Current and future climate of the Kaipara District

Prepared for Kaipara District Council

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Executive summary

Kaipara District Council commissioned NIWA to prepare a report summarising both the current and future projected state of climate in the Kaipara District.

The climate of Kaipara District can be characterised as mild, humid and rather windy; owing to its northern location, low elevation and proximity to the sea. Summers are warm and tend to be humid, while winters are mild, with much of the district only observing a few light frosts per year. Rainfall is typically plentiful year-round, with occasional very heavy falls. However, dry spells and drought can occur, especially during summer and autumn. Some of the key features of Kaipara District's present climate include:

- Annual average temperature of 14.8°C to 15.4°C. Summer average maximum temperatures in Dargaville average 22-24°C, with winter average minimum temperatures averaging 7-8°C.
- Average annual rainfall of 1,100 mm to 1,400 mm, with summer being the driest season. On average, Dargaville observes 140 wet days per year.
- Average annual sunshine of 1,850 hours to 1,950 hours.

Climate change is projected to impact New Zealand's climate considerably. Some of the key features of Kaipara District's projected future climate include:

- Annual average temperature increases of 2.0-3.5°C (by 2090 under RCP8.5).
- Annual hot days and heatwave days increasing by 60-80 days (by 2090 under RCP8.5).
- Growing degree day increases of 250-300 GDD by 2040 under RCP4.5, and increases of 900-1,000 GDD by 2090 under RCP8.5.
- Average annual rainfall decreases of 2-6% for northern inland areas (by 2090 under RCP8.5), but little change (±2%) for the District overall under remaining future scenarios. Increases to autumn rainfall of 2-15% projected under all future scenarios. Winter and spring rainfall projected to decrease by 6-15% by 2090 under RCP8.5.
- Annual wet days decreasing by 16-22 days (by 2090 under RCP8.5).
- Extreme, rare rainfall events are projected to become more severe in the future. The depth of a current 1:100-year 1-hour duration rainfall event is projected to increase by approximately 35% by 2090 under RCP8.5.
- Increase in amount of accumulated potential evapotranspiration deficit (PED), resulting in a projected increase in drought potential. An increase in PED of 120-160 mm per year is projected by 2090 under RCP8.5.
- Mean annual discharge generally decreases by mid-century across the Kaipara District. By late century, mean discharge decrease is accentuated in the north-eastern area of the district with increasing greenhouse gas concentrations.
- Floods (characterised by the Mean Annual Flood (annual peak flood)) are expected to become larger for many parts of the district under high radiative forcing scenarios.

Under RCP4.5, flood peaks are expected to increase by mid-century while decreasing by the end of the century.

- Coastal flooding from extreme sea levels will increase in frequency and magnitude as global climate change forces sea-level rise.
- Projected climate changes will bring challenges (e.g. higher PED resulting in increased demand for water resources) and opportunities (e.g. warmer temperatures more suitable to warm climate crops) to the horticulture industry of Kaipara District.

1 Introduction

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

Kaipara District Council commissioned the National Institute of Water and Atmospheric Research (NIWA) to undertake an assessment of the current and future climate change projections for the Kaipara District (Figure 1-1). This work follows the publication of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report in 2013 and 2014, and the New Zealand climate change projections report published by the Ministry for the Environment (updated 2018) (Ministry for the Environment, 2018). The contents of this technical report include analysis of climate projections for the Kaipara District in greater detail than the national-scale analysis.

This technical report describes the current climate of Kaipara District, and changes to the climate of the area which may occur over the 21st century. Consideration about future change incorporates knowledge of both natural variations in the climate and changes that may result from increasing global concentrations of greenhouse gases that are contributed to by human activities. Climatic variables discussed in this report include temperature, rainfall, and drought indicators as well as additional sections on sea level rise and changes to hydrology.

Some of the information that underpins portions of this report resulted from academic studies based on the latest assessments of the Intergovernmental Panel on Climate Change (IPCC, 2013, IPCC, 2014c, IPCC, 2014a, IPCC, 2014b). Details specific to Kaipara District were based on scenarios for New Zealand that were generated by NIWA from downscaling of global climate model simulations. This effort utilised several IPCC representative concentration pathways for the future and this was achieved through NIWA's Strategic Science Investment Fund (SSIF) programme on Regional Climate Modelling. The climate change information presented in this report is consistent with recently-updated national-scale climate change guidance produced for the Ministry for the Environment (2018).

The remainder of this chapter includes a brief introduction of global and New Zealand climate change, based on the IPCC Fifth Assessment Report. It includes an introduction to the climate change scenarios used in this report, and the methodology that explains the modelling approach for the climate change projections that are presented for Kaipara District. Chapter 2 presents the current climate of Kaipara District, and climate projections for the area are presented in Chapter 3.

Figure 1-1: Map of Kaipara District.

1.1 Global and New Zealand climate change

Key messages

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

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

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

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

The regional climate is changing. The Australasia region continues to demonstrate long-term trends toward higher surface air and sea surface temperatures, more hot extremes and fewer cold extremes, and changed rainfall patterns. Over the past 50 years, increasing greenhouse gas concentrations have contributed to rising average temperatures in New Zealand. Changing precipitation patterns have resulted in increases in rainfall for the south and west of the South Island

and west of the North Island and decreases in the northeast of the South Island and the east and north of the North Island. Some heavy rainfall events already carry the fingerprint of a changed climate, in that they have become more intense due to higher temperatures allowing the atmosphere to carry more moisture (Dean et al., 2013). Cold extremes have become rarer and hot extremes have become more common.

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

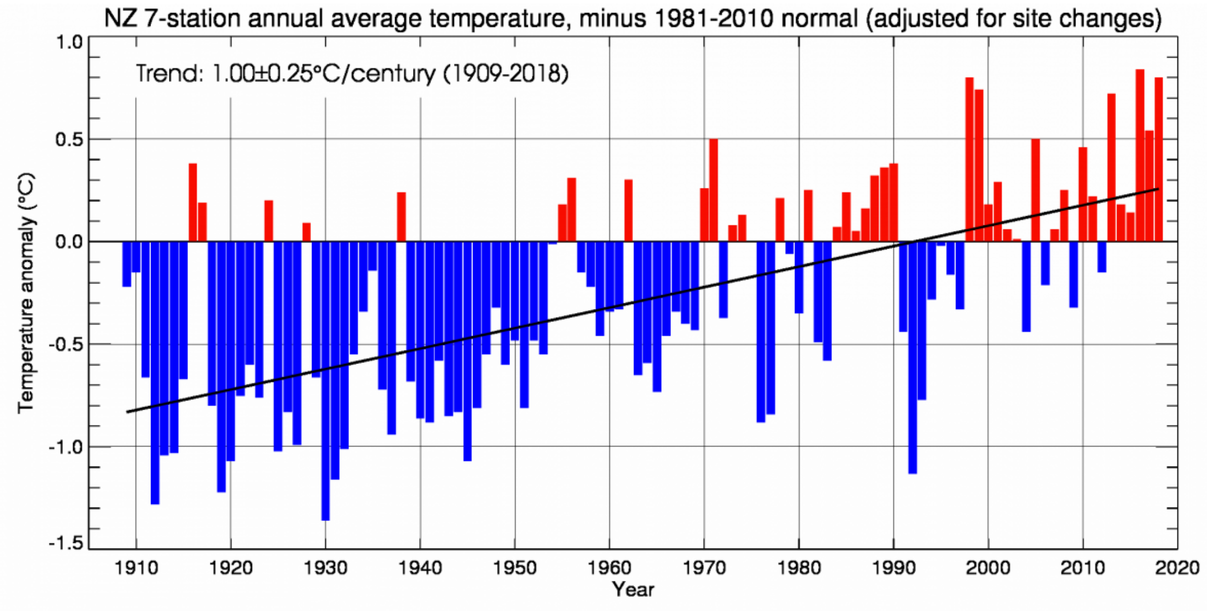

Figure 1-2: New Zealand national temperature series, 1909-2018. More information about the New Zealand seven-station temperature series can be found at https://www.niwa.co.nz/our-science/climate/information-and-resources/nz-temp-record/seven-station-series-temperature-data.

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

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

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

1.2 Year to year climate variability and climate change

Key messages

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

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

1.2.1 The effect of El Niño and La Niña

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

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

During El Niño events, the weakened trade winds cause New Zealand to experience a stronger than normal south-westerly airflow. This generally brings lower seasonal temperatures to the country and drier than normal conditions to the north and east of New Zealand, including Kaipara District (Salinger and Mullan, 1999). During La Niña conditions, the strengthened trade winds cause New Zealand to experience more north-easterly airflow than normal, higher-than-normal temperatures (especially during summer), and generally drier conditions in the west and south of the South Island (Figure 1-3).

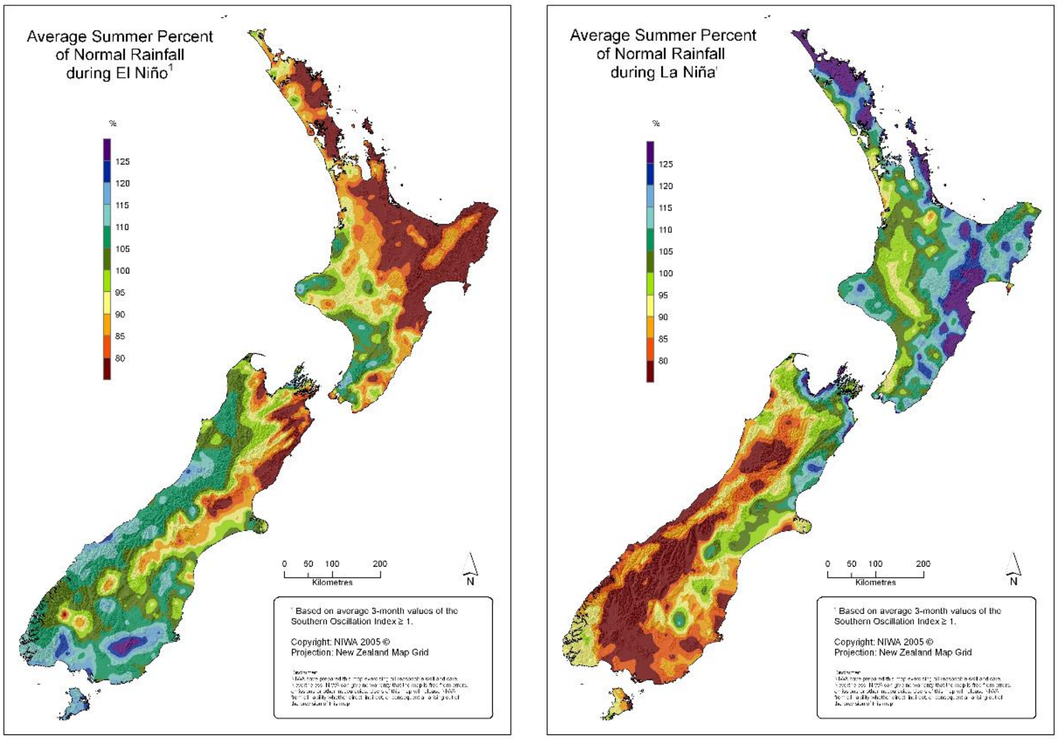

Figure 1-3: Average summer percentage of normal rainfall during El Niño (left) and La Niña (right). El Niño composite uses the following summers: 1963/64, 1965/66, 1968/69, 1969/70, 1972/73, 1976/77, 1977/78, 1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98, 2002/03. La Niña composite uses the following summers: 1964/65, 1970/71, 1973/74, 1975/76, 1983/84, 1984/85, 1988/89, 1995/96, 1998/99, 1999/2000, 2000/01. This figure was last updated in 2005. © NIWA.

