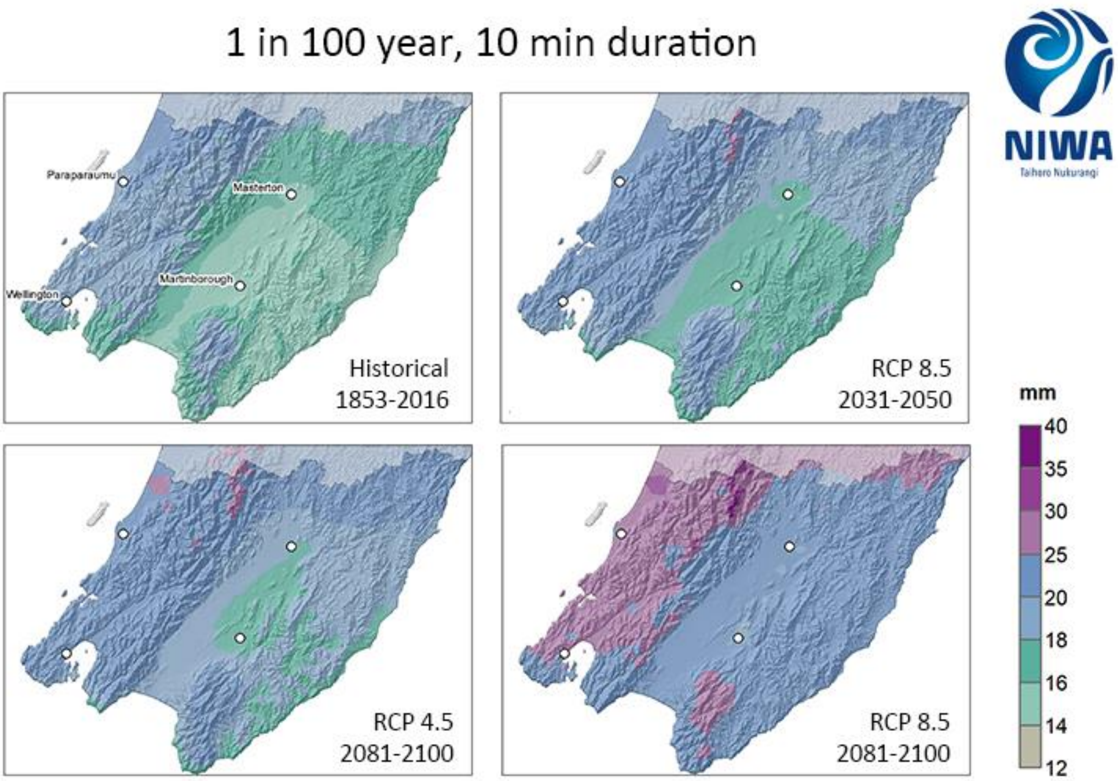


Figure 4-25: 10-minute duration, 100-year magnitude rainfall depths under historical conditions and for RCP8.5 at 2040 and RCP4.5 and RCP8.5 at 2090, for the Wellington Region.

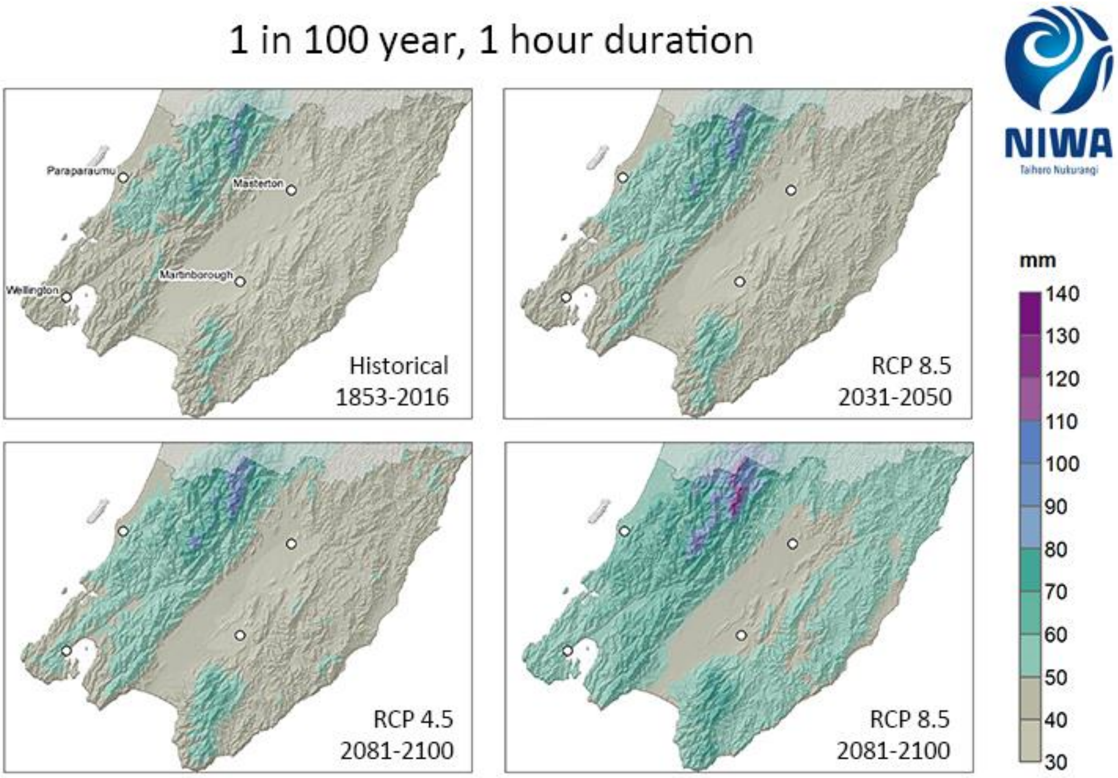


Figure 4-26: 1-hour duration, 100-year magnitude rainfall depths under historical conditions and for RCP8.5 at 2040 and RCP4.5 and RCP8.5 at 2090, for the Wellington Region.

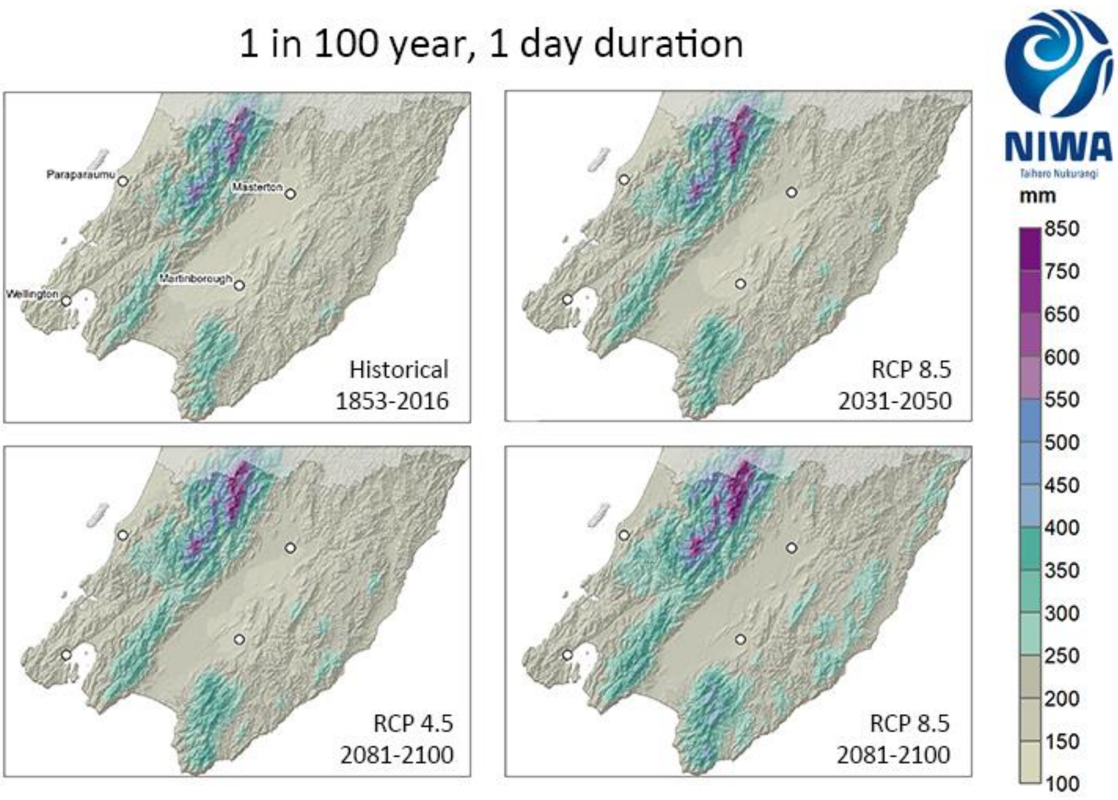


Figure 4-27: 1-day (24-hour) duration, 100-year magnitude rainfall depths under historical conditions and for RCP8.5 at 2040 and RCP4.5 and RCP8.5 at 2090, for the Wellington Region.

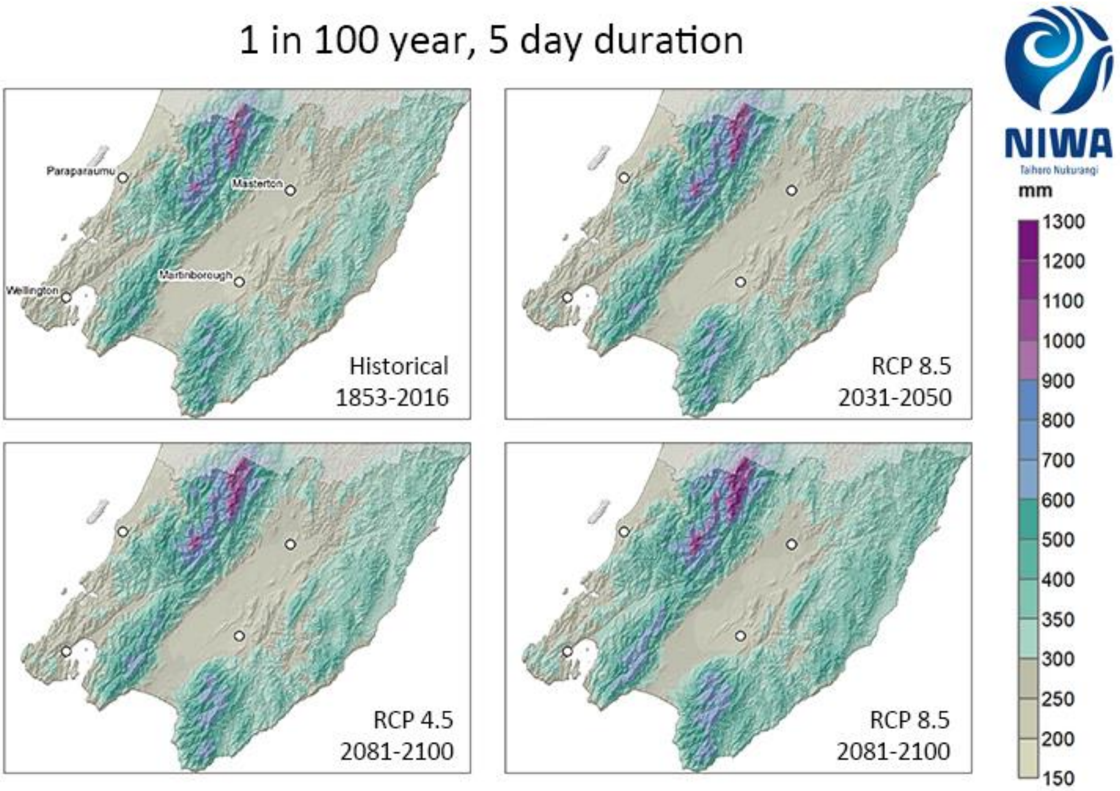


Figure 4-28: 5-day duration, 100-year magnitude rainfall depths under historical conditions and for RCP8.5 at 2040 and RCP4.5 and RCP8.5 at 2090, for the Wellington Region.

5 Other extremes

5.1 Additional analysis of extreme temperatures

5.1.1 Historical trends in station temperature extremes

In Section 3, projections of changes in temperature extremes were provided for a selection of thresholds. Figure 5-1 provides a historical perspective by showing how the same extremes have changed since 1910 at the two seven-station locations within the Wellington Region; that is, for Masterton and Wellington (Kelburn).

The analysis makes use of recent digitisation of early historical temperature data not yet available on NIWA's Climate Database. Time series of daily maximum and minimum temperatures were appended in the same way as noted in the seven-station report for monthly mean temperatures (Mullan et al., 2010). A simple first-order homogenisation was applied by using the same adjustments as Mullan et al. (2010) calculated for the monthly temperatures. Note that these recently digitised data have not been quality controlled beyond simple outlier assessment.

Table 5-1 and Table 5-2 show the periods and adjustments applied to build up the homogeneous records at Masterton and Kelburn. Note that adjustments are different for maximum and minimum temperatures. An important caveat is that the daily data have only been adjusted by the average monthly offsets. An improved (second-order) homogenisation would consider changes in the width of the normal distribution about the means which could be important when considering extremes, but this was outside the scope of this work. A further improvement, which might be investigated in future, is to consider how the distribution of daily temperatures varies with weather types (i.e. typical synoptic weather situations that New Zealand experiences, after Kidson (2000)).

Table 5-1: Site information and adjustments applied to the Masterton daily temperature record. The East Taratahi site is the 'reference' site, and therefore has zero adjustment.

Site Name (Agent Number)	Period	Maximum temperature Adjustment (°C)	Minimum temperature Adjustment (°C)
Workshop Road, Masterton (2473)	Feb 1912 to May 1920	-1.0	-0.1
Essex Street, Masterton (2473)	Jun 1920 to Nov 1942	-0.2	-0.4
Waingawa substation (2473)	Dec 1942 to Dec 1990	+0.2	-0.3
East Taratahi AWS (2612)	Jan 1991 to Oct 2009	0.0	0.0
Martinborough EWS (21938)	Nov 2009 to Present	+0.2	-0.8

Table 5-2: Site information and adjustments applied to the Wellington daily temperature record. The Kelburn (Wellington Botanic Gardens) site is the 'reference' site, and therefore has zero adjustment.

Site Name (Agent Number)	Period	Maximum temperature Adjustment (°C)	Minimum temperature Adjustment (°C)
Buckle St, Mount Cook (3431)	Jan 1909 to Jun 1912	-0.4	-1.1
Thorndon Esplanade (3391)	Jul 1912 to Dec 1927	-1.1	-0.7
Kelburn (3385)	Jan 1928 to Aug 2005	0.0	0.0
Kelburn AWS (25354)	Sep 2005 to Present	0.0	-0.1

Subject to this caveat, Figure 5-1 shows the time series of extremes for selected thresholds, as follows:

- Maximum temperature: Cold days < 10°C, Hot days > 25°C, Hot days > 30 °C
- Minimum temperature: Warm nights > 15°C, Cold nights < 5°C, Frosts (< 0 °C)

The time series were calculated by first counting the extremes for each calendar year (pro-rating if there were significant blocks of missing data in the summer or winter months), and then averaging the annual count over each decade from the 1910s to 2010s. The first decade (1910s) has only 8 years (1912-1919) for Masterton, and the last decade (2010s) has only nine years (2010-2018).

There is a significant difference between the Kelburn and Masterton sites in terms of the average number of extremes: Masterton experiences both hotter days and colder nights than Kelburn, a distinguishing feature found in many parts of New Zealand between inland and west coast sites. Decadal variability is apparent, as are some trends.

For maximum temperature:

- Cold days < 10°C: a decrease in the number of cold days at both sites since the 1930s.
- Hot days > 25°C: not much of a trend.
- Hot days > 30 °C: a lot of variability from decade to decade at Masterton, and very few occurrences of extreme hot days above 30°C recorded at Kelburn.

For minimum temperature:

- Warm nights > 15°C: an increase in the number of warm nights at both sites since the 1930s and 1940s.
- Cold nights < 5°C: a decrease in the number of cold nights, with the trend more evident at Kelburn.
- Frosts (< 0 °C): a general decline in frost occurrence over time at Masterton, with very low occurrences at Kelburn.

Table 5-3 and Table 5-4 show significant trends in the annual counts displayed graphically by decade in Figure 5-1. For maximum temperature, the reduction in cold days (maximum below 10°C) is statistically significant at the 95% level, but the hot day trends are not significant. For minimum temperature, trends in all three statistics are significant: warm nights > 15°C are increasing, cold nights < 5°C are decreasing, and frosts are decreasing. The sign of all trends is consistent with an overall warming of the climate.

Table 5-3: Trends in daily minimum temperature extremes over 1912-2018 at Wellington and Masterton. Trends are in "days per decade", and are shown only where statistically significant at the 95% level. Trends are calculated from 1912, since Masterton has no data for 1909-1912. Years with 30 days or more missing are not included. Time series of trends are shown in Figure 5-1.