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

1.2.2 The effect of the Interdecadal Pacific Oscillation

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

1.2.3 The effect of the Southern Annular Mode

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

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

1.2.4 The influence of natural variability on climate change projections

It is important to consider human-induced climate change in the context of natural climate variability. An example of this for temperature is shown in Figure 1-4. The solid black line on the left-hand side represents the observed annual average temperature for New Zealand[1], and the dashed black line represents the 1909-2014 trend of 0.92 °C/century extrapolated to 2100. All the other line plots and shading refer to the modelled air temperature averaged over the New Zealand region. Post-2014, the two line plots show the annual temperature changes for the New Zealand region under RCP8.5 (orange) and RCP2.6 (blue); a single model is selected to illustrate the inter-annual variability. The shading shows the range across all IPCC AR5 models for both historical and future periods.

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

Figure 1-4 should not be interpreted as a set of specific predictions for individual years. However, it illustrates that although we expect a long term overall upward trend in temperatures (at least for RCP8.5), there will still be some relatively cool years. For this example, a year which is unusually warm under our present climate could become the norm by about 2050, and an "unusually warm" year in 30-50 years' time (under the higher emission scenarios) is likely to be warmer than anything we currently experience.

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

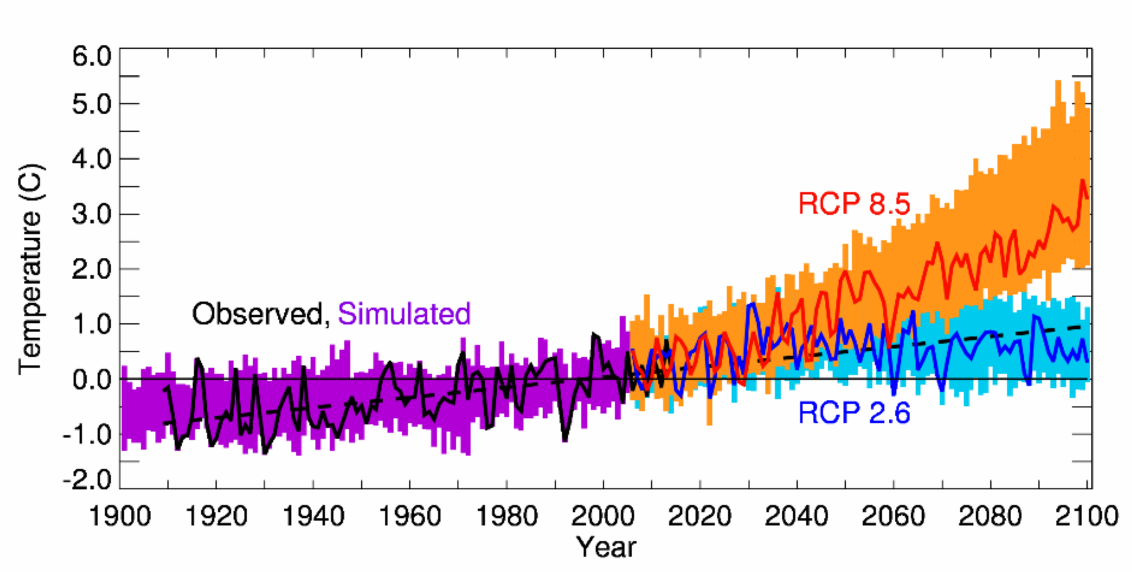

Figure 1-4: New Zealand Temperature - historical record and an illustrative schematic projection illustrating future year-to-year variability. (See text for full explanation). From Ministry for the Environment (2018).

For rainfall, multi-decadal variability associated with the IPO can enhance or counter the impacts of anthropogenic climate change. This influence may generate either slightly above normal or below normal rainfall for parts of New Zealand during summer. For the present period, IPO-negative conditions coupled with more frequent La Niña episodes could increase rainfall during spring and summer, essentially in the opposite direction as expected from anthropogenic factors (i.e. a potential reduction in spring and summer rainfall). A subsequent further reversal of the IPO in 10-20 years' time could have the opposite effect, enhancing part of the anthropogenic (drying) trend in rainfall for a few decades. The message from this section is *not* that anthropogenic trends in climate can be ignored because of natural variability. In the projections, we have discussed these anthropogenic trends because they become the dominant factor locally as the century progresses. Nevertheless, we need to bear in mind that at some times natural variability will be adding to the human-induced trends, while at others it may be offsetting part of the anthropogenic effect.

1.3 Representative Concentration Pathways

Key messages

- Future climate change projections are considered under four scenarios of future atmospheric greenhouse gas concentrations, called Representative Concentration Pathways (RCPs) by the IPCC.
- The four RCPs are related to projected economic, political and social pathways over the 21st century.
- RCP2.6 is a mitigation scenario requiring significant reduction in greenhouse gas emissions, RCP4.5 and RCP6.0 are mid-range scenarios where greenhouse gas concentrations stabilise by 2100, and RCP8.5 is a 'business as usual' scenario with greenhouse gas concentrations continuing to increase at current rates.
- Projections for the future climate in Kaipara are presented for RCP4.5 and RCP8.5 in this report.

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

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

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

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

The full range of projected globally-averaged temperature increases for all scenarios for 2081-2100 (relative to 1986-2005) is 0.3 to 4.8°C (Figure 1-5). Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit inter-annual-to-decadal variability and will not be regionally uniform.

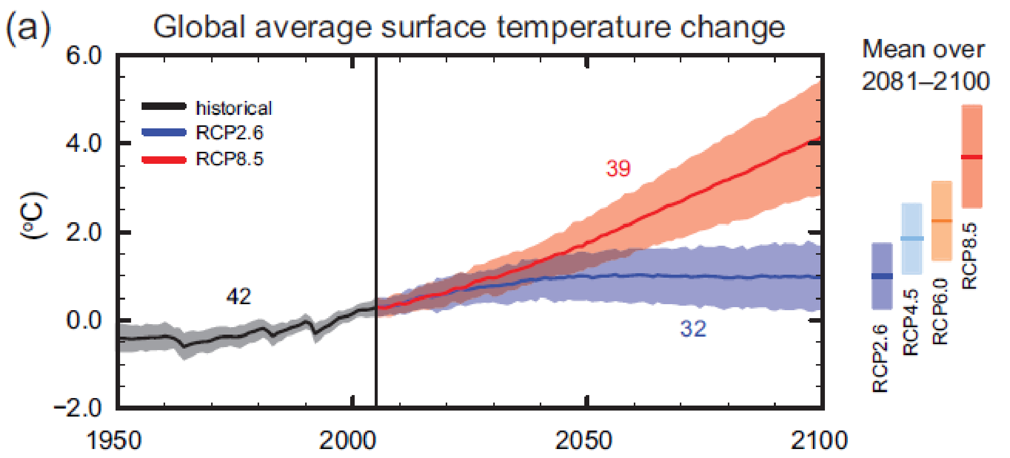

Figure 1-5: CMIP5 multi-model simulated time series from 1950-2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled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

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

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

In this report, global climate model outputs based on two RCPs (RCP4.5 and RCP8.5) have been downscaled to produce future climate projections for Kaipara District. The rationale for choosing these two scenarios was to present a 'business-as-usual' scenario if greenhouse gas emissions continue at current rates (RCP8.5) and a scenario which could be realistic if global action is taken towards mitigating climate change, for example the Paris climate change agreement (RCP4.5).

1.4 Climate modelling methodology

Key messages

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

1.5 Limitations

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

- The maps and tables presented in this report show the average of six dynamically downscaled global climate models. This is a relatively small number of models and a clear shift in the distribution of potential future outcomes is not available. This is particularly important when considering extremes (e.g. extreme hot days and extreme rainfall; not assessed in this report), where the models considered here may not accurately capture how rare events are changing.

- The average of six models is used in this report, which gives no indication of the range of results that the models project. However, the six models chosen represented historic climate conditions in New Zealand well, and span a range of future outcomes. Using the average balances out the errors that may be apparent in each model.
- The time periods chosen for historic and future projection span 20-year periods. This is seen as a relatively short timeframe to understand average conditions in the historic period and in the future, as there is likely an influence of underlying climate variability (e.g. decadal signals from climate drivers like the El Niño-Southern Oscillation etc.). However, the IPCC uses 20-year periods, so we have followed that approach for consistency.
- Care needs to be taken when interpreting grid-point-scale projections such as those presented in the tables in this report. The underlying climate data are Virtual Climate Station data, which are interpolated from physical climate stations. Therefore, the data from these grid points may be slightly different to on-the-ground observations, due to the interpolation procedure (particularly if the grid point is surrounded by multiple different stations or if there are no stations nearby). It is useful to look at broader patterns between grid points, e.g. coast vs. inland, and the magnitude of change at different time periods and scenarios, when considering the values.

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

2 Current climate of Kaipara District

Kaipara District's latitude means that the track of anticyclones (high pressure systems) crossing New Zealand are often centred to the south. As a result, winds tend to be southeasterly following the passage of a trough (low pressure system) as the next anticyclone advances. These winds shift to the northeast once the anticyclone moves off to the east. Northeast winds typically have an extended passage over warm surface waters north of New Zealand, and the associated airmass is usually relatively moist, resulting in high humidity over Kaipara District. Tropical cyclones, or storms of tropical origin, affect Northland (and Kaipara District) from time to time. These weather systems usually bring heavy rain and strong easterly winds to the area. Characteristic weather sequences in Northland include fine weather spells, showery weather and prolonged rainfall. See The Climate and Weather of Northland (Chappell, 2013) for further details. Sections 2.1-2.5 present recent climate observations for Kaipara District. Note that climate station data is relatively sparse for Kaipara District, so many of the sections below focus on observations recorded in Dargaville.

2.1 Temperature

Key messages

- The annual average temperature is between 14.8°C to 15.4°C for most of Kaipara District. Summer average temperatures are between 18.5°C to 19.5°C, while winter average temperatures are between 11.0°C and 12.0°C.
- For Dargaville, the annual average daily maximum temperature is 19.6°C, reaching a high of 24.4°C during February. The annual average daily minimum temperature is 11.0°C, reaching a low of 7.2°C during July.
- Dargaville averages 32 hot days (daily maximum temperature > 25°C) and 3 frost days (daily minimum temperature < 0°C) per year.
- The highest temperature on record for Dargaville is 32.4°C. Dargaville's lowest temperature on record is -5.0°C.

2.1.1 Average temperature

This section includes maps of annual (Figure 2-1), summer (Figure 2-2), autumn (Figure 2-3), winter (Figure 2-4) and spring (Figure 2-5) average temperature for Kaipara District. Monthly average temperature maps for Kaipara District are shown in Appendix A.