	Warm Nights > 15°C		Cold Nights < 5°C		Frosts < 0°C	
	Wellington	**Masterton**	**Wellington**	**Masterton**	**Wellington**	**Masterton**
Trend (days/decade)	+1.4	+0.9	-3.3	-2.2	-0.4	-1.6

Table 5-4: Trends in daily maximum temperature extremes over 1912-2018 at Wellington and Masterton. Trends are in "days per decade", and are shown only where statistically significant at the 95% level. Trends are calculated from 1912, since Masterton has no data for 1909-1912. Years with 30 days or more missing are not included. The 'x' in the table are shown where the trend is not statistically significant at the 95% level. Time series of trends are shown in Figure 5-1.

	Cold Days < 10°C		Hot Days > 25°C		Hot Days > 30°C	
	Wellington	**Masterton**	**Wellington**	**Masterton**	**Wellington**	**Masterton**
Trend (days/decade)	-1.3	-2.0	x	x	x	x

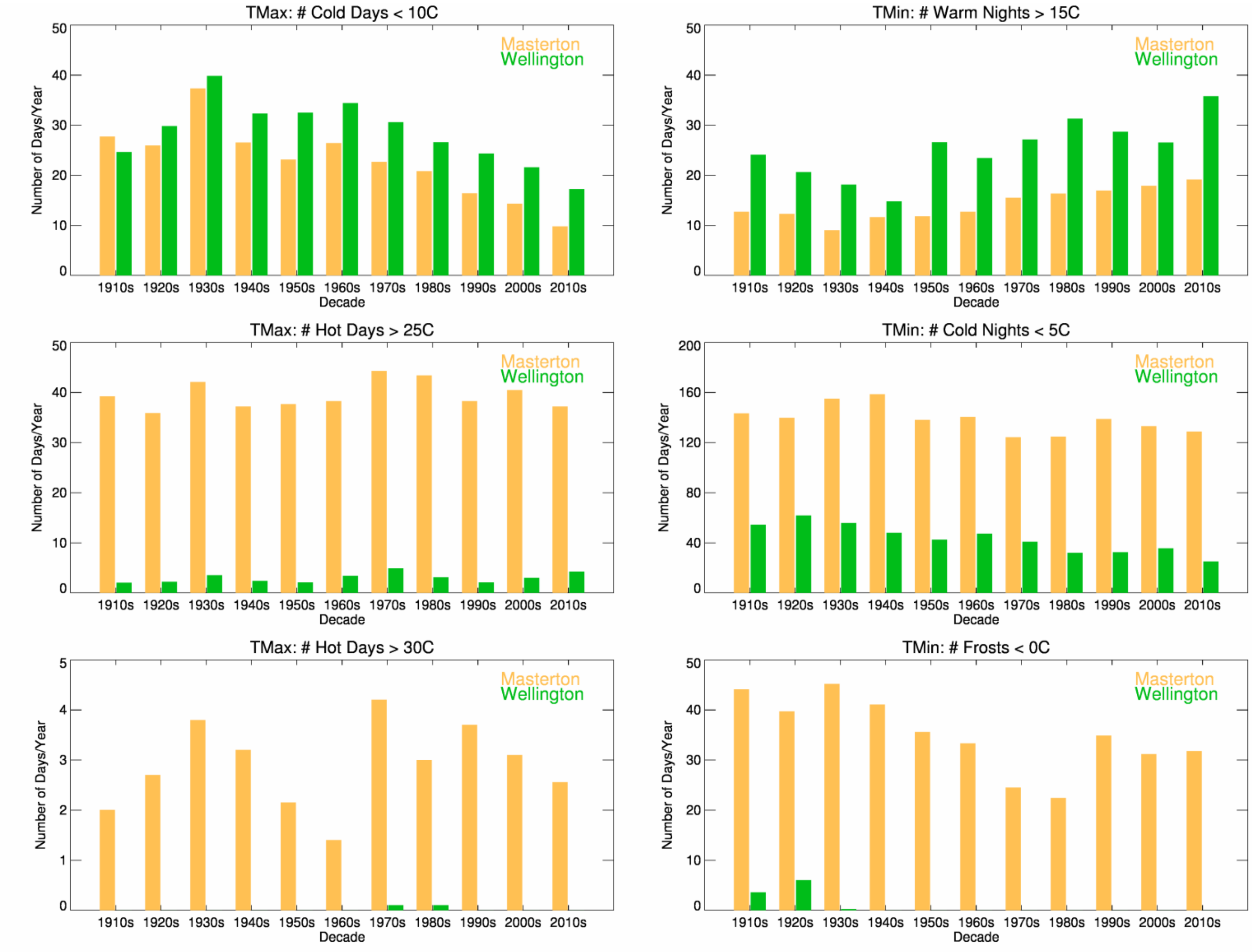


Figure 5-1: Annual-average (in days), for each decade from 1910-1919 to 2010-2018 of extremes for maximum (left) and minimum (right) temperature, as indicated.

5.1.2 Temperature extremes in Wairarapa from very large model ensembles (weather@home)

Key messages

- Very large ensembles of model (HadRM3P) simulations project an increasing number of 'hot days' (maximum temperature >25°C) in a 1.5-degree warmer future, and more again in a 2-degree future, for the Wairarapa region.
- These model results project changes to climate extremes of the Wairarapa region under 1.5 degrees and 2 degrees above pre-industrial temperatures (compared with the regional climate model results which project changes to extremes compared to 1986-2005 conditions).
- When comparing the means, approximately 15 more hot days per year are projected in the 2-degree world (compared to the current decade), while at the absolute extreme high end of the distribution approximately 20 more hot days are projected.
- Increasing numbers of 'warm nights' (minimum temperature >15°C) are also projected for the Wairarapa region in the 1.5-degree future, and more again in the 2-degree future.
- When comparing the means, approximately 15 more warm nights per year are projected in the 2-degree world (compared to the current decade), whilst at the extreme high end of the distribution the change in the 2-degree world (compared to current decade) is smaller than for hot days.
- It is projected that relatively more time will be spent in >25°C heatwaves (for periods of up to about 10 days) in the 1.5-degree future, and more again in the 2-degree future.

Information in this report on temperature extremes as revealed by dynamical downscaling of global climate models with NIWA's Regional Climate Model (Section 3) can be complemented by use of very large ensembles of simulations from the weather@home experiment (Massey et al., 2015). These weather@home ensembles use a model with lower spatial resolution (50 km) than the downscaled RCM results (5 km), but which has been run thousands of times. Hence, spatial detail has been sacrificed in order to radically improve our knowledge of climate and weather statistics (it is currently not computationally feasible to achieve both simultaneously). Although the weather@home approach is still very useful for investigating mean climate, the large size of the ensembles, and the enhanced statistical information, means these datasets lend themselves well to exploring climate and weather extremes and their uncertainties.

It is important to note that the weather@home results presented in this section have not been bias corrected as the regional climate model results have been. So, it is wise to use them to get a sense of the overall picture of projected changes (trends), rather than to provide particular values or thresholds. A further caveat is that, since it was deemed unwise to rely solely on information from one grid box only, the results presented here represent an average of three neighbouring grid boxes in the Wairarapa area. In a 50 km-resolution model this means the area averaged is potentially so large that it may not be fully representative of the region. However, it is encouraging that the results reported in this report (from the 3-gridbox average), and the general conclusions drawn, are broadly consistent with those that were analysed from the single grid box around Masterton (not shown).

The weather@home model used here is the U.K. Met. Office global atmospheric model HadAM3P (forced with SSTs), with the regional model HadRM3P for the Australia-New Zealand (ANZ) region embedded within it. The global model is of approximately 150 km resolution, whilst in the ANZ region it is about 50 km. The model was released to the general public via the distributed computing project 'climateprediction.net'; volunteers donated their spare PC processing time to return several thousand simulations (Allen, 1999). The results shown were taken from a stream of experiments performed under the 'HAPPI' project ('Half a degree Additional warming, Prognosis and Projected Impacts') (Mitchell et al., 2017). This project was established to respond to the call for detailed climate modelling, in particular of extremes, with 1.5 and 2 degrees warmer global temperatures than pre-industrial (the temperatures focused on by the 2015 Paris Agreement).

The weather@home ANZ model was run with greenhouse gas concentrations appropriate to the 'current decade' (2006-2015), and to the 2090s under both 1.5 and 2 degrees of warming (above pre-industrial). Note that the baseline period used here is different to the remainder of the report, which used the period 1986-2005. The weather@home model used greenhouse gas concentrations equivalent to RCP2.6 (for 1.5 degrees), and a combination of RCP2.6 and 4.5 (for 2 degrees), and hence do not represent particularly high emissions scenarios. For each of the three sets of experiments (current decade, 1.5 and 2 degrees), the model was run approximately 1800 times (about an order of magnitude more than the RCM simulations used in the rest of this report). Each model simulation was one year long – hence each of the three ensembles represents approximately 180 simulations per year for the ten years of the relevant decade.

The model results for the number of days per year with temperatures over 25°C ('hot days'), and how the model simulation results are distributed, for the Wairarapa area are shown in Figure 5-2. A clear shift is observed towards more hot days in the 1.5-degree world, and more again in the 2-degree world. Approximately 15 more hot days per year occur in the 2-degree world compared to the current decade (when comparing the means), and approximately 20 more hot days occur at the absolute extreme high end of the distribution. Note that the threshold of 25°C significantly impacts the shape of the distribution in the current decade, with a large number of simulations (just over 150) having no days in the year above this threshold. As mentioned previously, further work on bias correcting these datasets would be required to set the threshold adequately if absolute values were required.

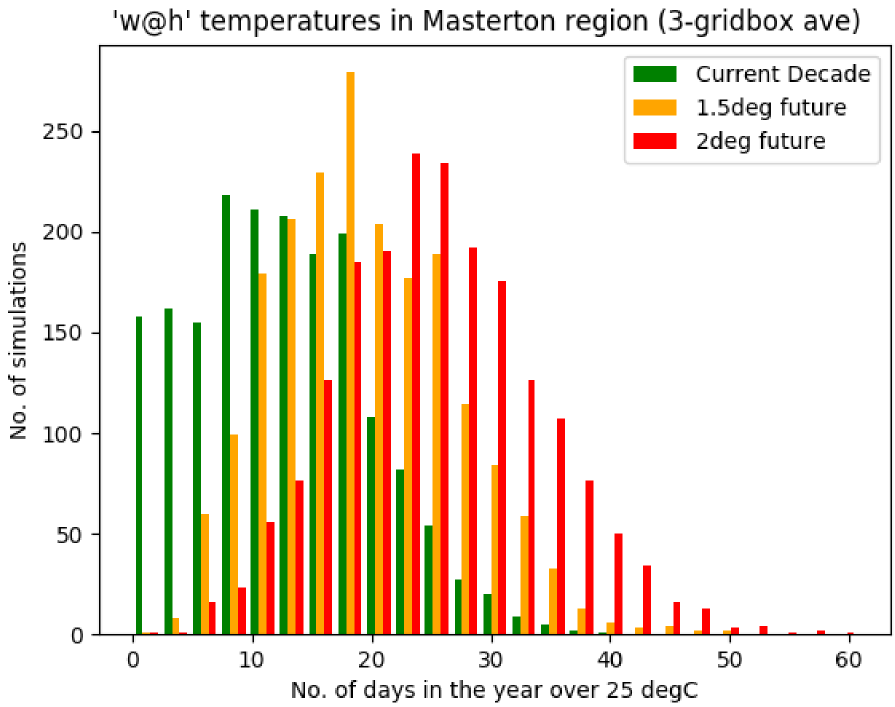


Figure 5-2: Distribution of weather@home ensembles for the number of hot days per year (Tmax >25°C) in the current decade, a 1.5-degree future and a 2-degree future.

The distributions for the number of nights per year over 15°C ('warm nights') is shown in Figure 5-3. A clear shift towards more warm nights is observed in the simulations, progressing from the current decade to 1.5-degree and 2-degree higher futures. Again, the shift in mean occurrence is approximately 15 more warm nights in the 2-degree world compared to the current decade, although the change in the 2-degree world (compared to current decade) at the high tail of the distribution (highest number of warm nights) is smaller than for hot days.

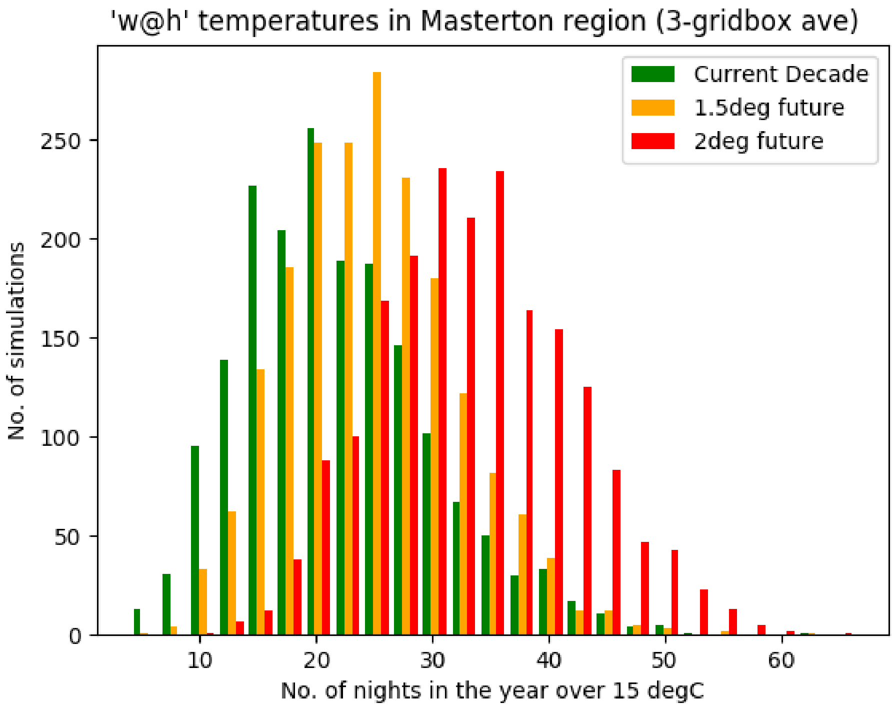
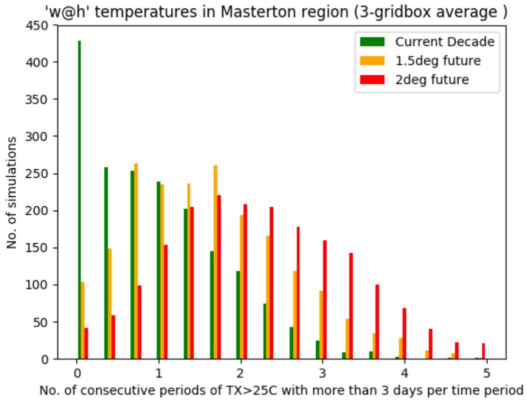


Figure 5-3: Distribution of weather@home ensembles for the number of warm nights per year (Tmin >15°C) in the current decade, a 1.5 degree future and a 2 degree future.

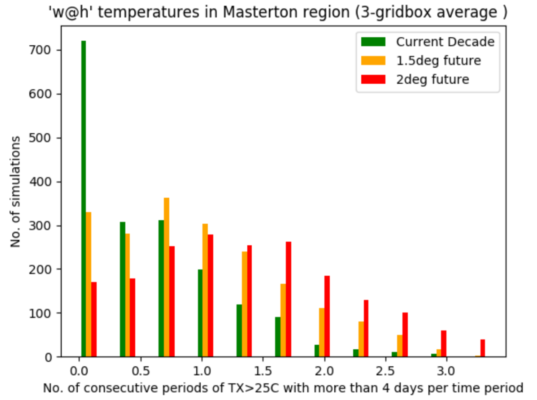
Figure 5-4 shows how heatwaves (defined as consecutive days over 25°C) are projected to change in the weather@home ensembles. Each panel shows how the model ensembles are distributed according to how many periods they have (per year, on average) of consecutive days over 25°C, where each period lasts at least 3 days (first panel), 4 days (second panel), 5 days (third panel) etc. In all, results are shown for periods of at least 3, 4, 5, 6, 7, 8, 9, 10, 15, and 20 days (10 panels in total). When results (not shown) were examined from a single model grid box over the Wairarapa, the numbers across the bottom of the graph (number of heatwave periods) were whole numbers. In Figure 5-4, however, since results have been aggregated for three grid boxes, these numbers can be non-integer (i.e. not whole numbers).

For heatwaves at least 3 days long in the current decade, most simulations have no heatwaves, while a very tiny number have the absolute extreme of nearly four 3-day heatwaves (Figure 5-3). In the 2-degree world, however, the largest number of simulations show 1.5-2 3-day heatwaves, and a small number at the absolute extreme show five of these events. The changes based on the current decade show more time will be spent in periods of heatwave at least three days long in the 1.5-degree world and even more again in the 2-degree world. The same general shift is observed for the heatwaves of at least 4, 5, 6, 7, 8, 9 and 10 days duration. There are virtually no occurrences of heatwaves longer than about 10 days in any model ensemble.