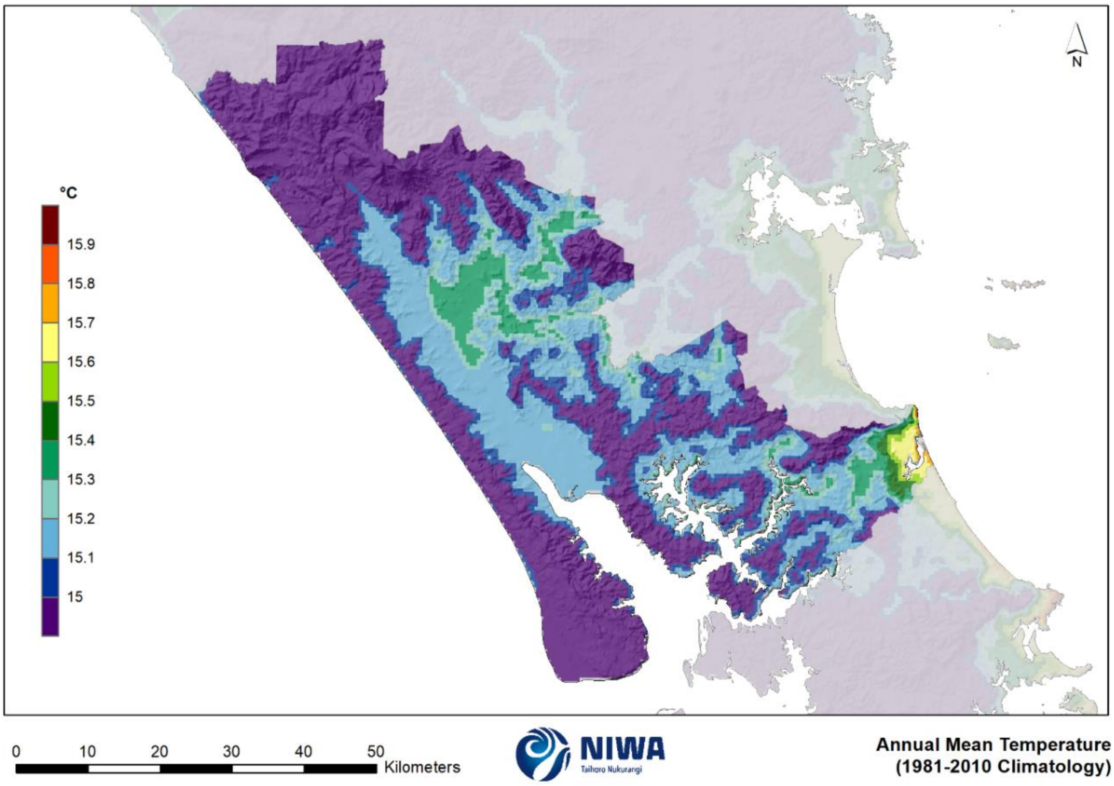

Figure 2-1: Annual average temperature for Kaipara District. Based on the 30-year average from 1981-2010.

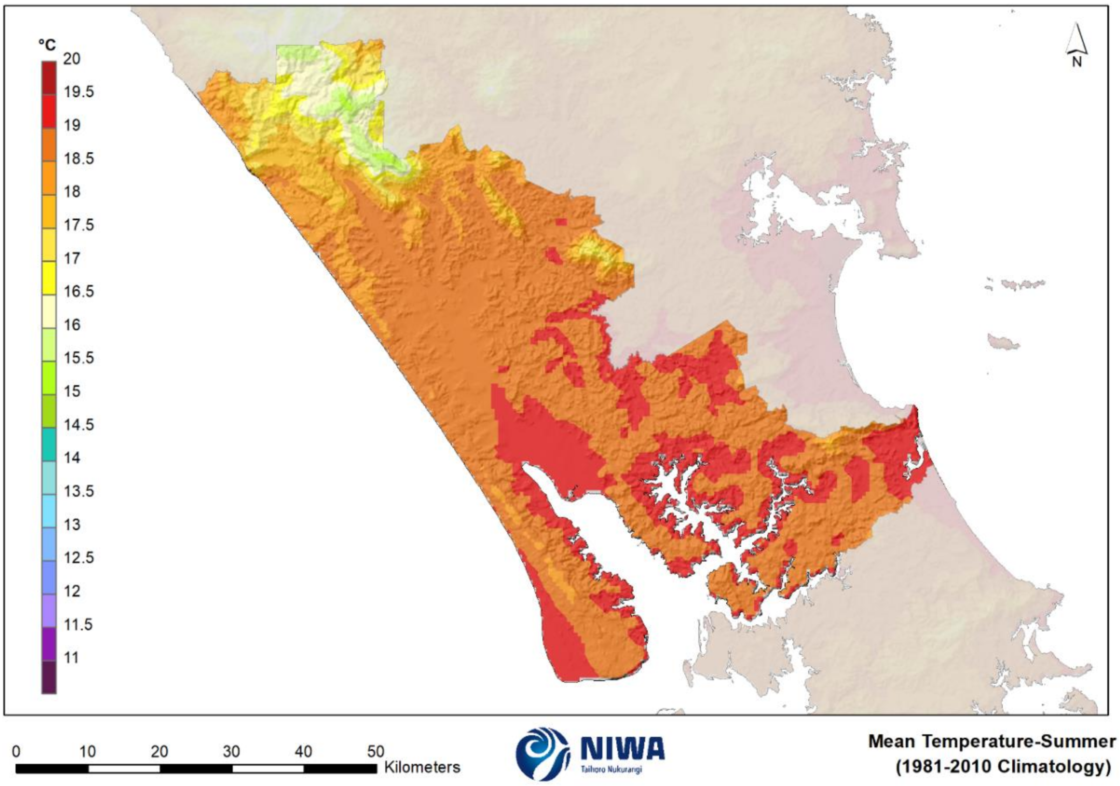

Figure 2-2: Summer average temperature for Kaipara District. Based on the 30-year average from 1981-2010.

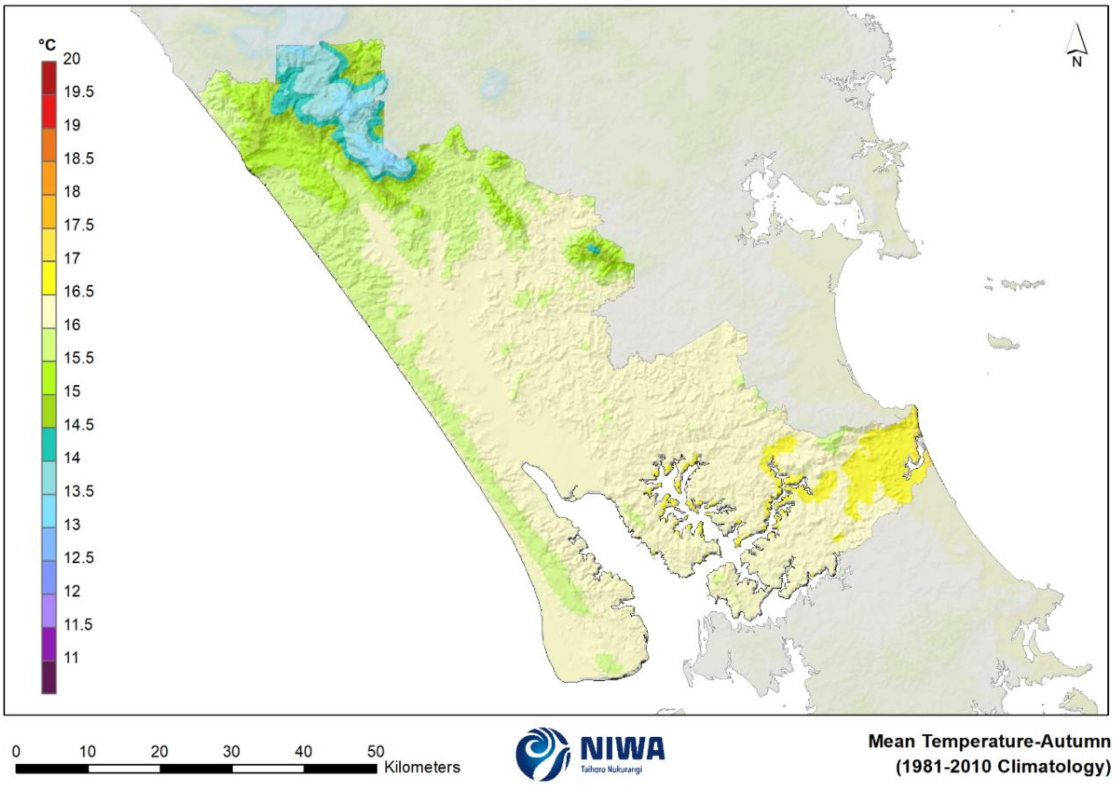

Figure 2-3: Autumn average temperature for Kaipara District. Based on the 30-year average from 1981-2010.

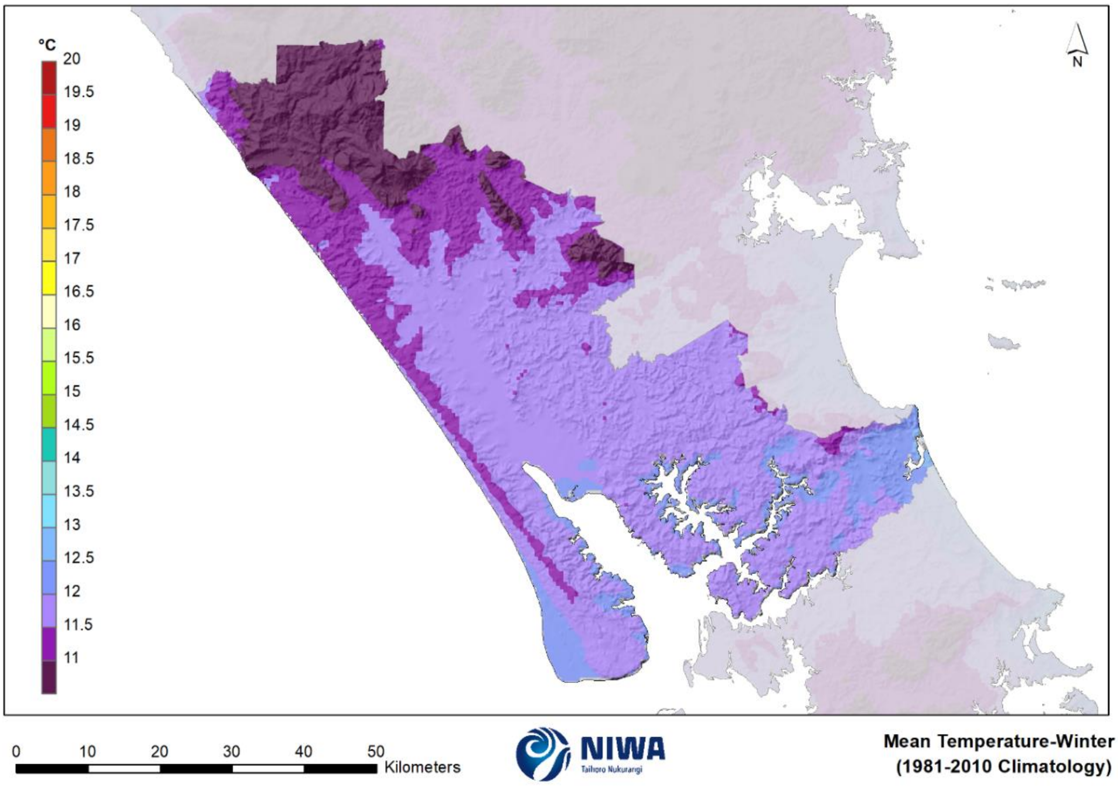

Figure 2-4: Winter average temperature for Kaipara District. Based on the 30-year average from 1981-2010.

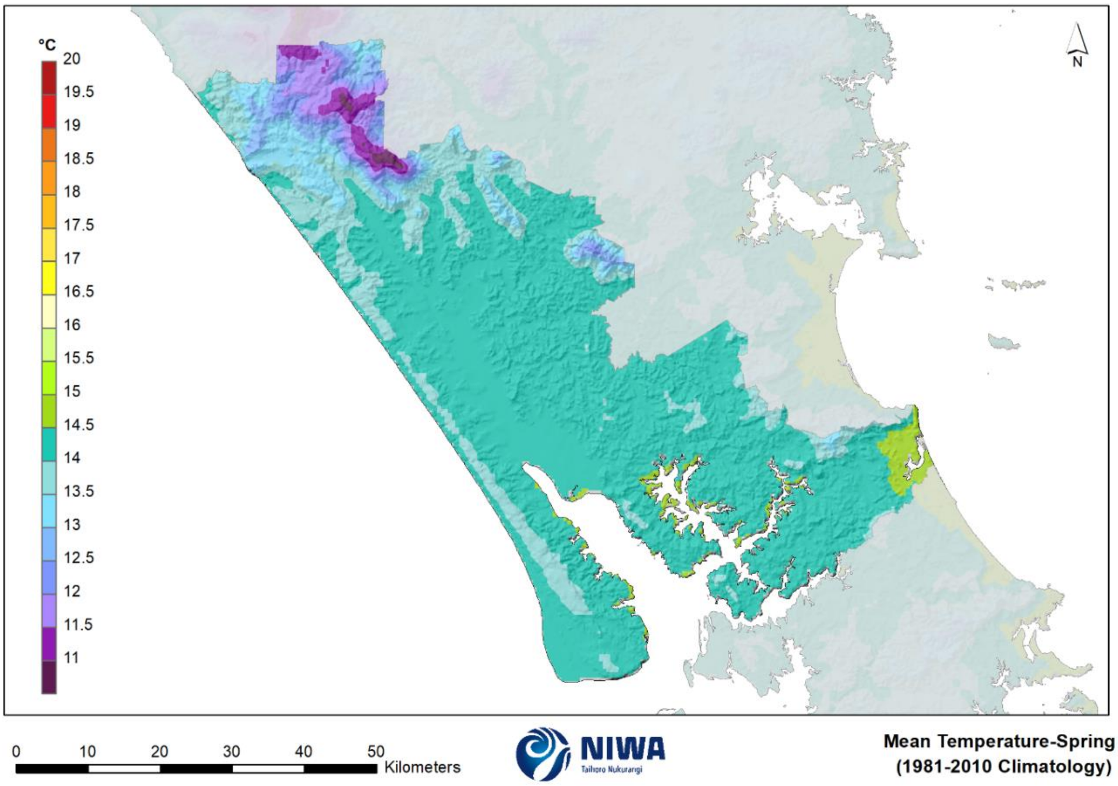

Figure 2-5: Spring average temperature for Kaipara District. Based on the 30-year average from 1981-2010.

2.1.2 Maximum temperature

Key messages

- Most of Kaipara District observes an average of 25-40 hot days (days above 25°C) per year.
- Average daily maximum temperatures in Dargaville range from 15.3°C in July to 24.4°C in February.
- Dargaville averages 32 hot days per year, and the highest temperature on record occurred in February 1998 (32.4°C).

Monthly and annual maximum temperature statistics for Dargaville are presented in Table 2-1. Average daily maximum temperature and average number of hot days are based on the climate normal period 1981-2010. Highest recorded temperatures are based on all available data for Dargaville, which spans the period 1943-2019. Data were obtained from NIWA's National Climate Database (CliDB). Figure 2-6 shows the average annual number of hot days observed in Kaipara District. In this report, a hot day is when the daily maximum temperature is above 25°C. Hot days are defined as such because temperatures over this threshold are considered 'hot' given New Zealand's temperate maritime climate. This threshold is consistent with Ministry for the Environment (2018).

Table 2-1: Monthly and annual maximum temperature statistics for Dargaville. Statistics included are average daily maximum temperature (Avg Tmax, °C), highest temperature recorded (Extreme Tmax, °C) and average number of days with a maximum temperature >25°C (Mean hot days).

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ANN
Avg Tmax	24.1	24.4	22.9	20.8	18.2	16.1	15.3	15.6	17.0	18.1	19.9	22.2	19.6
Extreme Tmax (year)	31.8 (1954)	32.4 (1998)	32.1 (1946)	28.9 (1998)	24.9 (1995)	24.4 (1998)	21.7 (1999)	23.2 (2001)	24.5 (1995)	25.6 (1949)	27.3 (1949)	29.9 (1998)	32.4
Mean hot days	10	11	5	1	0	0	0	0	0	0	0	5	32

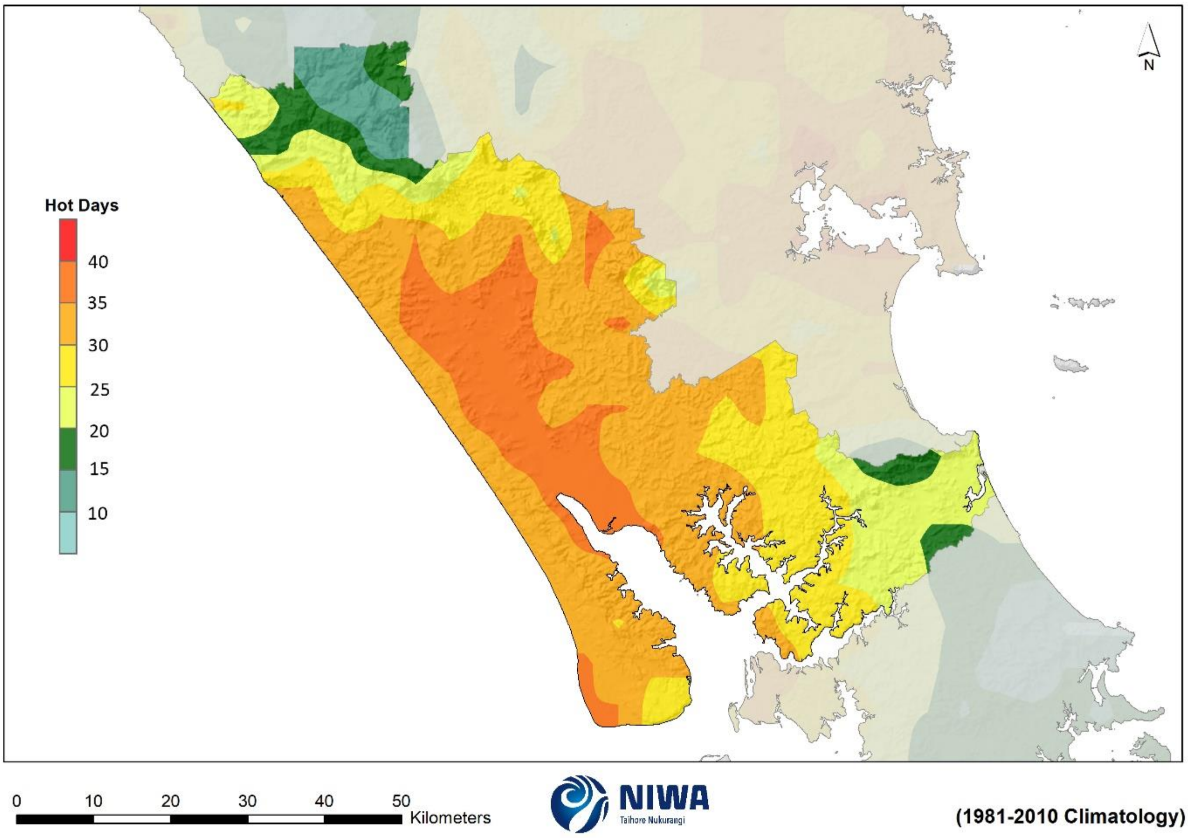

Figure 2-6: Annual number of hot days for Kaipara District. Based on the 30-year average from 1981-2010. A hot day is defined as the daily maximum temperature exceeding 25°C.

2.1.3 Minimum temperature

Key messages

- Frosts are typically not observed in Kaipara District after 8 August in a given year.
- Average daily minimum temperatures in Dargaville range from 7.2°C in July to 15.0°C in February.
- Dargaville averages three frost days per year, and the coldest temperature on record occurred in August 1949 (-5.0°C).

Monthly and annual minimum temperature statistics for Dargaville are presented in Table 2-2. Average daily minimum temperature and average number of frost days are based on the climate normal period 1981-2010. Lowest recorded temperatures are based on all available data for Dargaville, which spans the period 1943-2019. Data were obtained from NIWA's National Climate Database (CliDB).

A frost day is defined in this report when the daily minimum temperature falls below 0°C. This is purely a temperature-derived metric for assessing the potential for frosts. Frost conditions are influenced at the local scale by temperature, topography, wind, and humidity, so the results presented in this section can be considered as the large-scale *temperature* conditions conducive to frosts. Figure 2-7 depicts the average day of last frost, showing that frosts typically do not occur in Kaipara District after 8 August (Julien day 220) in a given year.

Table 2-2: Monthly and annual minimum temperature statistics for Dargaville. Statistics included are average daily minimum temperature (Avg Tmin), lowest temperature recorded (Extreme Tmin) and average number of days with a minimum air temperature <0°C (Mean frost days).

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ANN
Avg Tmin	14.4	15.0	13.5	11.7	10.0	7.8	7.2	7.8	8.9	10.4	11.7	13.4	11.0
Extreme Tmin (year)	4.0 (1987)	1.7 (1950)	0.0 (1947)	-1.3 (1992)	-3.3 (1964)	-3.3 (1959)	-5.0 (1949)	-3.3 (1965)	-1.9 (1957)	0.6 (1973)	2.2 (1947)	1.2 (1961)	-5.0
Mean frost days	0	0	0	0.1	0	1.0	1.3	0.3	0	0	0	0	2.7

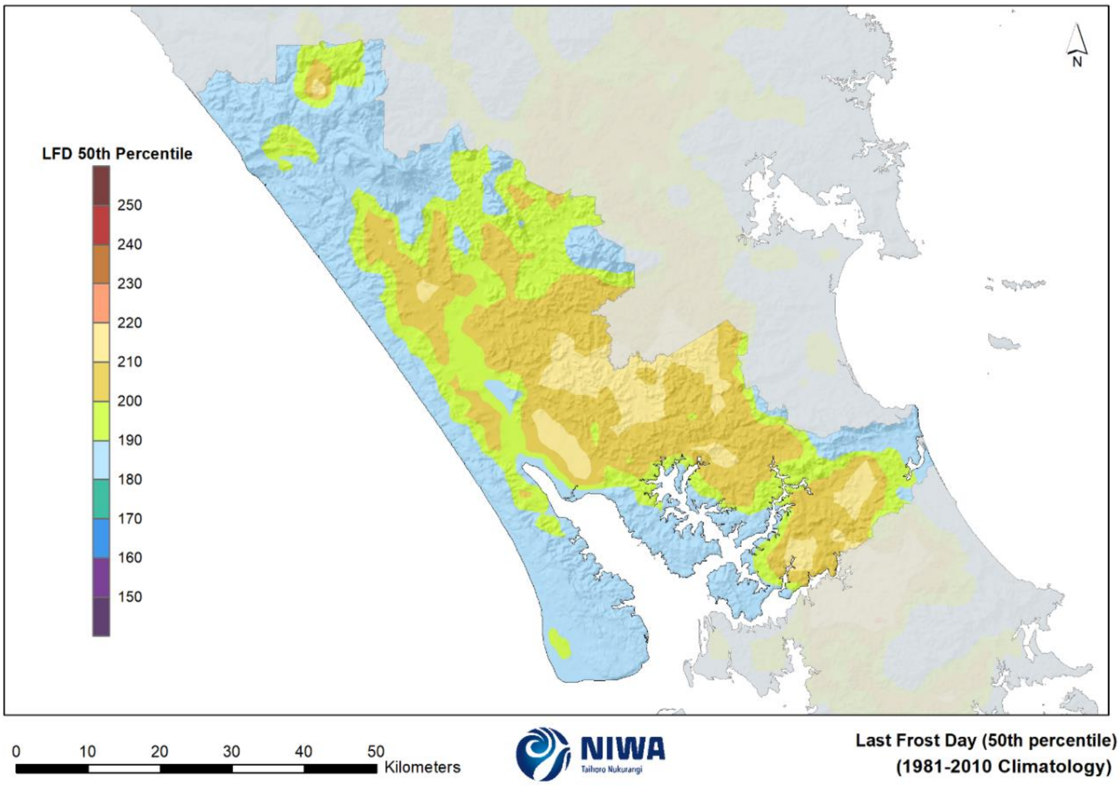

Figure 2-7: Average day of last frost in Kaipara District. Presented as Julien days; e.g. 1 June is Julien day 152 and 1 August is Julien day 213. Based on the 30-year average from 1981-2010.