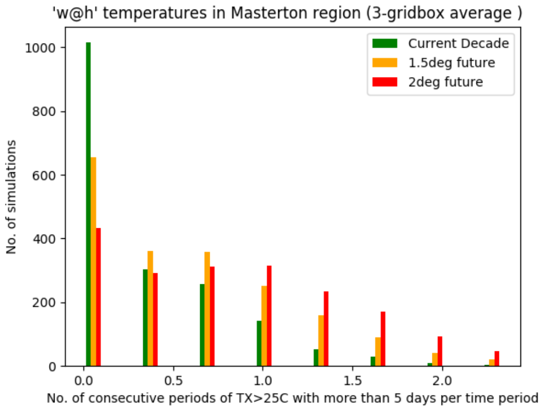
Heatwave length 3 days



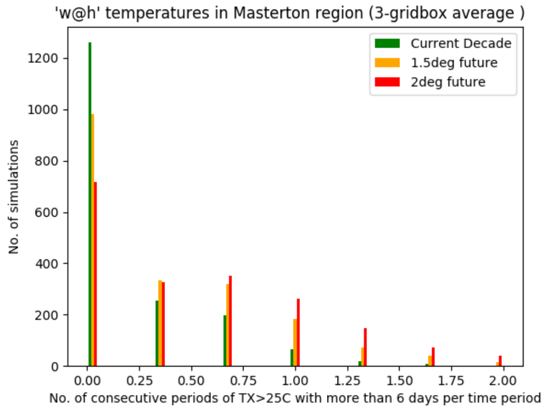
Heatwave length 4 days



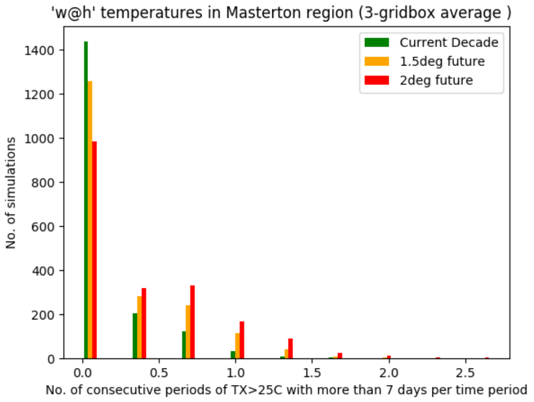
Heatwave length 5 days



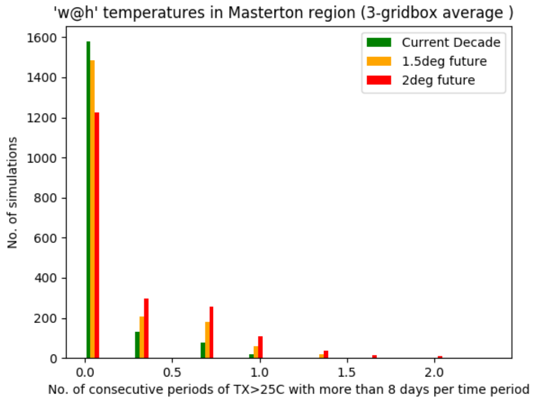
Heatwave length 6 days



Heatwave length 7 days



Heatwave length 8 days



(Figure continued overleaf)

Figure 5-4: Distribution of weather@home ensembles for different heatwave lengths (consecutive days >25°C) in the current decade, a 1.5-degree future and a 2-degree future.

As discussed previously, limits to computational resources require the trade-off between spatial detail and sample size. The downscaled RCM results presented earlier in this report represent much more spatially detailed modelling than the weather@home results; however, the RCM sample size is significantly smaller (at least an order of magnitude). This may not be such an issue when considering mean climate states, but when looking in particular at climate extremes caution should be exercised. In Section 3, results from the RCM sample were averaged, in order to provide absolute numbers for the projected trends in extremes. In the case of the weather@home results, we have chosen to display the full distribution of around 1800-member ensembles and highlight overall key messages, in part also because these data were not bias-corrected in any way.

The two different modelling approaches do reinforce similar overall key messages: The Wairarapa area is expected to experience more hot days and warm nights in a 1.5-degree warmer future compared to the present day, and even more so in a 2-degree future. Also, it is projected that relatively more time will be spent in >25°C heatwaves (for periods of up to about 10 days) in the 1.5-degree future, and more again in the 2-degree future.

5.1.3 Summer 2017/18 extreme temperatures

The summer of 2017/18 was New Zealand's hottest summer on record (NIWA, 2018), according to NIWA's "seven-station" temperature record (Mullan et al., 2010) which begins in 1909. The very next year, in 2018/19, New Zealand experienced its third hottest summer (NIWA, 2019). In both summers, sea surface temperatures were also unusually warm in the Tasman Sea and east of the country, although again the 2017/18 summer was exceptional (Bureau of Meteorology and NIWA, 2018).

Figure 5-5 shows the seven-station time series for each December-January-February (summer) since the start of that series in 1909/10. The hottest national temperature is 2017/18 with an anomaly of +2.12°C relative to the 1981-2010 climatology, followed by 1934/35 (+1.82°C), then two summers almost equally warm, 2018/19 (+1.20°C) and 1974/75 (+1.16°C). There is a clear warming trend over time in Figure 5-5 consistent with global warming patterns, but the fact that the second warmest summer occurred 84 years before 2017/18 shows that factors in addition to anthropogenic warming play a role in guiding regional temperature anomalies.

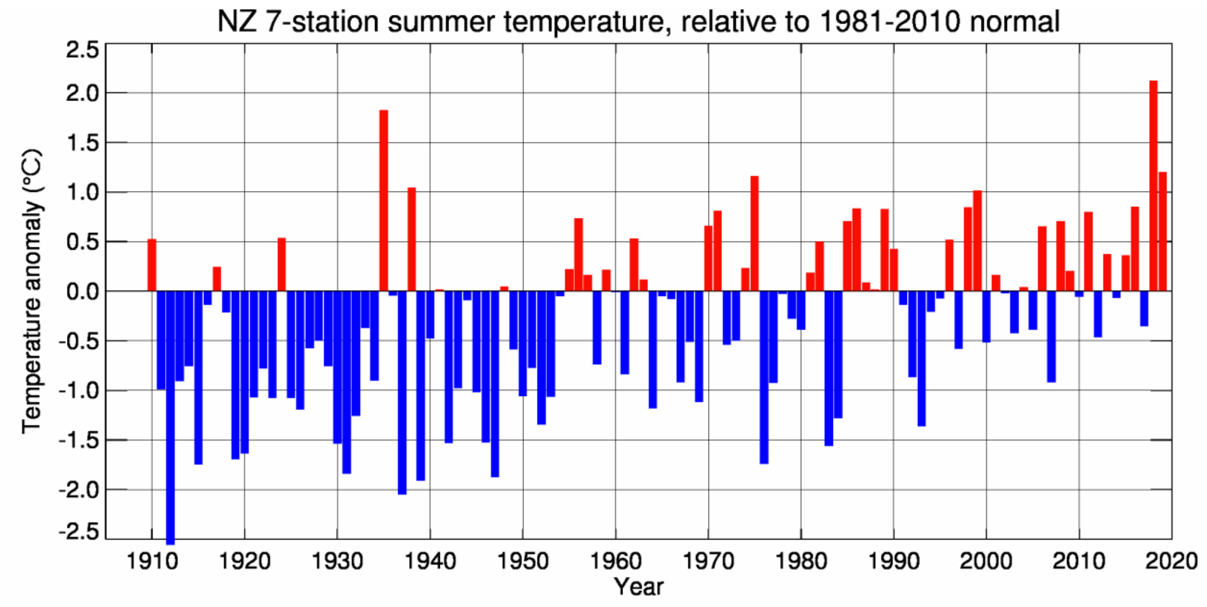


Figure 5-5: New Zealand 7-station summer temperature anomaly 1909/10 to 2018/19. The year marked on the horizontal axis represents the Jan-Feb year of the relevant summer.

The accompanying sea-surface temperature (SST) anomalies are shown in Figure 5-6. For the three-month period as a whole (December 2017-February 2018), SST anomalies exceeded 2°C above normal to the west of the South Island (Figure 5-6, left), based on monthly interpolated observations from ERSST version 5 (Huang et al., 2017). The time series generated by averaging SSTs over the inset box of Figure 5-6 (left) shows that the 2017/18 summer was clearly the warmest summer in the seas immediately around New Zealand (Figure 5-6, right). Again, the 1934/35 summer stands out as second warmest.

On the annual time-scale, 2016 is the warmest year so far (up to December 2018) in the seven-station temperature record, with 2017 in 6th place. Neither 1934 or 1935 were particularly warm as a whole; it was the November 1934 to February 1935 period that was exceptional, and so much so that the then-Director of the New Zealand Meteorological Service was motivated to write correspondence about the season (Kidson, 1935). Both the 1934/35 and 2017/18 summers had very similar sea-level pressure anomalies (Figure 5-7), showing a pattern of blocking (higher than normal pressure) to the east and southeast of New Zealand, with negative (low) pressure anomalies to the west and north of the country. This circulation anomaly not only produced more of a warm northerly airflow than usual, but also light winds in the Tasman Sea. An analysis of the 2017/18 event by Salinger et al. (2019) demonstrated that the lower wind speeds in the eastern Tasman Sea reduced upper ocean mixing and resulted in strong heat fluxes from the atmosphere to the ocean, producing substantial warming in a shallow stratified surface layer.

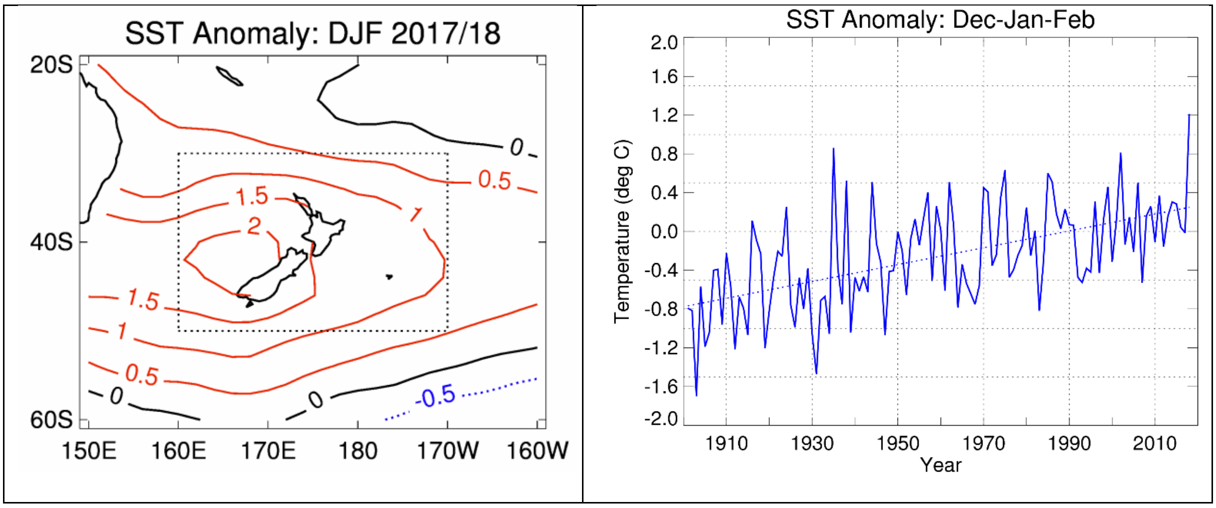


Figure 5-6: Sea-surface summer temperature anomalies from ERSSTv5, relative to 1981-2010 climatology: spatial pattern for 2017/18 (left) and time series (right) averaged over the inset (left) box from 1900/01 to 2018/18.

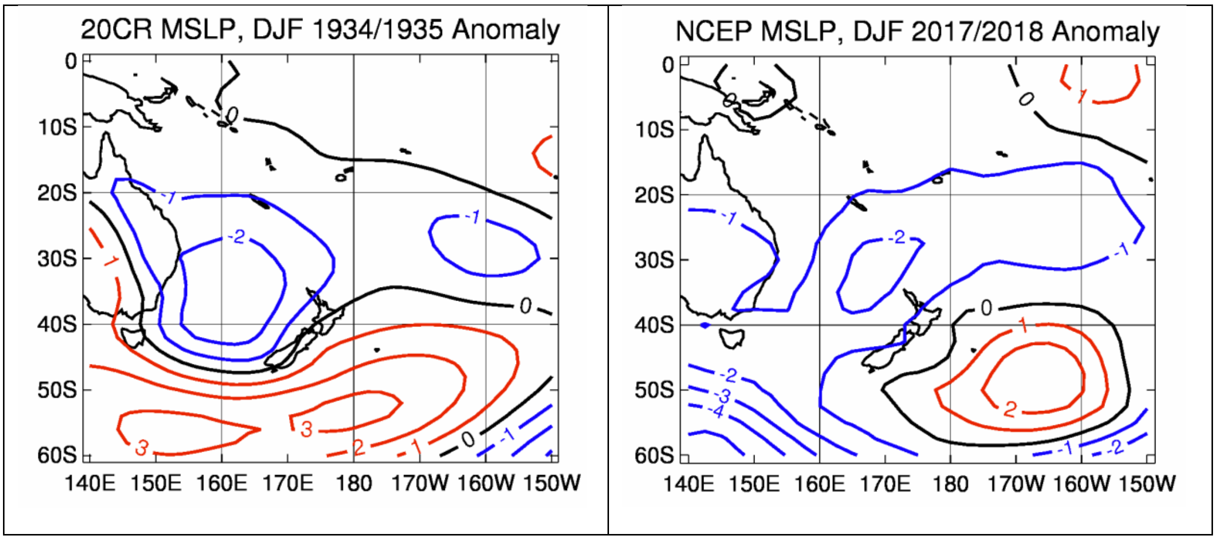


Figure 5-7: Mean sea-level pressure anomalies (in hPa), for the summers of 1934/35 (left) and 2017/18 (right), relative to the 1981-2010 climatology. Negative (positive) anomalies given by the blue (red) contours.

Thus, the extreme warmth of the 2017/18 summer was likely a consequence of two factors: global warming over the past 80 years or so, plus an unusually persistent pressure pattern over the eastern Tasman Sea that facilitated warming of ocean and land around New Zealand. Salinger et al. (2019) put the 2017/18 summer in the context of global warming by drawing on the projected trends of Ministry for the Environment (2018), claiming that the unprecedented heatwave of 2017/18 provided a good analogue for possible mean conditions late in the 21st century. The best match suggested this extreme summer may be typical of average New Zealand summer climate for 2081-2100, under the RCP4.5 or RCP6.0 scenarios. The RCP8.5 scenario would lead to even hotter conditions.

5.2 Drought

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[3] 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.

Annual accumulated PED was presented in Pearce et al. (2017). Another way of presenting this drought indicator, to get an idea of changes to extremes, is to present the probability of PED above a certain threshold. Here, we have chosen 300 mm as the threshold, which represents very dry conditions in the Wellington Region. Figure 5-8 shows the historic (1986-2005 average) probability that PED exceeded 300 mm in any year. The area around Martinborough has the highest probability of 300 mm PED being exceeded, with the annual probability being 40-60%. Around Wellington city, the annual probability is 5-10%. For most of the region including the west coast and higher elevation areas, the annual probability of PED exceeding 300 mm is very small, i.e. 0-5%.

In the future (Figure 5-9), the annual probability of PED exceeding 300 mm increases throughout the region except for the highest elevations of the Tararua Ranges. Note that Figure 5-9 shows future <u>absolute</u> probability of PED >300 mm, not change in probability. The increased probability of PED >300 mm is amplified with time and emission scenario. In the driest part if the Wairarapa near Martinborough (where current annual PED >300 mm probability is 40-60%), future probability ranges from 60-80% (under RCP2.6 and RCP4.5 at both future time periods) to 80-100% under RCP6.0 and RCP8.5 by 2090. This means that almost every year is likely to have PED exceeding 300 mm in this part of the region. Likewise, the area around Wellington city (which currently experiences an annual probability of PED >300 mm of 5-10%, may experience an annual probability of 20-40% under all scenarios and time periods except for RCP8.5 by 2090, where the annual probability increases to 40-60%.