2.1.4 Growing degree days

Key messages

- Annual mean growing degree days (base 10°C) ranges between 1,700-2,000 GDD for most of Kaipara District.
- In higher elevation terrain to the north of Kaipara District, growing degree days (base 10°C) ranges between 1,200-1,400 GDD.
- Monthly mean Growing Degree Day maps for Kaipara District are shown in Appendix B.

Growing degree-days (GDD) express the sum of daily temperatures above a selected base temperature (e.g. 10˚C) that represent a threshold for plant growth. The average amount of GDD in a location may influence the choice of crops to grow, as different species have different temperature thresholds for survival. The daily GDD total is the amount the daily average temperature exceeds the threshold value (e.g. 10°C) per day. For example, a daily average temperature of 18°C would have a GDD base 10°C value of 8. Here, GDD are accumulated from July to June, and presented for the historic 1981-2010 average (Figure 2-8 to Figure 2-12).

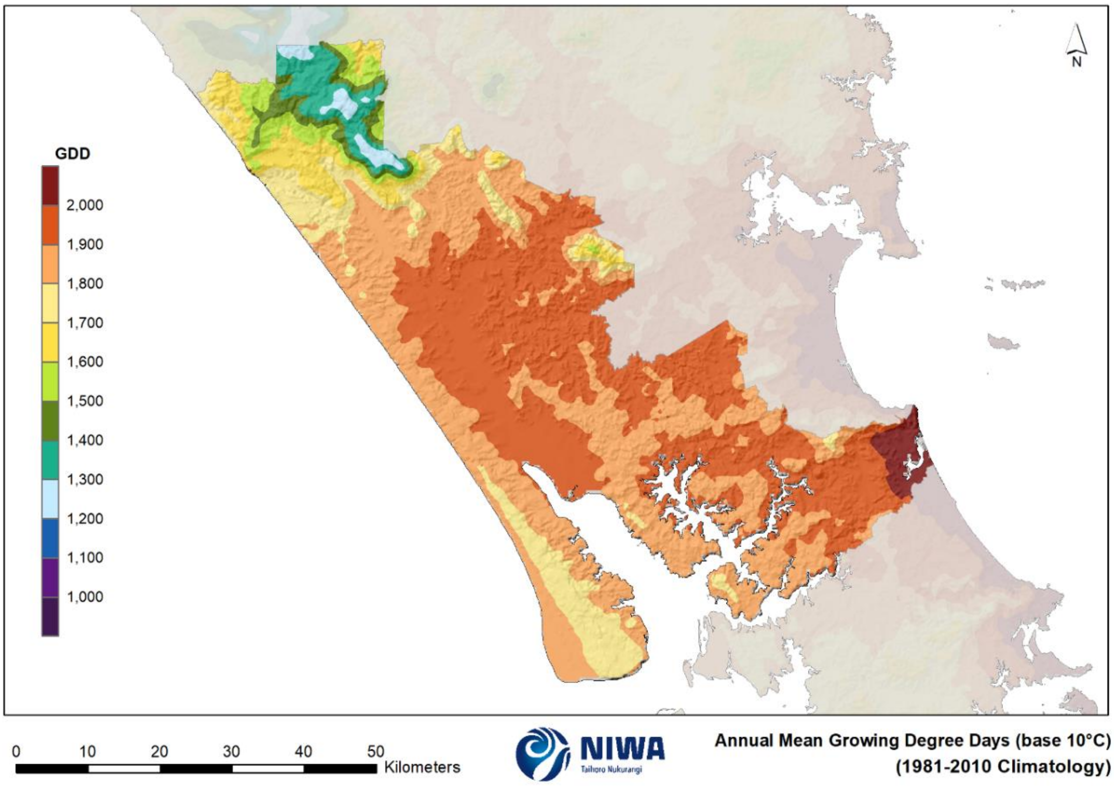

Figure 2-8: Annual mean growing degree days (base 10°C). Based on the 30-year average from 1981-2010.

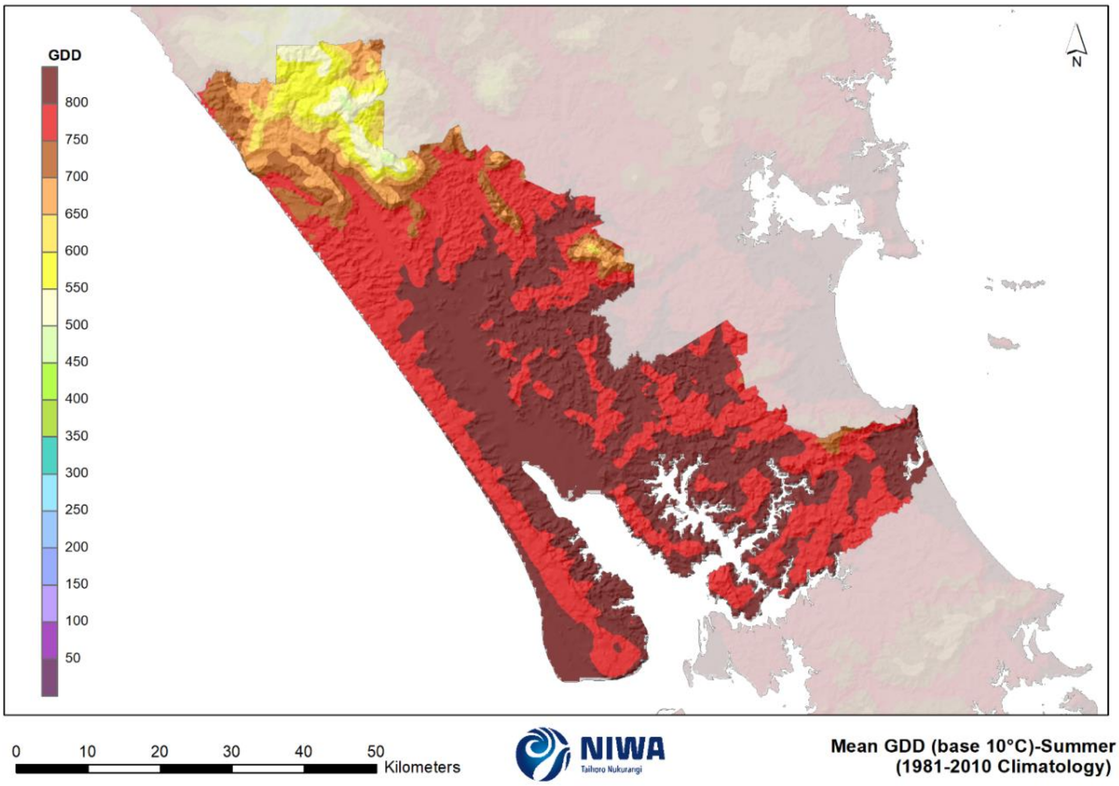

Figure 2-9: Summer mean growing degree days (base 10°C). Based on the 30-year average from 1981-2010. Note the change in colour scale compared to the annual figure above.

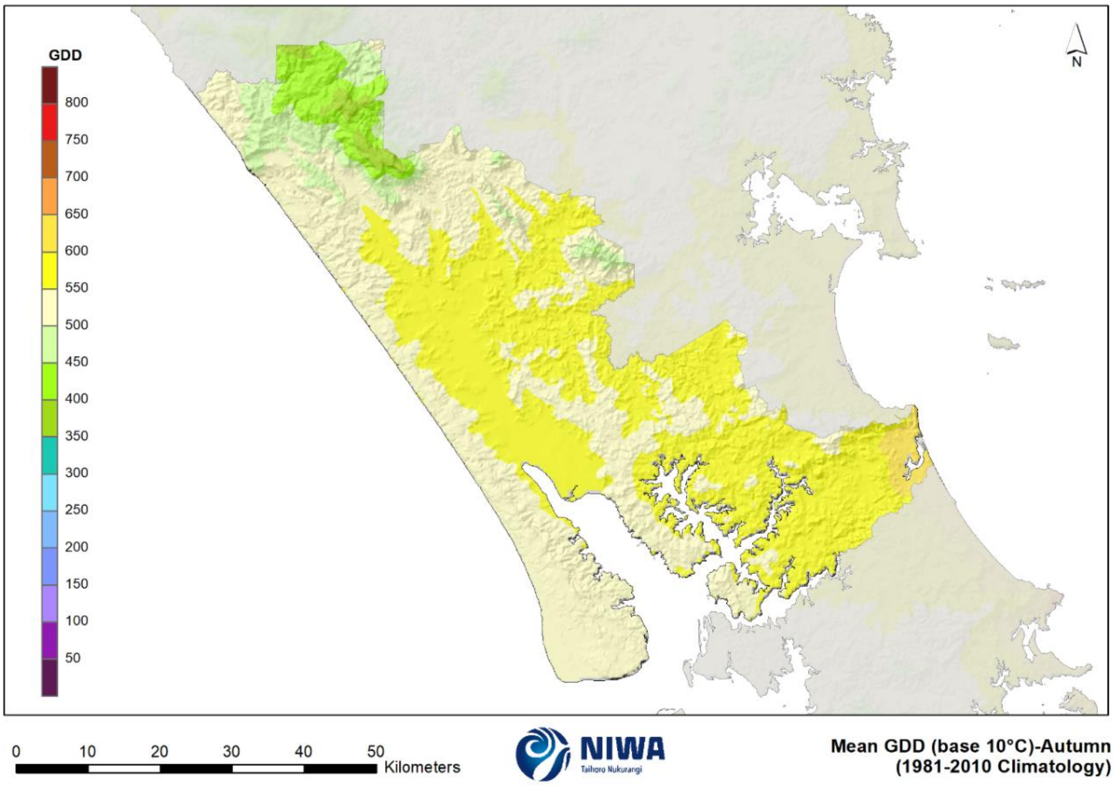

Figure 2-10: Autumn mean growing degree days (base 10°C). Based on the 30-year average from 1981-2010.