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

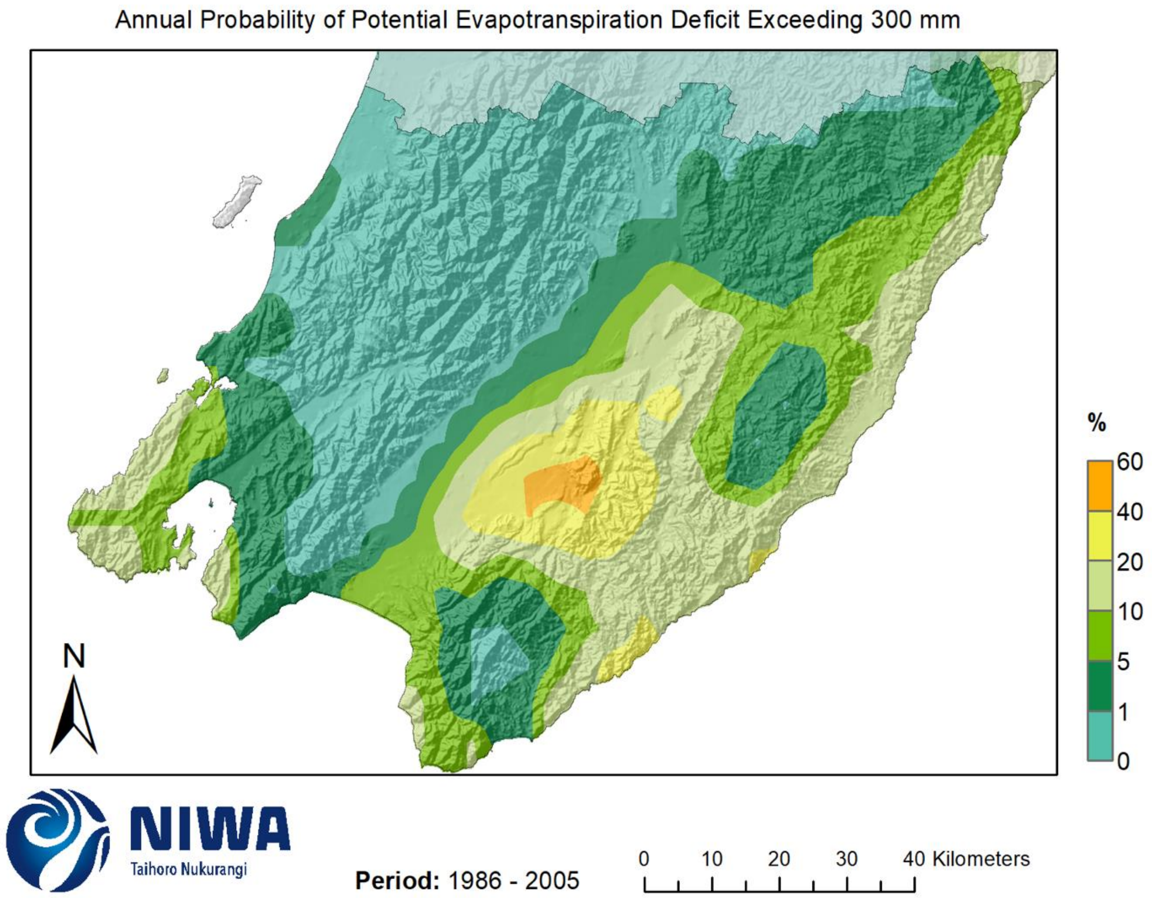


Figure 5-8: Modelled probability of Potential Evapotranspiration Deficit exceeding 300 mm in any year, average over 1986-2005. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

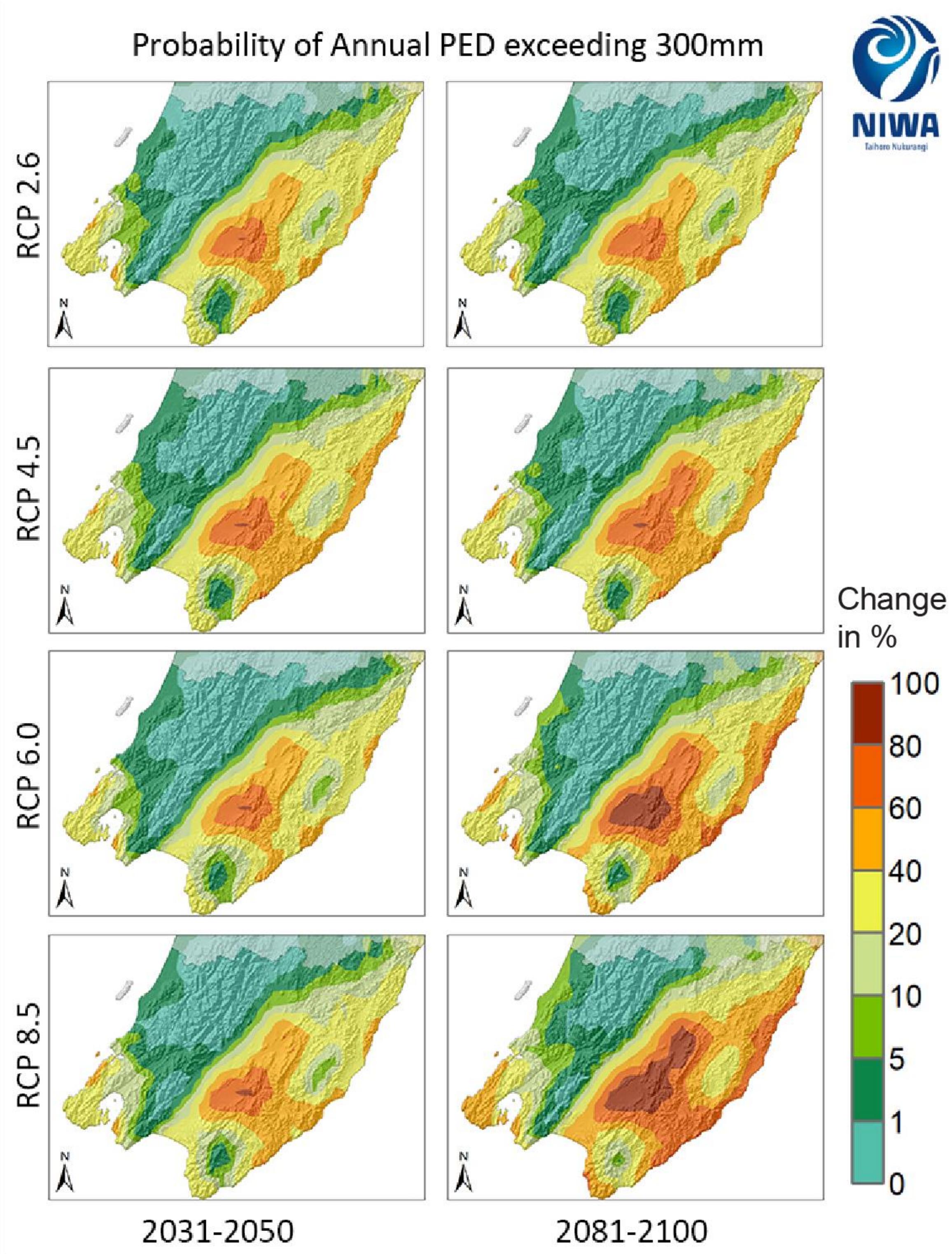


Figure 5-9: Projected probability of annual Potential Evapotranspiration Deficit exceeding 300 mm by 2040 and 2090. Relative to 1986-2005 average, for four IPCC scenarios, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

5.3 Extreme storm tide events in Wellington with sea-level rise

The Wellington Region's coastline is exposed to extreme storm tide events, and this exposure will increase further with sea-level rise. Figure 5-10 to Figure 5-15 show potential inundation in the most exposed parts of the Wellington Region for a 1% annual exceedance probability storm-tide event (i.e. a 1-in-100-year storm-tide event) with different sea-level rise elevations. The different elevations of SLR are mapped between 0 m (present sea level) and 1.5 m of SLR.

These maps were produced using LiDAR[4]-derived digital elevation models (DEM) of the Wellington Region. The historic 1% AEP storm tide event elevation and sea-level rise elevations were projected onto the DEM to show the inland extent of water under these different scenarios. See Paulik et al. (in preparation) for more details on the methodology used.

It is evident that parts of the region that are not likely to be affected by a 1% AEP storm tide event at present (inland of the light grey areas on the figures) may be affected in the future, depending on how far sea levels rise (green, blue and purple areas on the figures). For example, considerable parts of the Wellington CBD, Kilbirnie, Miramar, Petone, Otaki, Waikanae and east of Lake Wairarapa, are at risk from inundation during these types of extreme events.

Note that this inundation mapping method does not consider the potential amplifying effects of inundation from coastal erosion and waves. It also does not consider flood protection systems (e.g. stop banks) that may prevent passage of water - it only considers land which falls within the certain elevation bands.

[4] Light Detection and Ranging

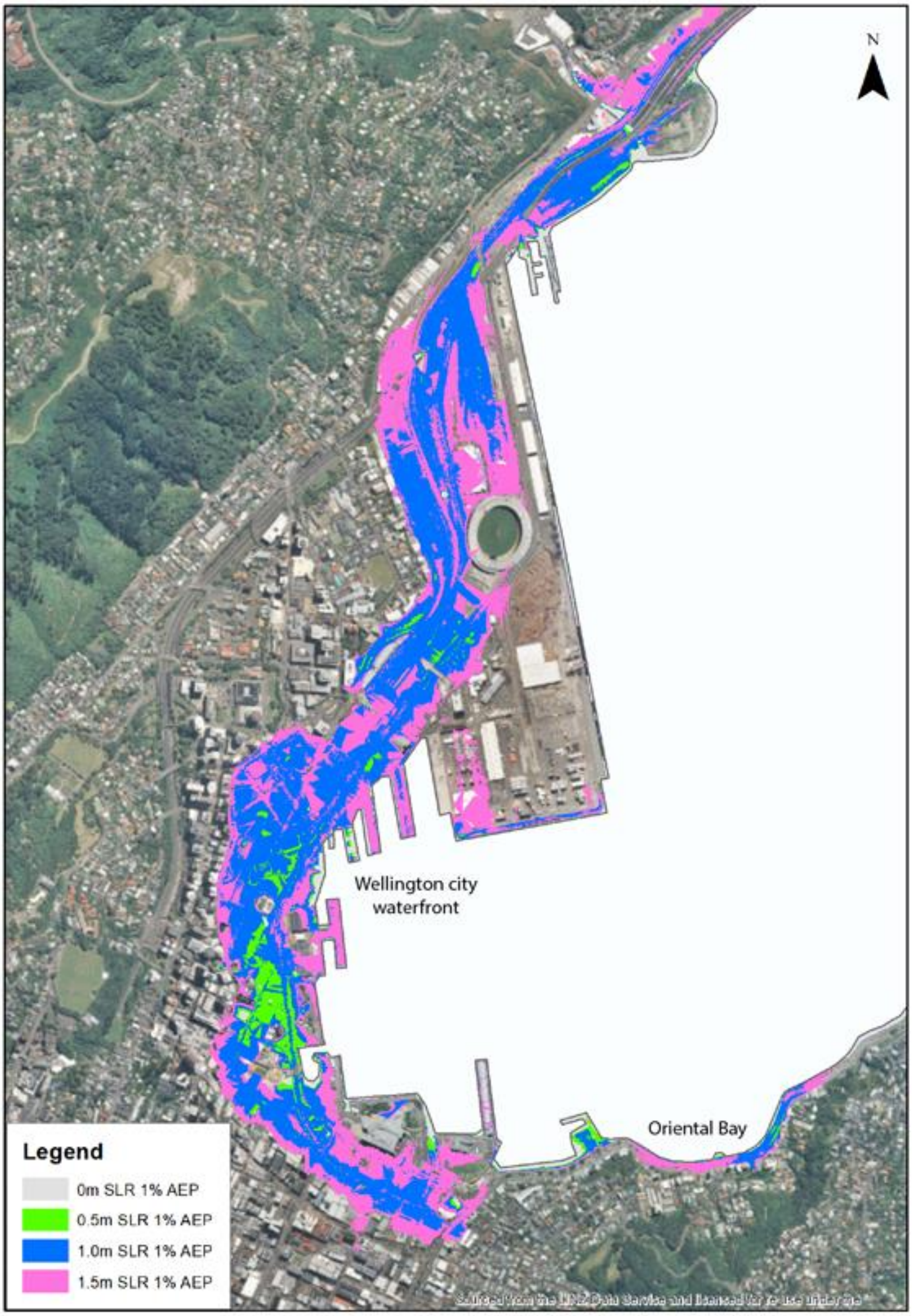


Figure 5-10: Wellington CBD exposure from a 1% Annual Exceedance Probability storm tide event at different sea level elevations. Source: NIWA.

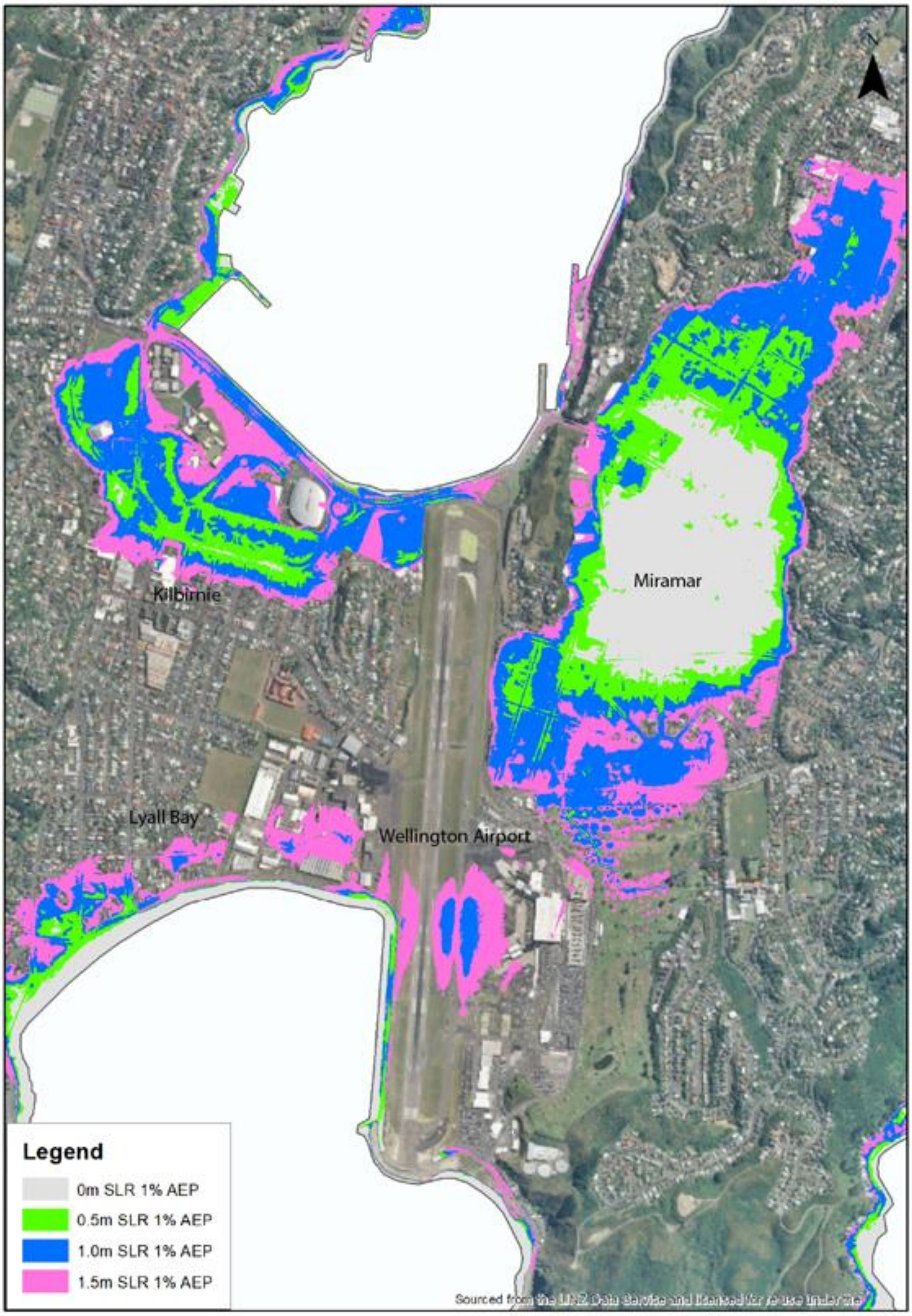


Figure 5-11: Rongotai, Kilbirnie and Miramar exposure from a 1% Annual Exceedance Probability storm tide event at different sea level elevations. Source: NIWA.