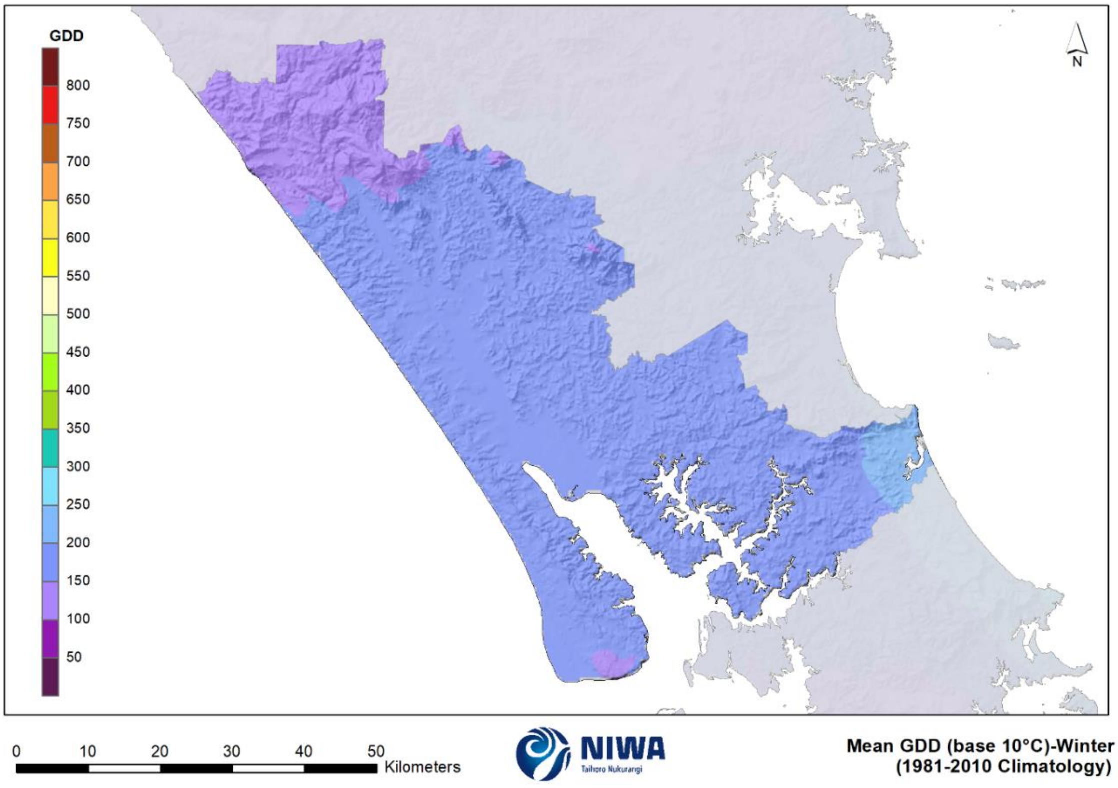

Figure 2-11: Winter mean growing degree days (base 10°C). Based on the 30-year average from 1981-2010.

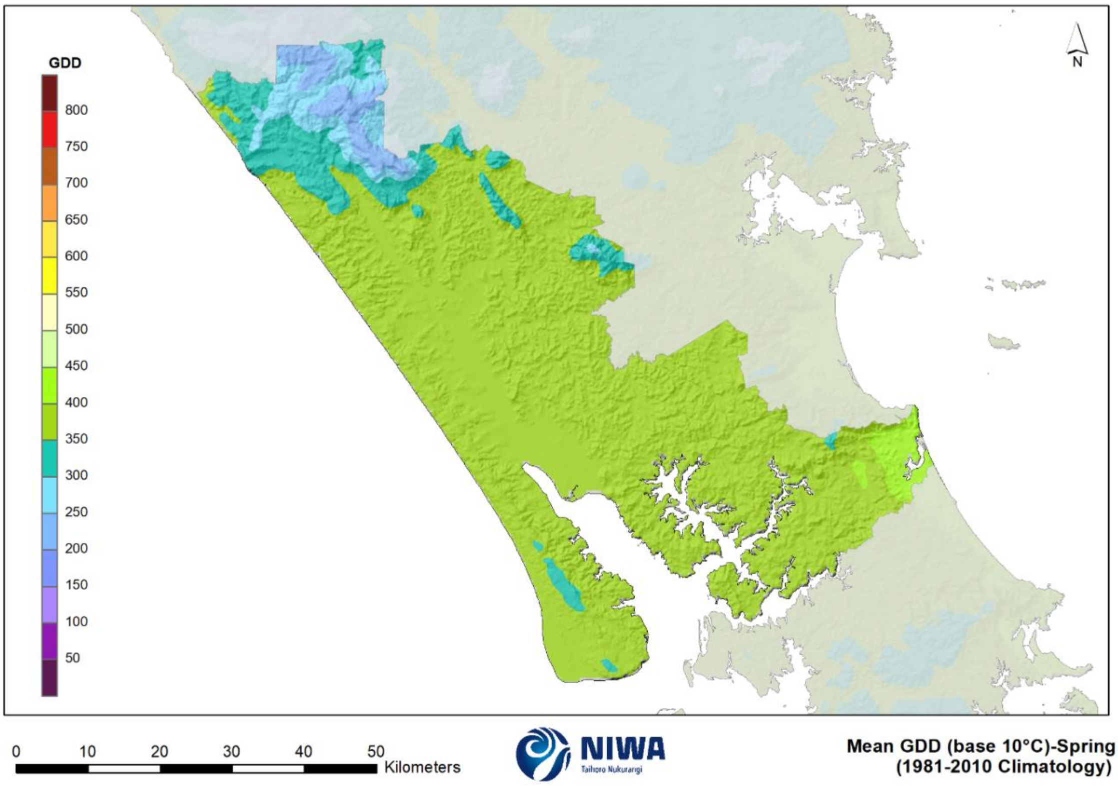

Figure 2-12: Spring mean growing degree days (base 10°C). Based on the 30-year average from 1981-2010.

2.2 Rainfall

Key messages

- The annual average rainfall is between 1,100 mm and 1,400 mm for most of Kaipara District; western areas typically drier than eastern areas.
- Summer typically the driest season, with summer total rainfall ranging from 225 mm to 300 mm for much of the District.
- Winter typically the wettest season, with winter total rainfall ranging from 350 mm to 500 mm for much of the District.
- Dargaville averages 140 wet days per year (i.e. days with at least 1 mm total rainfall). Dargaville averages 7 wet days in January and February, with 17 wet days in August.

2.2.1 Average rainfall

This section includes maps of annual (Figure 2-13), summer (Figure 2-14), autumn (Figure 2-15), winter (Figure 2-16) and spring (Figure 2-17) average rainfall for Kaipara District. Monthly average rainfall maps for Kaipara District are shown in Appendix C.

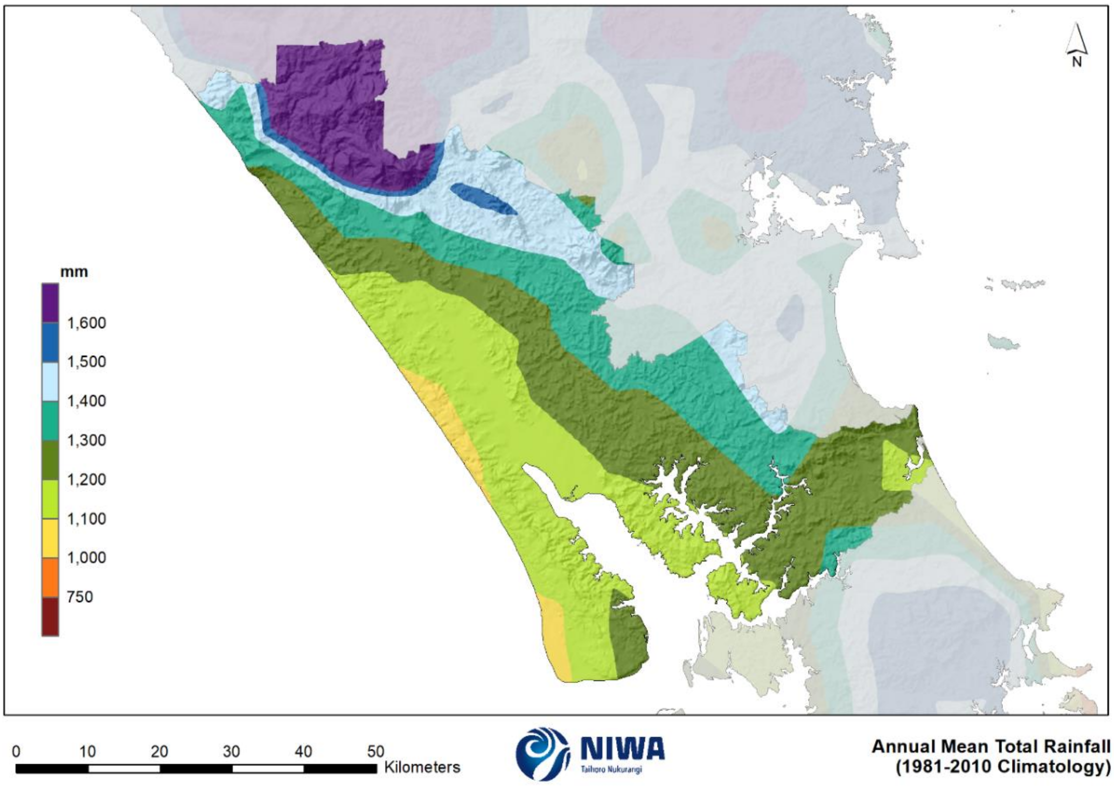

Figure 2-13: Annual average total rainfall (mm). Based on the 30-year average from 1981-2010.

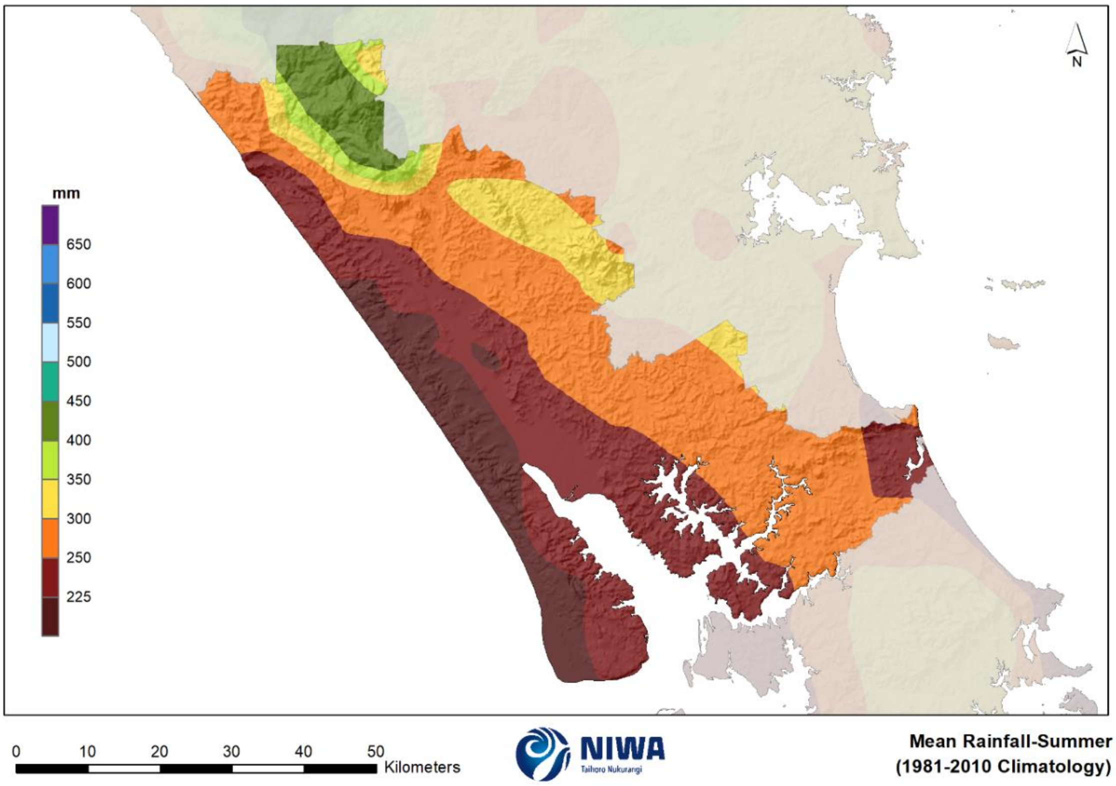

Figure 2-14: Summer average total rainfall (mm). Based on the 30-year average from 1981-2010.

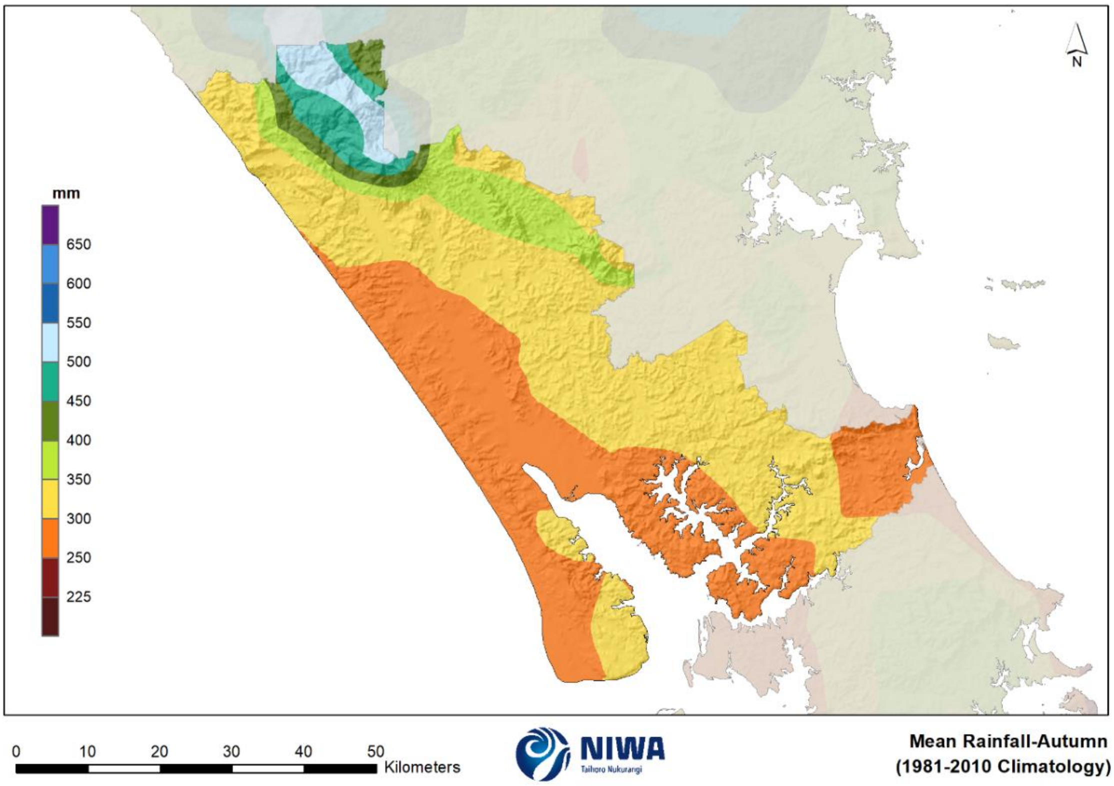

Figure 2-15: Autumn average total rainfall (mm). Based on the 30-year average from 1981-2010.

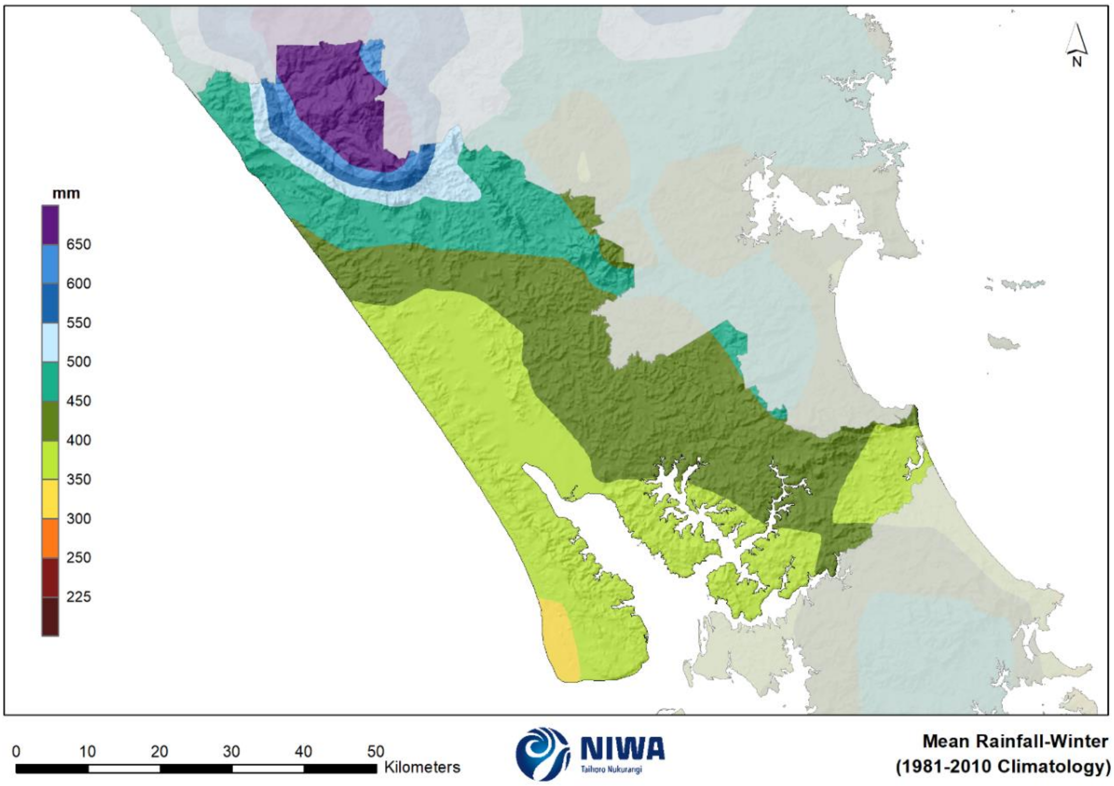

Figure 2-16: Winter average total rainfall (mm). Based on the 30-year average from 1981-2010.

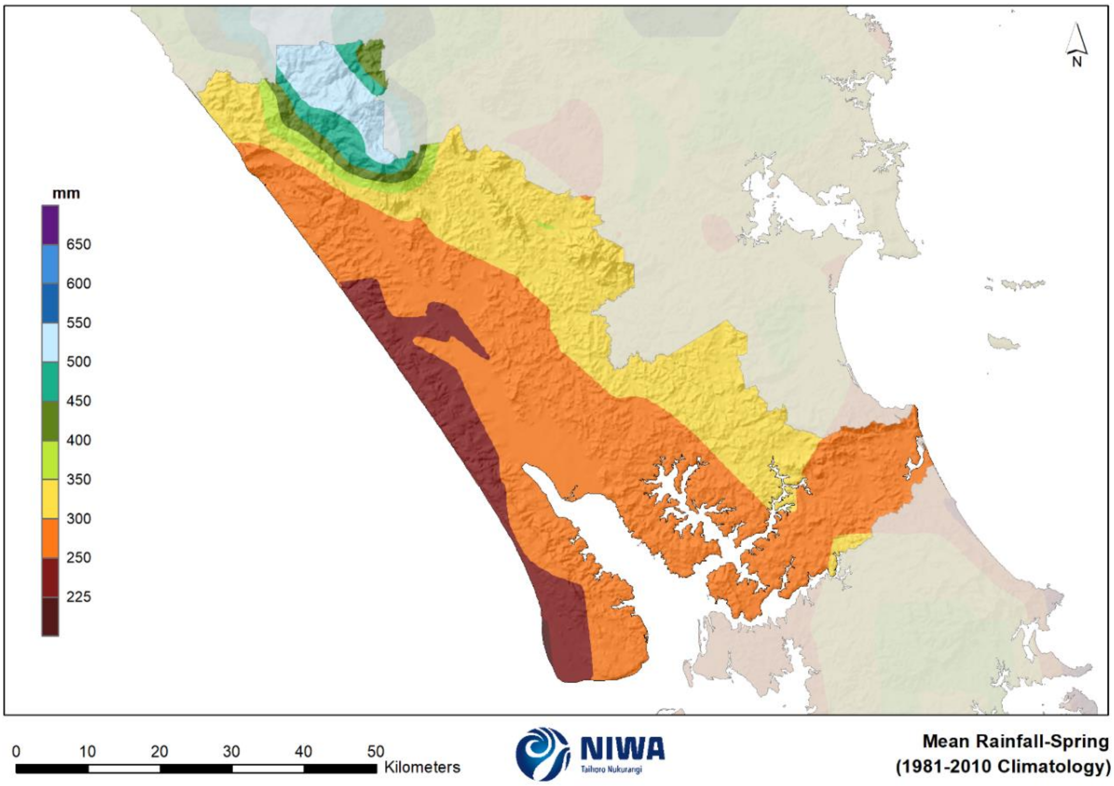

Figure 2-17: Spring average total rainfall (mm). Based on the 30-year average from 1981-2010.

2.2.2 Wet days

In this report, 'wet days' are days when greater than 1 mm of rainfall is recorded. Monthly and annual wet days statistics for Dargaville are presented in Table 2-3. Average number of wet days are based on the climate normal period 1981-2010. Minimum and maximum number of wet days are based on all available data for Dargaville, which spans the period 1905-2019. Data were obtained from NIWA's National Climate Database (CliDB).

Table 2-3: Monthly and annual wet day statistics for Dargaville. Statistics included are average number of wet days (Avg wet days), minimum number of wet days on record (Fewest wet days), and maximum number of wet days on record (Most wet days).

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ANN
Avg wet days	7	7	9	10	14	16	16	17	13	12	9	9	140
Fewest wet days	0	1	1	4	4	7	3	8	5	3	2	1	108
Most wet days	15	14	18	24	26	24	28	25	22	21	20	18	178

2.2.3 Dry spells and drought

Periods of fifteen days or longer with less than 1 mm of rain on any day are referred to as "dry spells". Dry spells in Kaipara are not uncommon and occur most frequently during summer and early autumn. There is usually at least one, and frequently two dry spells each year between December and March. NIWA recently developed a standardised climate index called the New Zealand Drought Index (NZDI), in order to keep track of drought conditions across New Zealand. Note that this index is a measure of meteorological drought[2] and is not to be confused with Government declarations of adverse events due to drought. Figure 2-18 shows the NZDI for Kaipara District from January 2007 to September 2019. According to this index, Kaipara District has regularly observed periods of drought, with three severe droughts occurring since 2007. The most severe drought since 2007 occurred in early 2013, when the NZDI value peaked at 2.49 on 25 March 2013. An adverse event due to drought was declared in Northland by the Government on 27 February 2013. Subsequent analyses determined that the potential evapotranspiration deficit (PED) accumulation for the period July 2012 to May 2013 exceeded 450 millimetres in southern Northland, making it the highest PED accumulation for the area since 1949-50 (Porteous and Mullan, 2013).