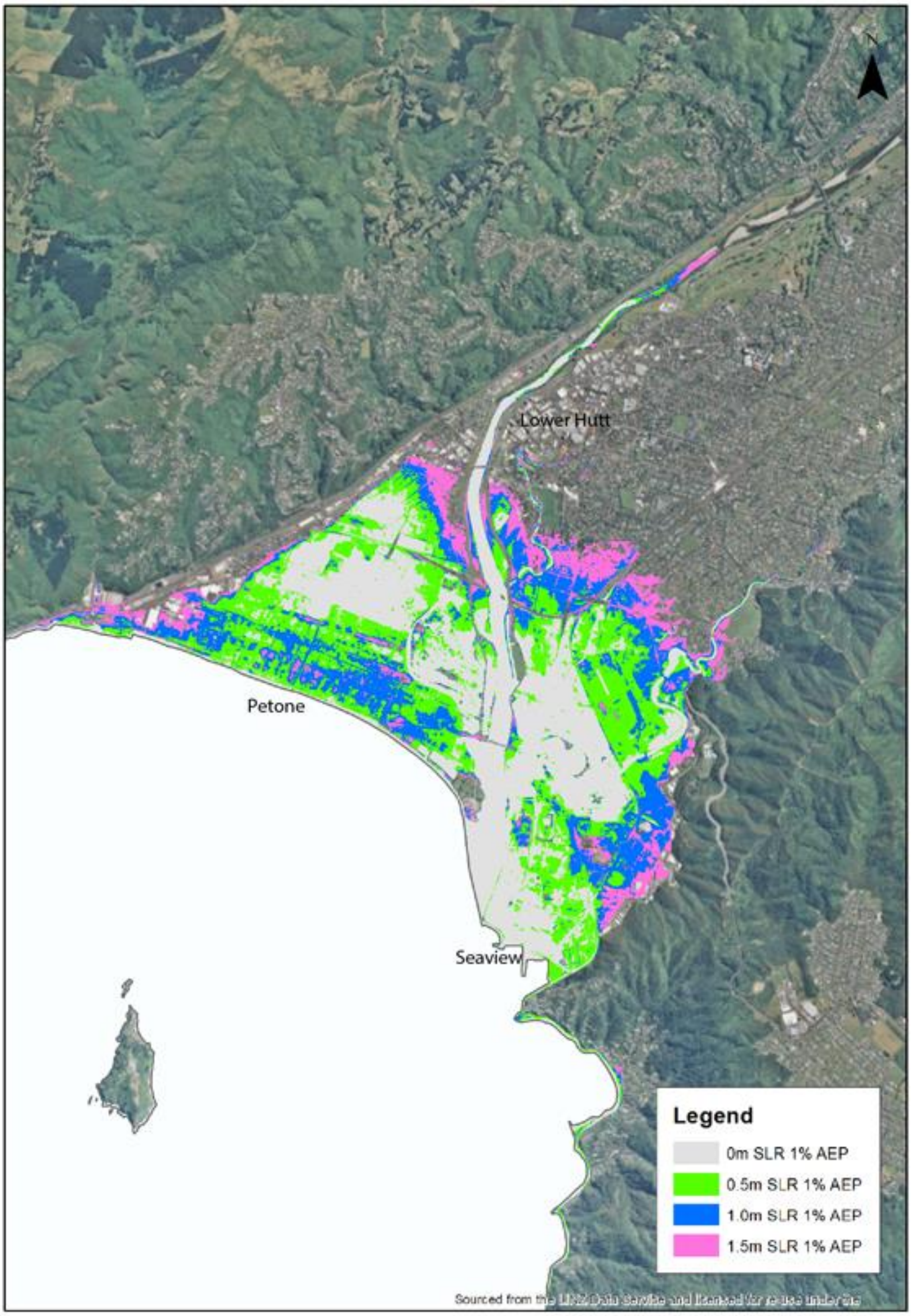


Figure 5-12: Petone and Lower Hutt valley exposure from a 1% Annual Exceedance Probability storm tide event at different sea level elevations. Source: NIWA.

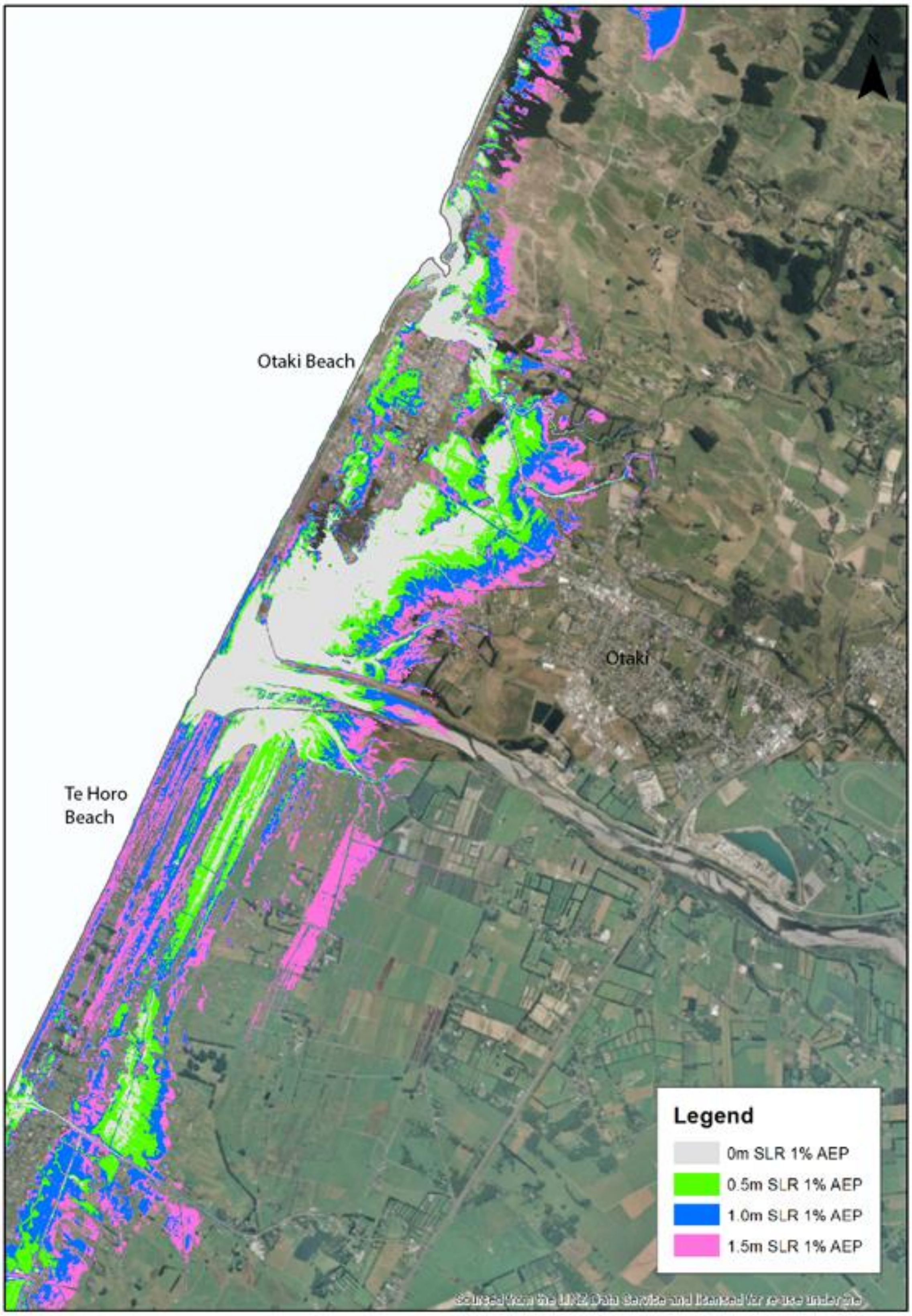


Figure 5-13: Otaki exposure from a 1% Annual Exceedance Probability storm tide event at different sea level elevations. Source: NIWA.

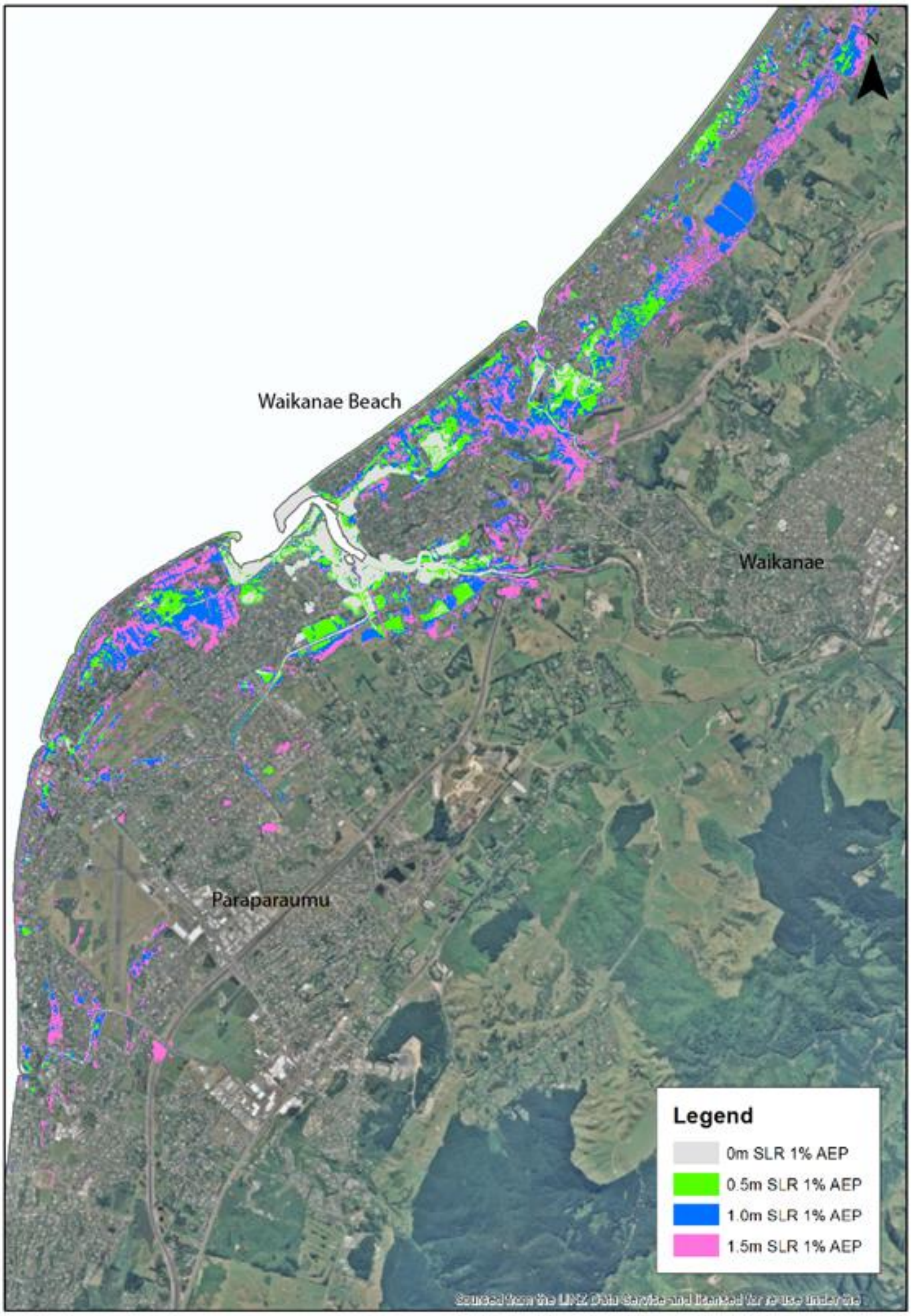


Figure 5-14: Waikanae exposure from a 1% Annual Exceedance Probability storm tide event at different sea level elevations. Source: NIWA.

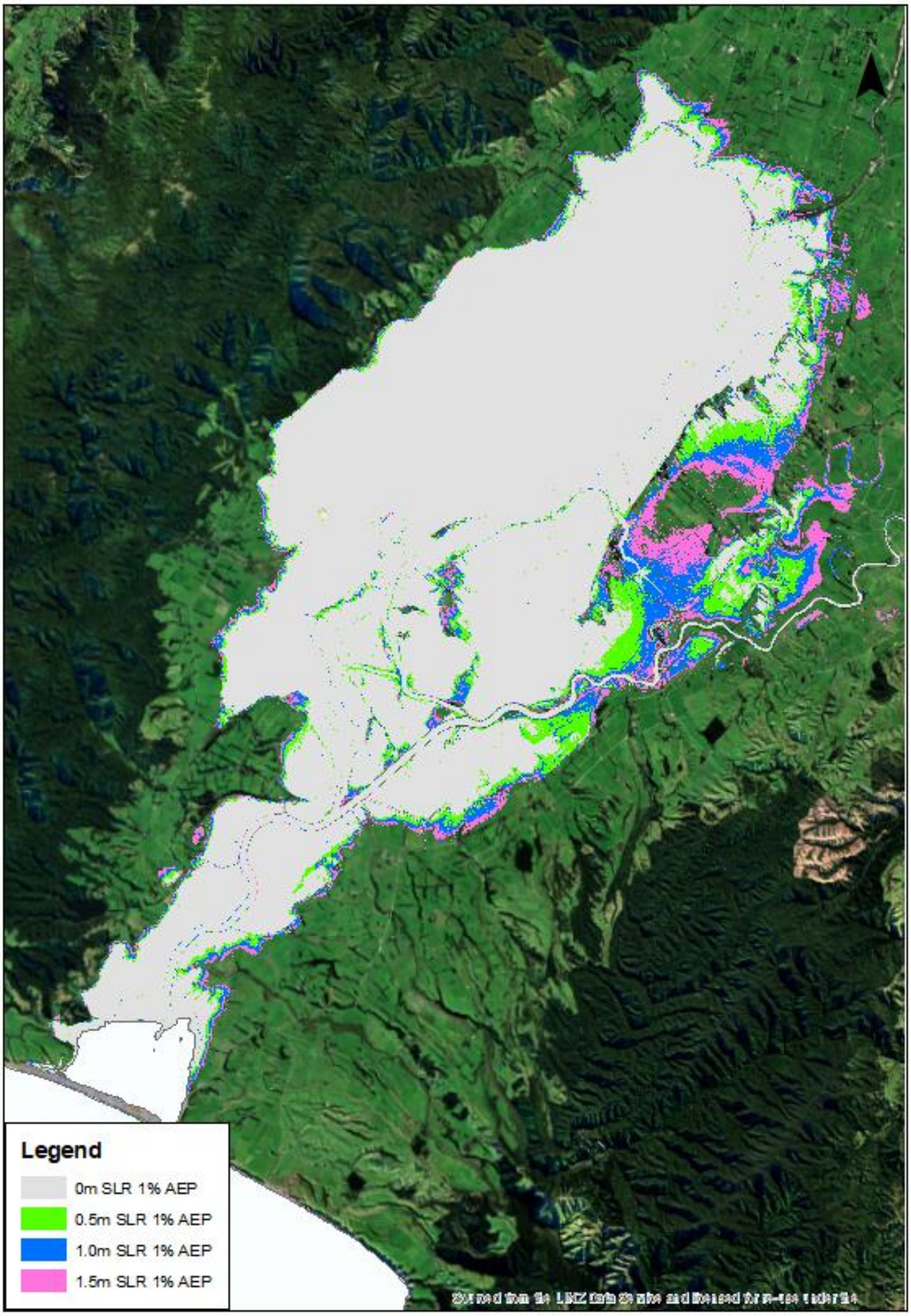


Figure 5-15: Lake Wairarapa surrounds exposure from a 1% Annual Exceedance Probability storm tide event at different sea level elevations. Source: NIWA.

6 Implications of changes in climate extremes

6.1 Implications for insurance

Key messages

- Private insurers may reduce or remove insurance cover from certain areas when the natural disaster risks related to climate change become more certain (e.g. sea-level rise)
- Insurance companies may continue to provide insurance to high risk areas, but premiums and excesses may increase significantly.
- Insurers could require that mitigation measures are put in place to protect assets before they can be insured.

The cost of weather-related hazards to the New Zealand insurance industry has increased over the past few decades (Figure 6-1). This cost is driven by multiple factors: population increase, higher value assets, investment in vulnerable areas (e.g. close to the coast or river mouths), and climate change, which has driven an increase in extreme weather events.

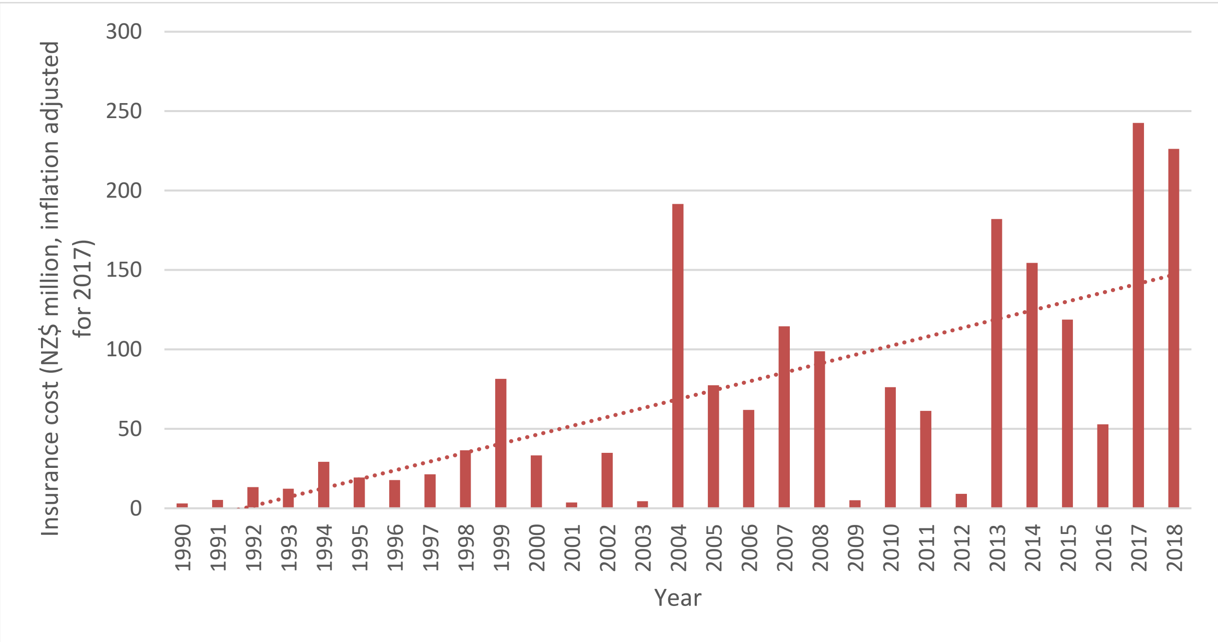


Figure 6-1: Insurance costs from weather-related hazards in New Zealand, 1990-2018. Data source: Insurance Council of New Zealand.

A report for The Treasury (Frame et al., 2018) found that climate change related floods and droughts has cost the New Zealand economy at least $120 million for privately-insured damages from floods and $720 million for economic losses from droughts between 2007 and 2017. Due to the methods used to determine these figures[5], they are likely to be a significant underestimate of the true costs (financial and non-financial) of climate change related floods and droughts during this period. The

[5] Methodological choices that may have contributed to the underestimate of true costs include the inclusion of only two weather-related hazards, the choices made regarding the attribution of droughts, the neglect of nonfinancial losses, and the use of insured damages rather than full economic losses for some events (Frame et al., 2018).

report provided an indication of cost as a starting point to considering the financial impact of climate change on extreme weather events. This fraction of attributable risk (FAR) of human-induced climate change to the cost of extreme events is expected to continue to increase over time with the increasing amount of greenhouse gases in the atmosphere and consequent human-induced climate impacts increasing over time (Frame et al., 2018). Note that a large research programme is starting in 2019 to better understand costs attributed to climate change-related hazards.

Although the cost to the insurance industry from weather-related hazards has increased over time, there is considerable variability from year to year (Figure 6-1). This is because severe weather events do not happen every year to the same extent, and the costs incurred for the insurance industry depend on the impact – for example a large storm causing flooding in sparsely populated Westland is unlikely to have the same financial impact as that same storm hitting an area of intensive development such as Auckland city.

Given this increasing cost of climate change related weather hazards (and weather hazards in general, due to the other factors listed above) to the New Zealand insurance industry, the industry is changing how it assesses risk. Traditionally, risk has been based on historic losses. However, because the frequency and intensity of extreme events are changing due to climate change, this makes historical data less relevant and therefore the categorisation of risk (and calculation of premiums) by insurance companies is made more difficult (Storey et al., 2018).

Over time, the nature of insurance cover may change in response to climate change. Insurance includes covering risk for which there is significant uncertainty. Therefore, once there is more knowledge about climate change related hazards (e.g. coastal inundation and large floods), insurers will retreat from certain areas (Storey et al., 2018). Insurance retreat by a single insurer can cause industry-wide retreat. Insurers may retreat from an area in New Zealand following a climate event in that location or in another location (so retreat is not only determined based on events happening in that specific location). In addition, New Zealand insurers are generally international companies, so climate related experiences in other countries may cause insurance retreat in New Zealand too. Insurance retreat could increase the risk to the Crown and decrease house prices as mortgages become unavailable (or costlier).

The New Zealand government's Earthquake Commission (EQC) provides insurance for property and contents damaged by natural hazards (climate and geologic). EQC land cover includes storm and flood hazards but excludes coastal erosion (EQC does not cover residential structures or contents from storms or floods, only land). EQC premiums are collected by private insurance companies and are embedded within residential insurance policies. Therefore, if private insurers retreat from certain areas, homeowners would need to apply directly to EQC for cover. This could increase the fiscal risk to the Crown, particularly if EQC is found liable for damage from storm surge related to climate change (and enhanced by coastal erosion) (Storey et al., 2018). In early 2019, IAG (the largest private insurer in New Zealand) announced it would introduce stricter criteria for issuing new policies for customers in earthquake-prone Wellington (Stock et al., 2019). While this move is not climate change related, something similar might be considered in the future for areas perceived to be at risk from climate change related hazards.

Private insurance companies may continue to provide insurance to high risk areas if they decide to differentiate between the high-risk areas and lower risk ones in terms of premium prices, excesses, or in the policy wording. This may be done at the property level. In early 2019, IAG announced that it would introduce risk-based pricing based on location, with customers in areas prone to weather-related natural hazards (e.g. floods and storms) charged more in their premiums than others in less risky areas (Parker, 2019).

Several parts of the Wellington Region are particularly exposed to climate change related hazards, which may be affected by changes to insurance cover in the future (i.e. rising premiums, excesses, or retreat of insurance cover altogether). Parts of the region that are particularly exposed to sea-level rise and coastal inundation include parts of Wellington City, Lower Hutt and Petone, Waikanae Beach and Otaki (Parliamentary Commissioner for the Environment, 2015, Section 5.3 of this report). River flooding could particularly affect parts of the Hutt Valley, Otaki, Waikanae, and settlements near the Ruamahanga River (and tributaries) and Lake Wairarapa[6]. Much of Wellington city is built on steep hillsides which could be at risk from landslips with increasing extreme rainfall events.

[6] Locations listed based on GWRC's flood hazard maps: https://mapping.gw.govt.nz/GW/Floods/

6.2 Implications for agriculture and horticulture

Key messages

- Increases in extreme heat may reduce milk production and cause crops to grow faster and ripen earlier. It may also affect water availability for plants due to increased evapotranspiration.
- Reductions in cold conditions may allow for expansion of warm climate varieties of crops to be grown in Wellington. However, there may be increasing risk of pests and diseases with a warmer climate.
- Extreme rainfall events may cause slips and landslides which reduce land productivity and create issues for connectivity to markets. Saturated soils cause issues for pastoral farming through animals compacting soil, and for growers through reductions in growth rates of vegetables.
- Increased prevalence of drought is likely to impact water availability for agriculture and horticulture, particularly in the Wairarapa.
- Increases in carbon dioxide concentrations may favourably influence growth rates of forestry, pasture and crops, however this may be offset by increasing drought conditions and high temperatures.

6.2.1 Increases in extreme heat and reductions in cold impacts

New Zealand's maritime climate and position in the southern mid-latitudes minimises the occurrence of very high temperatures like those observed >40°C in parts of Australia, Europe and the Middle East. However, occurrences of hot days in twenties and thirties are likely to become more frequent in the Wellington Region, as this report has shown in Sections 3 and 5.1. This is important because New Zealand's agricultural systems, animals, and plant varieties presently rely on a moderate climate with occasional hot days during summer. A change in the distribution of hot days may impact animal health, plant growth, and the efficiency of existing agricultural and horticultural systems.

Cattle experience heat stress in hot and humid conditions. Generally, the threshold for heat stress for Jersey cows is 25°C (Bryant et al., 2007). Heat stress results in reduced feed intake, which in turn results in lower milk production. Heat can also affect milk composition in terms of proportions of fats and proteins (Bryant et al., 2007). Farmers may have to consider adaptation strategies like providing more shade, water, and shorter walking distances to milk sheds. As cattle release heat during the night to cool down, increased numbers of warm nights may have a detrimental impact on their ability to do so.

Plant phenological development may occur at a faster rate with increasing extreme heat. Different stages of plant growth (e.g. bud burst, flowering, and fruit development) may happen at different times, which may affect the harvested crop. For example, the hottest summer on record for New Zealand in 2017/18 saw wine grapes in multiple New Zealand regions ripen faster than usual (Salinger et al., 2019). In Central Otago, this resulted in the earliest start to harvest of Pinot Noir grapes on record (almost a month earlier than usual). In Wairarapa, the period from flowering to harvest for wine grapes was about 10 days shorter than usual[7]. Some plants require winter chilling for increasing flavour (e.g. carrots) and prompting flowering (e.g. kiwifruit). Reductions in cold temperatures may impact the productivity of these varieties.

Extreme heat affects the rate of evapotranspiration, or the uptake of water by plants. Therefore, increases to extreme heat may affect water availability, as under hot conditions plants use more water than usual. Extreme heat may also result in current varieties of crops and pasture becoming unsustainable if they are not suited to growing in hot conditions.

Reductions in cold conditions may have positive impacts for diversification of new crop or grass varieties that are not able to currently be grown in the Wellington Region. For example, certain crops (e.g. kumara) are currently grown in warmer parts of New Zealand like Northland. However, in the future with a warmer climate there may be opportunities for growers in the Wellington Region to take advantage of the overall warmer climate to diversify their crops.

On the other hand, future warmer temperatures may create issues for current crop and grass varieties that are grown in the Wellington Region. Increasing risk from pests (plants and animals) and diseases is a concern. Currently, many pests are limited by cold conditions, so that they cannot survive low winter temperatures, and therefore their spread is limited (Kean et al., 2015). Under a warmer climate, these pests may not be limited by cold conditions and therefore cause a larger problem for farmers and growers in the Wellington Region.

6.2.2 Extreme rainfall and drought impacts

Increases in extreme rainfall event magnitudes may impact agriculture and horticulture in several different ways. Slips on hill country farmland may become more prevalent during these events, and soil erosion may also be exacerbated by increasing drought conditions (Basher et al., 2012). This has impacts on the quality of soil for agriculture and horticulture, the area of land available for production, and other impacts such as sedimentation of waterways (which can impact flooding and water quality). Slips may also impact transport infrastructure (e.g. roads, farm tracks) which may in turn affect connectivity of farms and orchards to markets.

High rainfall will impact soil moisture, and saturated soils may be detrimental for both agriculture and horticulture. Pugging by animals occurs when soils are saturated, which compacts soil and damages soil structure, leading to reduced pasture production and increased runoff (Greater Wellington Regional Council, 2013). Wet soils may cause issues for vegetable growers in particular, as crops may get washed away or the lack of oxygen around the plants reduces their growth rate. Heavy rain at harvest times for fruit may cause a decline in fruit quality, with skins splitting and increased prevalence of diseases.

Afforestation is a key climate change mitigation strategy for carbon sequestration (Parliamentary Commissioner for the Environment, 2019). Over the coming decades, it is likely that tracts of land will be planted for this purpose, mostly with *Pinus radiata* plantations. However, planting permanent native forest (rather than cyclical exotic plantations) may be preferable in some steep locations where soil erosion during and after harvest is a major issue, particularly considering projected increases in extreme rainfall.

Increased prevalence of drought and longer dry spells in the Wellington Region will likely have impacts on water availability for irrigation and other agricultural and horticultural uses. Low river

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

flows are likely to decline in Wairarapa, with reduced flow reliability (the time period where river water abstraction is unconstrained) (Collins and Zammit, 2016). In addition, soils are generally projected to be drier in the Wairarapa plains, which may further impact pasture and crop growth and increase the need for irrigation.

Assuming increasing carbon dioxide 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). However, the increase in productivity may be offset by reduced water availability and increasing drought conditions in parts of the Wellington Region.

6.3 Implications for ecosystems

Key messages

- Ecosystems will be affected by changing distributions and species of pests because of changes to temperature (air and water) and rainfall patterns.
- Extreme warm temperatures may influence masting events in native beech forests.
- Wetlands will be affected by changes to rainfall patterns, particularly increasing incidence of drought.
- Reductions in low river flows will have impacts on freshwater ecosystems as this may reduce habitat availability and quality.
- Increases in extreme rainfall may lead to more sedimentation and turbidity in freshwater and estuarine systems, affecting habitat quality.
- Increased water temperatures may move current habitats outside of tolerable ranges for some aquatic species, and water quality problems (e.g. cyanobacterial blooms) may be exacerbated.

6.3.1 Terrestrial ecosystems

Wellington's indigenous forests may be put under pressure in the future due to changing rainfall patterns and increasing frequency and severity of droughts. Changes to the abundance of pests (both animal and plant) in Wellington with climate change will influence distribution and pressures on Wellington's indigenous forests. The risk of wildfire is projected to increase with climate change in the Wellington Region, particularly due to increasing hot extremes and drought conditions (Pearce et al., 2011).

Extreme warm temperatures may impact native forests through masts, or years with higher seed production than usual. Masting events are likely to occur if the last summer was warmer than the preceding summer. Beech forests (located in the Tararua and Remutaka Ranges) have particularly significant masting events. During these mast years, populations of invasive rodents (rats and mice) increase significantly which causes increases in the populations of top predators, particularly stoats. These increases in predator populations results in increased predation of indigenous species, particularly birds and lizards (Barron et al., 2016, McGlone and Walker, 2011).

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 Wellington may negatively impact wetland ecosystems through drying and consequent loss of habitat. 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 species with small populations and low genetic diversity, such as those that survive only on sanctuary islands (e.g. Kapiti and Matiu/Somes Islands), may be less able to cope with challenges such as a changing climate (Parliamentary Commissioner for the Environment, 2017).

Wellington's indigenous bird populations will be affected by future changes to pests such as rats, which may survive in greater numbers during mild winters (McGlone and Walker, 2011).

6.3.2 Freshwater ecosystems

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/periphyton growth in streams is related to shading from riparian vegetation (Burrell et al., 2014) as well as water temperature. Increasing water temperature as a result of increased air temperatures, as well as changes to riparian vegetation, may alter instream plant assemblages.

Reductions in rainfall and low river flows, 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). 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.

Future changes to rainfall patterns may affect the functionality of wetlands. Reductions in rainfall may increase methane emissions, and wetlands are important carbon sinks so reductions in changes to this storage due to climatic impacts may have negative consequences for overall greenhouse gas emissions (Parliamentary Commissioner for the Environment, 2019).

Increases in rainfall may lead to more sedimentation and turbidity in waterways. Increased intensity in extreme rainfall events is likely to increase erosion and habitat loss in affected stream catchments. Banded kokopu (*Galaxias fasciatus*) have been found to have reduced abundance in turbid streams, so increasing runoff and sediment flowing into streams could limit their distribution (Rowe et al., 2000).

Water temperatures are 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). 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 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. periphyton) (Settele et al., 2014).

6.3.3 Coastal and marine ecosystems

Coastal and marine ecosystems are sensitive to climate extremes, although the moderating effect of the ocean dampens these extremes compared to terrestrial and freshwater ecosystems. As shown in Section 5.1.2, marine heatwaves occur on seasonal timescales around New Zealand – the 2017/2018 marine heatwave was the warmest on record for the seas around New Zealand. Increased sea temperatures over short timescales (although not as instantaneous as climate extremes) have detrimental effects on species. For example, during the 2017/18 marine heatwave, extensive colonies of kelp were absent from southern New Zealand coastlines due to temperature thresholds being breached, and considerable mortality rates of salmon in the Marlborough Sounds were reported (Salinger et al., 2019). In addition, commercial fishers found that certain species (e.g. snapper, *Pagrus auratus*) spawned weeks earlier than usual.

A climate change risk assessment for Auckland showed that intertidal mud flats and rocky reefs, along with kelp forest and subtidal rocky reefs are highly sensitive to increased water temperatures (Foley and Carbines, 2019). This is likely to be the same for Wellington. Many species in these habitats are already close to their thermal limit and are sensitive to temperature increases.

As discussed above, increases to extreme rainfall may cause more sedimentation of waterways. When discharged into the sea, terrestrial sediment can be a serious environmental contaminant. It may degrade coastal habitats and is toxic to many marine organisms. 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. Increased extreme rainfall and consequently increases to large floods may impact the coastal environment through sedimentation and increased erosion around river mouths and estuaries.

6.4 Implications for the urban environment

Key messages

- Climate change extremes may cause negative health impacts for city-dwellers, including heat stress, mental health impacts, and disease.
- Increases in hot days and heatwaves are likely to exacerbate effects of the urban heat island and increase air pollution.
- Increases in extreme rainfall magnitudes may place pressure on urban water infrastructure, causing disruptions to levels of service during periods of high rainfall and flooding. Increased slips may reduce road and rail connectivity.
- Increased drought potential may increase pressure on water sources, both for humans and the natural environment (e.g. urban green space).
- Sea-level rise and coastal erosion are likely to affect urban infrastructure and buildings. Over 14,000 buildings and 173 km of roads in the Wellington region are exposed to a 1% AEP storm tide event with 1 m of sea-level rise.

Climate change may exaggerate the negative effects of urbanisation already experienced, such as increased urban temperatures and flooding. Impacts from changing climate extremes is likely to affect the health of urban dwellers, such as through increased direct impacts (e.g. injury caused by increased magnitude of floods and storms), heat stress, mental health impacts, and disease (Royal Society of New Zealand, 2017).

Increases in hot days and heatwaves (Section 3) are likely to exacerbate effects of the urban heat island (UHI), which may increase the level of heat stress and other health issues experienced by people in urban areas compared with rural areas (Revi et al., 2014). The UHI is most prominent during the night, so increases in night-time temperatures may have a disproportionate impact on heat stress and health of city-dwellers. Energy consumption is likely to increase in summer due to additional need for cooling/air conditioning, but winter energy consumption for heating may decrease. Increases in extreme heat may also result in worsening air pollution (Hong et al., 2019).

Reductions in cold extremes may be a positive for cold-related mortality, but this trend may potentially increase incidence of mosquito-borne diseases such as dengue fever (Derraik and Slaney, 2007). These disease-transmitting mosquitos are frequently intercepted at New Zealand ports of entry but do not establish here due to current climatic conditions (Derraik, 2004). Warming trends may allow these mosquitos to establish (seasonally or longer-term) (Royal Society of New Zealand, 2017).

The magnitude of extreme rainfall events is projected to increase, with larger rainfall totals over shorter durations (Section 4.5). This is likely to place pressure on urban water infrastructure, potentially leading to overflows (particularly an issue for combined wastewater and stormwater systems) and possible service disruptions during times of high rainfall and flooding. In addition, water supply issues are possible, as was experienced in Auckland in 2017 with extreme sedimentation of reservoirs following a large rainfall event. Increasing extreme rainfall intensity is also likely to lead to more slips, potentially causing damage to property and reducing connectivity by road or rail.

Increasing drought potential may also place pressure on the urban environment. In the future, additional and alternative sources of potable water may be required, as well as increased storage to cope during periods of low rainfall and drought. Urban green spaces may be adversely affected by more intense droughts.

Coastal urban environments are at significant risk from sea-level rise and associated coastal erosion and inundation during storm events. This could have widespread impacts on population, property, coastal vegetation and ecosystems, and present threats to commerce, business, and livelihoods (Revi et al., 2014). Sea-level rise will likely cause problems for stormwater, wastewater and drinking water infrastructure that is located at the coast, due to sea water flooding into pipes (not allowing stormwater to drain to the sea) and coastal erosion. Paulik et al. (2019) studied the exposure of different asset classes (e.g. houses, roads, industrial buildings, etc.) to an extreme storm-tide event with different elevations of sea-level rise for New Zealand. At present sea levels, 4084 buildings and 36.2 km of roads in the Wellington region are exposed to a 1% annual exceedance probability storm-tide event, which rises to 14,336 buildings and 173 km of roads under 1 m of sea-level rise and 21,755 buildings and 319 km of roads under 2 m of sea-level rise. See Paulik et al. (2019) for more statistics from this study for the Wellington region.

7 Conclusions

Much of the conversation around climate change focuses on changes to average conditions, however it is by considering the potential changes to extremes in temperature and rainfall that some of the more significant impacts are understood. This report has explored projections for a range of extreme climate indices in the Wellington Region, comparing the recent past to modelled future conditions, and considered implications of changes in extremes on different sectors.

Over the past century in Wellington and Masterton, the number of warm night-time extreme temperatures has increased and the number of cold extreme temperatures (day and night) has decreased. The amount of extreme rainfall recorded in short periods has increased at Kelburn. Ongoing climate change will lead to further changes to climatic extremes experienced in the Wellington region. Overall, more warm extremes are expected (e.g. hot days, heatwave days, warm nights) and fewer cold extremes will occur (e.g. frosts, cold days, cold nights). These trends are likely to be amplified under higher emission scenarios (i.e. more hot days are projected under RCP8.5 than RCP2.6, etc.). These trends from NIWA's Regional Climate Model are supported with results from the lower resolution, large ensemble weather@home simulations.

For rainfall, a reduction in the number of rain days at high elevations is projected, but an increase in the number of rain days for some lower elevation locations is projected for different thresholds (>10 mm, >20 mm, >30 mm). The length of wet spells is projected to decrease in general, and consequently the length of dry spells is projected to increase. When extreme rainfall occurs in the region, it is likely to be more intense, particularly for shorter duration events (e.g. 13.6% increase in rainfall depth per degree of warming for 1-hour, 100-year return period events). Drought or very dry conditions (indicated by annual Potential Evapotranspiration Deficit exceeding 300 mm) are projected to increase for all lowland parts of the region. In particular, there is an annual probability of 80-100% of PED >300 mm in the future for the area around Martinborough (up from 40-60% in the historic period).

Changing climate extremes will have implications for different sectors. Private insurance cover is likely to be considerably affected by ongoing sea-level rise and increasing coastal hazards, as well as other climate extremes (e.g. storms) which may result in loss of cover or increasing cost of insurance premiums. For the agriculture and horticulture sectors, increasing warm temperature extremes (and reducing cold extremes) may affect stock heat stress, crop and fruit growth rates and ripening/harvest timing, water uptake by plants, and pest and disease prevalence. There may be opportunities to grow new varieties of crops or grass that are currently not viable in the region due to temperature limitations, but that may be more resilient to changes and extremes that are expected. An increase in extreme rainfall intensity is likely to result in more slips as well as saturating soils. This may have implications for getting products to market (through damage to transport networks) and the quality of the products themselves (e.g. saturated soils may lead to reduced vegetable harvests). On the other side, drought is likely to affect productivity, through reductions in pasture and crop growth.

For terrestrial, freshwater, and coastal and marine ecosystems, changes to climate extremes will have significant impacts. Increasing warm temperature extremes (e.g. through heatwaves on land and in the water) will likely influence distribution and viability of species – both native and exotic. Pest species may become more prevalent and native species may be pushed to (or beyond) thermal tolerance limits. Increasing drought conditions will likely have impacts on river flows, reducing habitat availability and quality, as well as reducing the functionality of wetlands and forest health.

In the urban environment, changes to climatic extremes are likely to exert pressure on health, through heat stress, mental health impacts, and disease. Also, the increasing intensity of extreme rainfall events may significantly impact the functionality of urban stormwater drainage systems. Ongoing sea-level rise and coastal erosion are likely to place many assets at risk of damage.

For all extreme indices considered in this report, it is evident that more significant changes are likely to occur under higher greenhouse gas emission scenarios (e.g. RCP8.5) than scenarios that represent strong emissions reduction (e.g. RCP2.6). By taking action to reduce greenhouse gas concentrations in the atmosphere globally, the worst impacts of anthropogenic global warming may be reduced.

8 Acknowledgements

Thanks to Ryan Paulik (NIWA) for supplying sea-level rise GIS data, and to John-Mark Woolley (NIWA) for preparing the drought maps.

9 Glossary of abbreviations and terms

Term	Definition
Anthropogenic	Human-induced; man-made. Resulting from or produced by human activities.
Bias correction	Procedures designed to remove systematic climate model errors.
Clausius-Clapeyron 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 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.
Downscaling	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.
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.
Greenhouse gas	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).
Heatwave days	A period of three or more consecutive days where the maximum daily temperature (T_{max}) exceeds a given threshold, either 25°C or 30°C.
High Intensity Rainfall Design System (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
Mitigation	A human intervention to reduce the sources or enhance the sinks of greenhouse gases.
Paris climate change 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.
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.
Projections	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	A numerical climate prediction model run over a limited geographic domain (here around New Zealand), and driven along its lateral atmospheric boundary and oceanic boundary with conditions simulated by a global climate model (GCM). The RCM thus downscales the coarse resolution GCM, accounting for higher resolution topographical data, land-sea contrasts, and surface characteristics. RCMs can cater for relatively small-scale features such as New Zealand's Southern Alps
Representative Concentration Pathway	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)
Sea-level rise	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.
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
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).
Virtual climate station network (VCSN)	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).
weather@home	Weather @ home ensembles use a model with lower spatial resolution (50 km) than the regionally downscaled results (5 km), but which has been run on the order of thousands of times. Hence, spatial detail has been sacrificed in order to radically improve our knowledge of the statistics of particular climate and weather outcomes (it is currently not computationally feasible to achieve both simultaneously).
Wet/dry spell	A period of three or more consecutive days where the daily rainfall total exceeds 1 mm (wet spell) or is less than 1 mm (dry spell).

10 Appendix: Ministry for the Environment coastal hazards and climate change guidance

Updated coastal hazards and climate change guidance was published by Ministry for the Environment (2017)[8]. This section provides a summary of recent sea-level rise trends and future projections for New Zealand. There are no regional or local projections for sea-level rise available (only national projections), however this is a subject of current research under the NZSeaRise project.

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

- gradual inundation of low-lying marsh and adjoining dry land on spring high tides
- escalation in the frequency of nuisance and damaging coastal flooding events
- exacerbated erosion of sand/gravel shorelines and unconsolidated cliffs (unless sediment supply increases)
- 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. Local government road and 'three waters' 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. 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 sea-level rise (SLR) in relation to observations and projections:

- absolute (or eustatic) rise in ocean levels, measured relative to the centre of the Earth, and usually expressed as a global mean (which is used in most sea-level projections e.g. IPCC).
- offsets (or departures) from the global mean absolute SLR for a regional sea, e.g. the sea around New Zealand. Significant variation can occur in response to warming and wind patterns between different regional seas around the Earth.
- local (or relative) SLR, which is the net rise from absolute, regional-sea offsets and local vertical land movement, measured relative to the local landmass. Local or regional adaptation to SLR needs to focus on this local rise.

The first two types of sea-level change are measured directly by satellites, using radar altimeters, or by coalescing several tide-gauge records after adjusting for local vertical land movement and ongoing changes in the Earth's crust following ice loading during the last Ice Age[9].

[8] http://www.mfe.govt.nz/publications/climate-change/coastal-hazards-and-climate-change-guidance-local-government
[9] Scientific term is glacial isostatic adjustment (GIA)

Local SLR is measured by tide gauges. One advantage of knowing the local SLR 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 local (relative) SLR will be larger than the absolute rise in the adjacent ocean level acting alone (Figure 10-1).

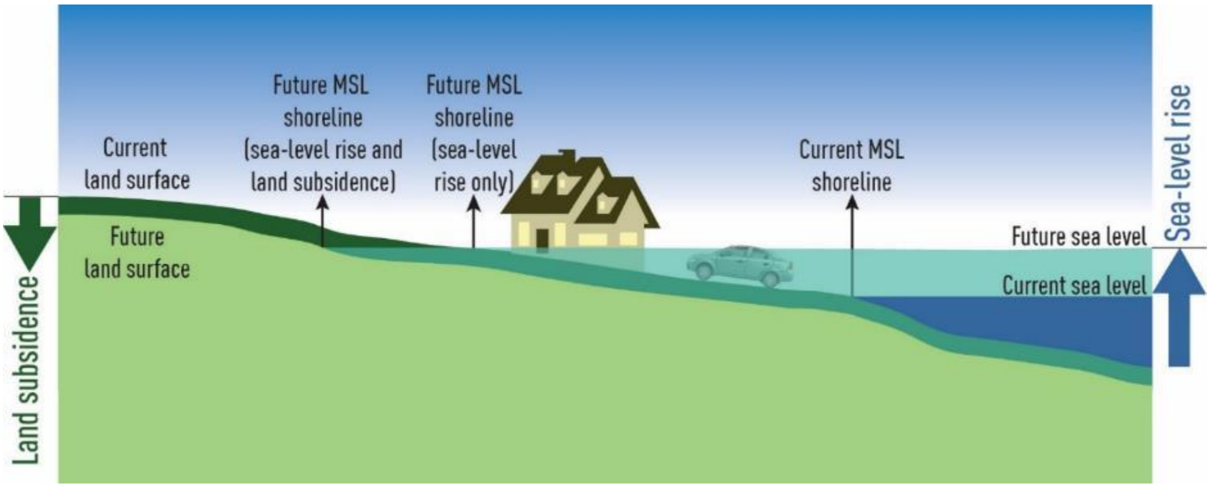


Figure 10-1: Difference in mean sea level (MSL) shoreline between absolute and local (relative) SLR where land subsidence occurs.

Changes in rate of rise

After a period of relative local stability over the past 2000–3000 years, with small rates of sea-level change of up to ±0.2 mm/year (Kopp et al., 2016), global sea level began to rise in the late 1800s. The steady rise in global mean sea level (MSL) since then is shown in Figure 10-2, based on updates of the data from Church and White (2011).

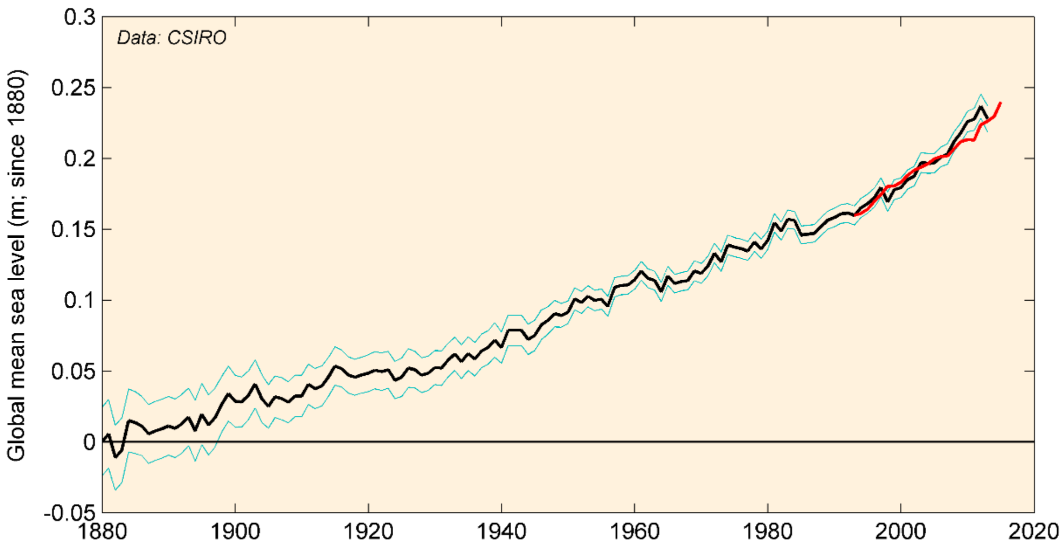


Figure 10-2: Cumulative changes in global mean sea level (MSL) since 1880, based on a reconstruction of long-term tide gauge measurements to end of 2013 (black) and recent satellite measurements to end 2015 (red). Lighter lines are the upper and lower bounds of the likely range (± 1 standard deviation) 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).

From a synthesis of scientific publications, the Intergovernmental Panel on Climate Change determined that it is very likely that the mean rate of globally averaged sea-level rise was 1.7 ± 0.2 mm/year between 1901 and 2010, producing a total rise in global sea level over that period of 0.19 metres (±0.02 metres). A slightly higher annual rise of 2.0 ± 0.3 mm/year occurred in the 40-year period from 1971 to 2010 (Church et al., 2013b).

Contributors to global sea-level rise

As the temperature of the Earth's atmosphere changes so does sea level, although with a lagged response. Rising atmospheric temperature and sea-level change are linked by two main processes:

- Volume increase: As ocean water warms, its volume expands slightly – an effect that is cumulative over the entire depth of the oceans. This is converted mainly into a height increase as the oceans are largely constrained by continental coastlines (despite inundation of low-lying land areas).
- Mass increase: Changes in the land-based volumes of ice and water on land (namely glaciers and ice sheets, and to a lesser extent the net change in freshwater budgets) have led to an increase in the mass of water in the ocean, especially as ice stores diminish with increasing surface and ocean temperatures.

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 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 10-3), the recent trend in global-average MSL to July 2017, based on the CSIRO analysis of satellite altimeter data[10], 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). 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), has contributed to part of the increased rate of rise. However, 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).

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

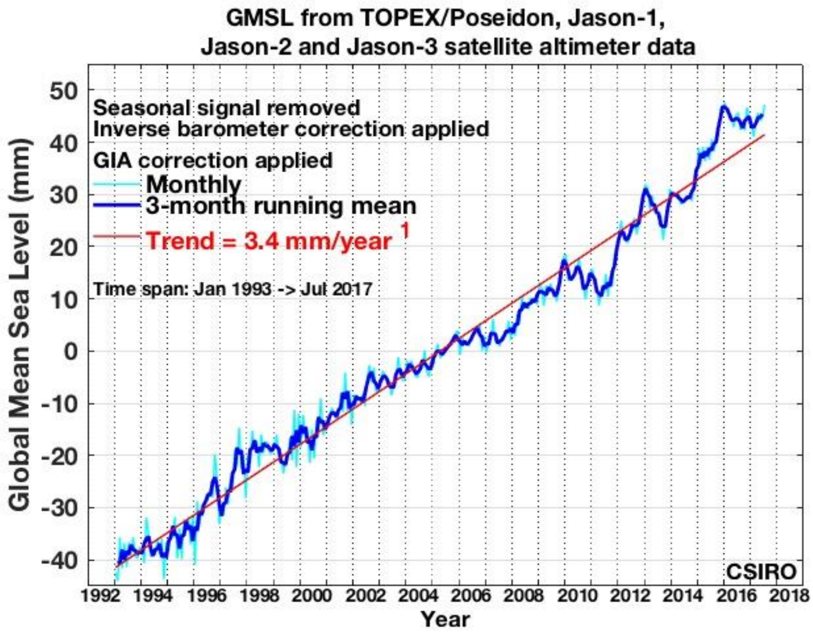


Figure 10-3: Time series and trend in global average sea level over the satellite era from January 1993 to July 2017. Adjustments for glacial isostatic adjustment (GIA), following crustal response to the last Ice Age, and inverted barometer (annual air pressure differences) have been made. Retrieved from CSIRO web site: http://www.cmar.csiro.au/sealevel/sl_hist_last_decades.html

Sea-level rise for New Zealand waters

Changes in annual local MSL at the four main ports in New Zealand from 1900 to 2015 are shown in Figure 10-4. MSL is plotted relative to the average for each time series over the same 1986–2005 baseline period used for IPCC AR5 projections. The initial period of IPCC global-mean projections of SLR for RCP8.5 and RCP2.6 scenarios are also shown for a general comparison.

Considerable variability occurs from year to year, influenced by seasonal changes, the two- to four-year El Niño-Southern Oscillation and the IPO over 20-30-year cycles. The notable rapid rise in SLR in 1999 across all port sites is a result of a regime shift to the negative phase of the IPO.

Climate variability masks the underlying rise caused by climate change. This requires long records to extract robust trends, and also may require one or two decades more of monitoring to confirm which sea-level rise scenario is being followed (because there is little difference at present between scenarios - Figure 10-4).

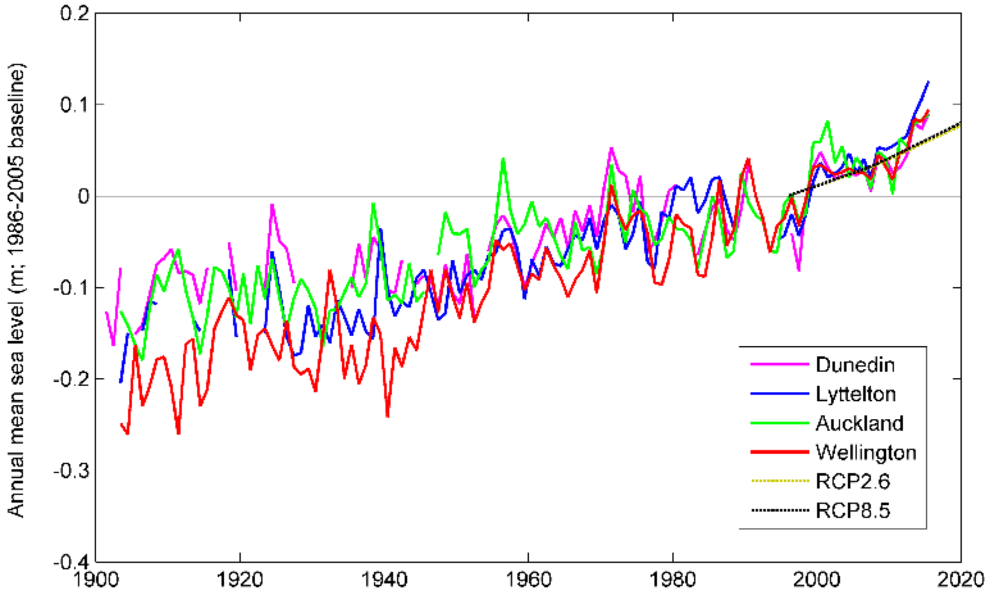


Figure 10-4: Change in annual local MSL for the four main ports from 1900–2015, and initial global-mean SLR projections for RCP2.6 and RCP8.5 to 2020 (dashed lines). Relative to the average MSL over the baseline period 1986–2005 (used for IPCC AR5 projections of SLR, with mid-point at 1996). (Source data: Hannah and Bell (2012), updated to 2015; Church et al. (2013a)).

Trends from these long-term port records, along with inferred trends from six other gauge sites used to establish local survey datums last century, were derived by Hannah and Bell (2012) for records up to and including 2008. The average trend for the local or relative SLR at the four main ports up to 2008 was 1.7±0.1 mm/yr, ranging from a local rate of 1.3 mm/yr at Dunedin to 2.0 mm/yr in Wellington.

Adding on the average glacial isostatic adjustment (GIA) for New Zealand, due to post-Ice Age rebound of the Earth's crust of around 0.3 mm/yr (Hannah and Bell, 2012) yields an absolute SLR of around 2.0 mm/yr for New Zealand ocean waters. This is at the upper end of observations of global mean SLR of 1.7±0.2 mm/yr from 1900 to 2010 from the IPCC AR5 (Church et al, 2013).

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 10-5, with the national average rate now closer to 1.8 mm/year.

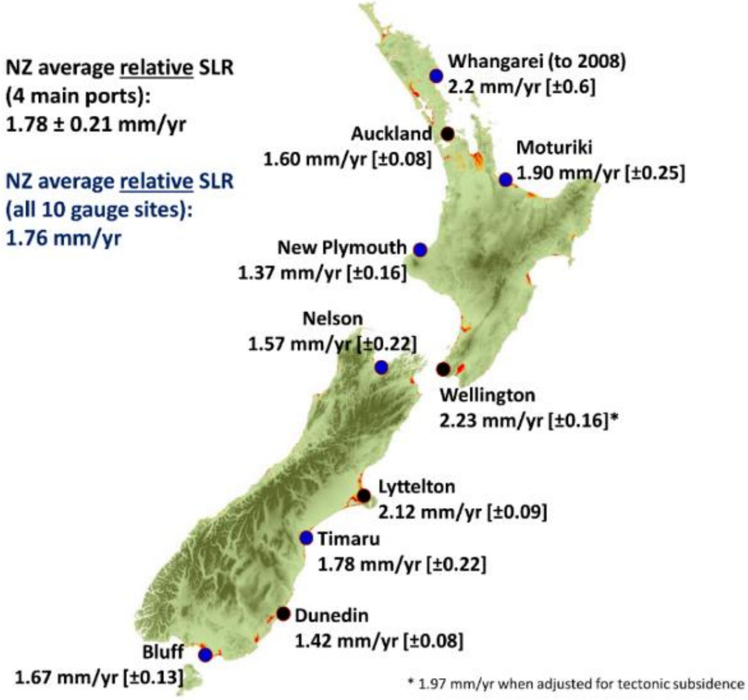


Figure 10-5: Historic long-term RSLR rates for the 20th century up to and including 2015 (excluding Whangarei), determined from longer sea-level gauge records at the four main ports. Note: Standard deviations of the trend are listed in the brackets. Sources: analysis up to end of 2008 from Hannah and 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 SLR 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 10-1).

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. Vertical land movement was analysed by Beavan and Litchfield (2012), who determined that the lower North Island (including the Wellington Region) is subsiding presently on average at 1-3 mm/yr due to interseismic slow-slip activity (Figure 10-6). It is not clear whether subsidence will continue at this rate. Any significant long-term vertical land movement (beyond ±0.5 mm/yr, the accuracy of the rate at which trends can be extracted from 10-year records) should be factored into local SLR projections, especially if the land is subsiding, because this will exacerbate the local net rise in sea level that will need to be adapted to (Figure 10-1).

Future major earthquake displacements for a particular locality are deeply uncertain (both when and by how much). Unlike the ongoing sea-level rise, they could be either subsidence or uplift, other than those areas with a clear geological history of only uplift or subsidence (Beavan and Litchfield, 2012).

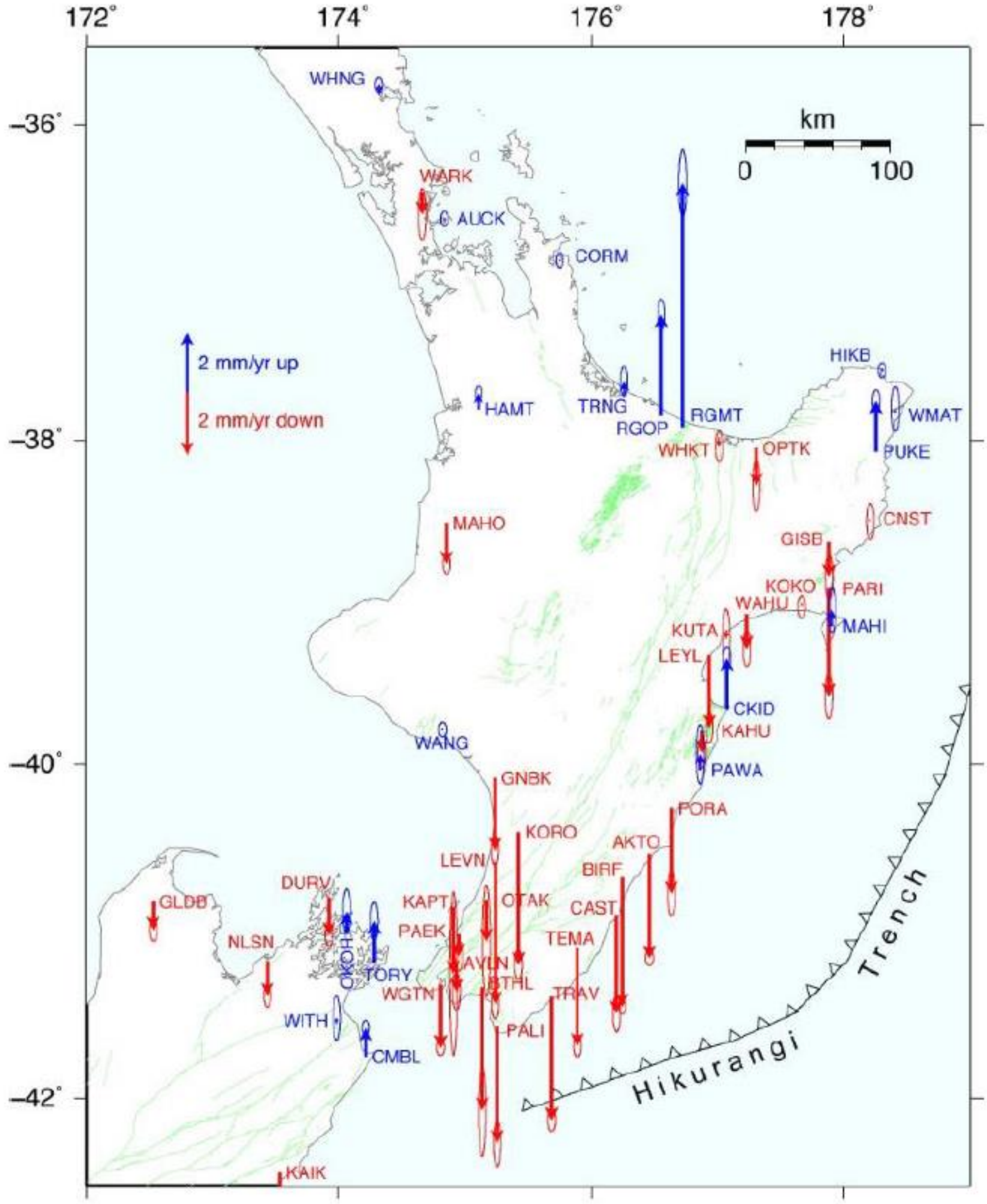


Figure 10-6: Average vertical land movements (mm/yr) for near-coastal continuous GPS sites across central New Zealand regions. Source: Beavan and Litchfield (2012).

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 in Figure 10-7. These projections cover the likely range of variability for the lowest and highest RCP2.6 and RCP8.5 scenarios out to 2100, and all four RCPs for the averaging period 2081-2100. The zero baseline for these projections is the averaging period for MSL from 1986–2005 (same as for Figure 10-4).

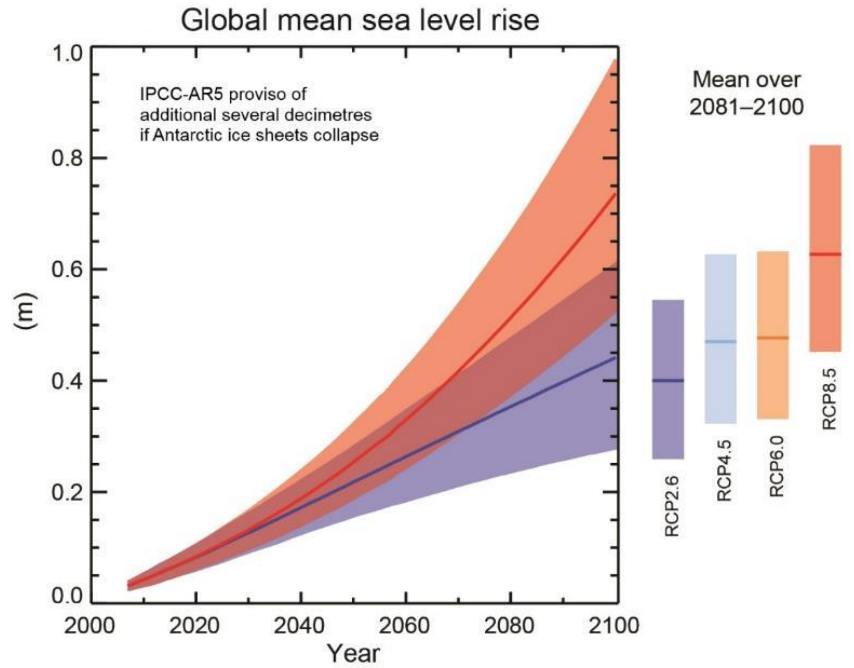


Figure 10-7: IPCC AR5 projections of global-average MSL rise (metres, relative to a base MSL of 1986-2005) covering the range of scenarios from RCP2.6 to RCP8.5. The heavy line shows the median estimate for that RCP, while the shaded area covers the "likely range" projections for the RCP, with a 33% 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 could cause global MSL to rise substantially above the *likely* range (Figure 10-7) during this century. While the contribution cannot be precisely quantified, there is *medium confidence* that it would not exceed several tenths of a metre[11] 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.

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

- 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 from the Antarctic ice sheet is possible, but current evidence and understanding is insufficient to make a quantitative assessment.

Use of global projections to generate New Zealand SLR scenarios

A set of all four RCP projections for New Zealand is shown in Figure 10-8, 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). The base set of global SLR projections is extended to 2120, to align with the planning timeframe of at least 100 years stipulated in the New Zealand Coastal Policy Statement 2010.

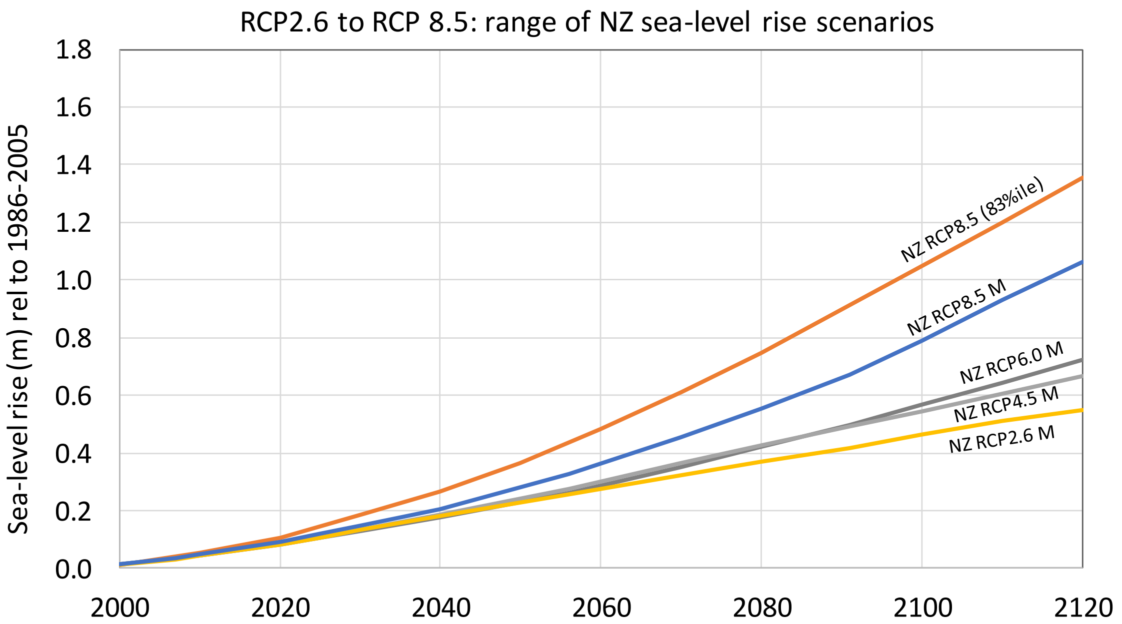


Figure 10-8: SLR scenarios for New Zealand seas, based on a set of median projections for all four RCPs (based on Church et al., 2013b) plus a higher 83rd percentile RCP8.5 projection (based on (Kopp et al., 2014)). The M next to the RCP on the plot stands for median. Note: for New Zealand seas, SLR 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 10-1 (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 10-1: 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

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