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

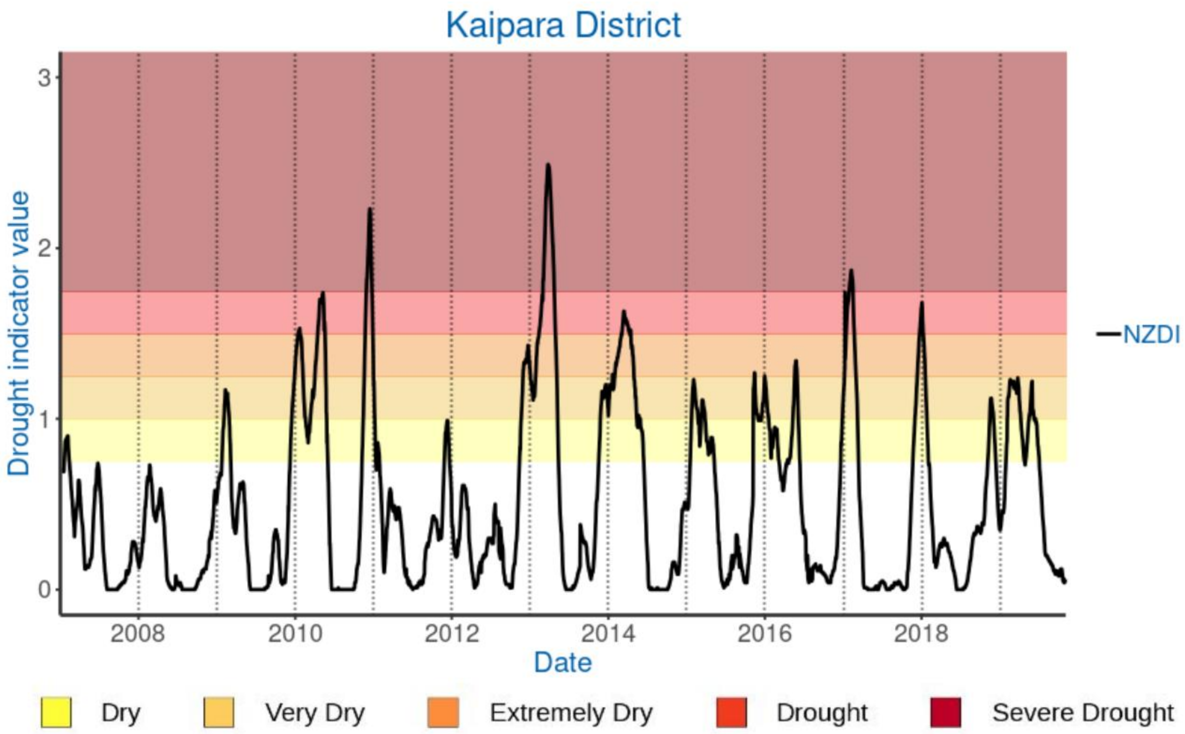

Figure 2-18: New Zealand Drought Index values calculated for Kaipara District, 2007-2019. For more information about this index see https://niwa.co.nz/climate/information-and-resources/drought-monitor.

2.3 Soil moisture deficit

Key messages

- Annual average days of soil moisture deficit between 40-60 days for majority of Kaipara District.
- Days of soil moisture deficit highest in summer (30-50 days), and lowest in winter (< 1 day).
- Monthly average Soil Moisture Deficit maps for Kaipara District are shown in Appendix D.

Soil moisture deficit (SMD) is calculated based on incoming daily rainfall (mm), outgoing daily potential evapotranspiration (PET), and a fixed available water capacity of 150 mm (the amount of water in the soil 'reservoir' that plants can use). In the calculation, evapotranspiration continues at its potential rate until about half of the water available to plants is used up (75 mm out of the total 150 mm available). Subsequently, the rate of evapotranspiration decreases, in the absence of rain, as further water extraction takes place. Evapotranspiration is assumed to cease if all the available water is used up (i.e. all 150 mm).

A day of SMD is considered in this report to be when soil moisture is below 75 mm of available soil water capacity. The timing of changes in the days of soil moisture deficit projections indicates how droughts may change in timing throughout the year.

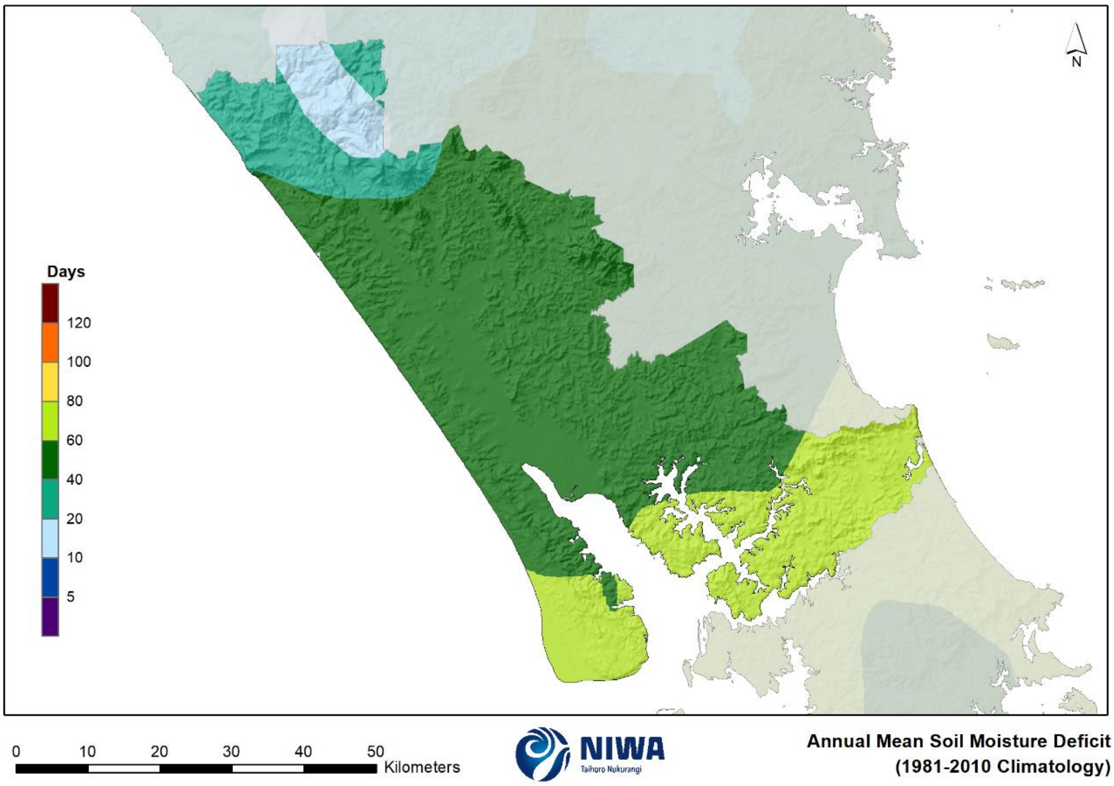

Figure 2-19: Annual mean days of soil moisture deficit. Based on the 30-year average from 1981-2010.

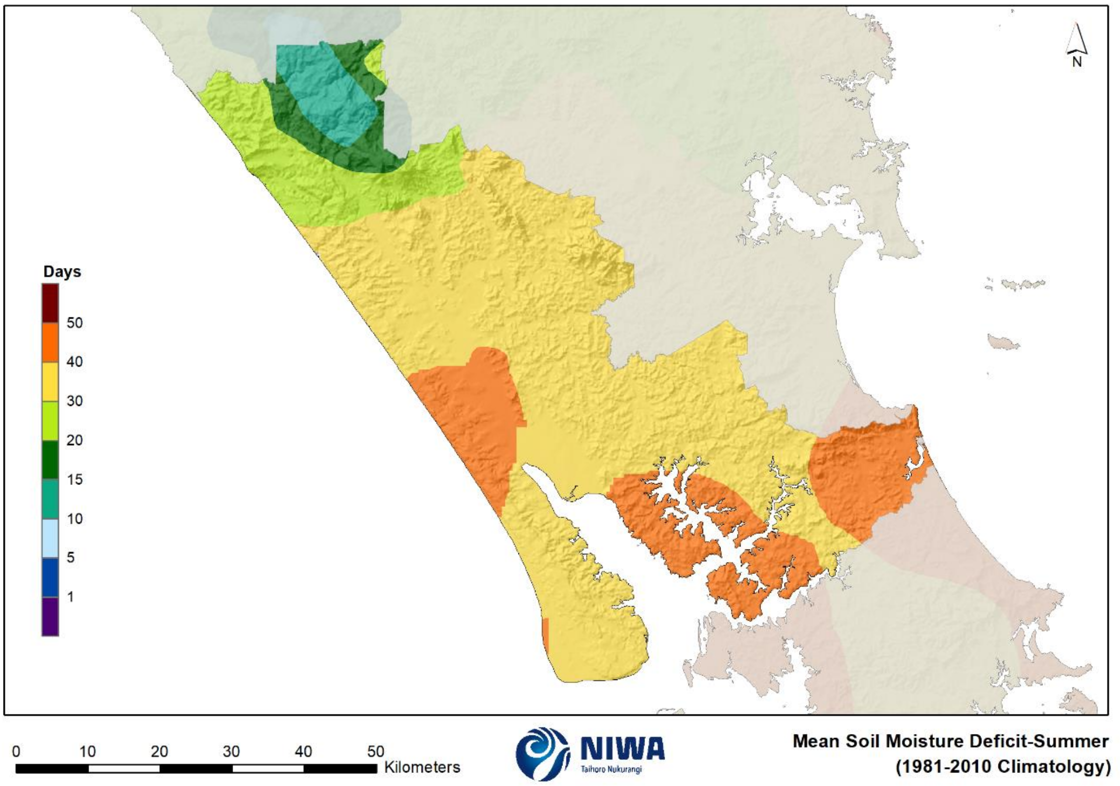

Figure 2-20: Summer mean days of soil moisture deficit. Based on the 30-year average from 1981-2010.

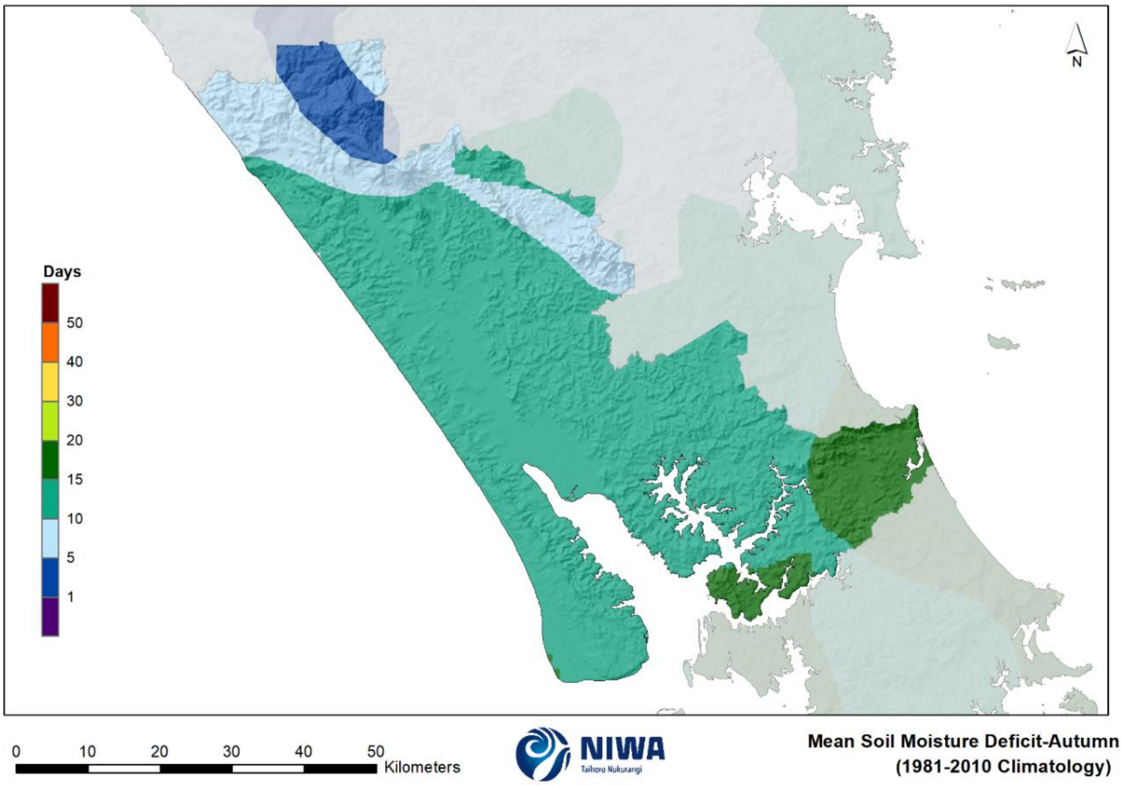

Figure 2-21: Autumn mean days of soil moisture deficit. Based on the 30-year average from 1981-2010.

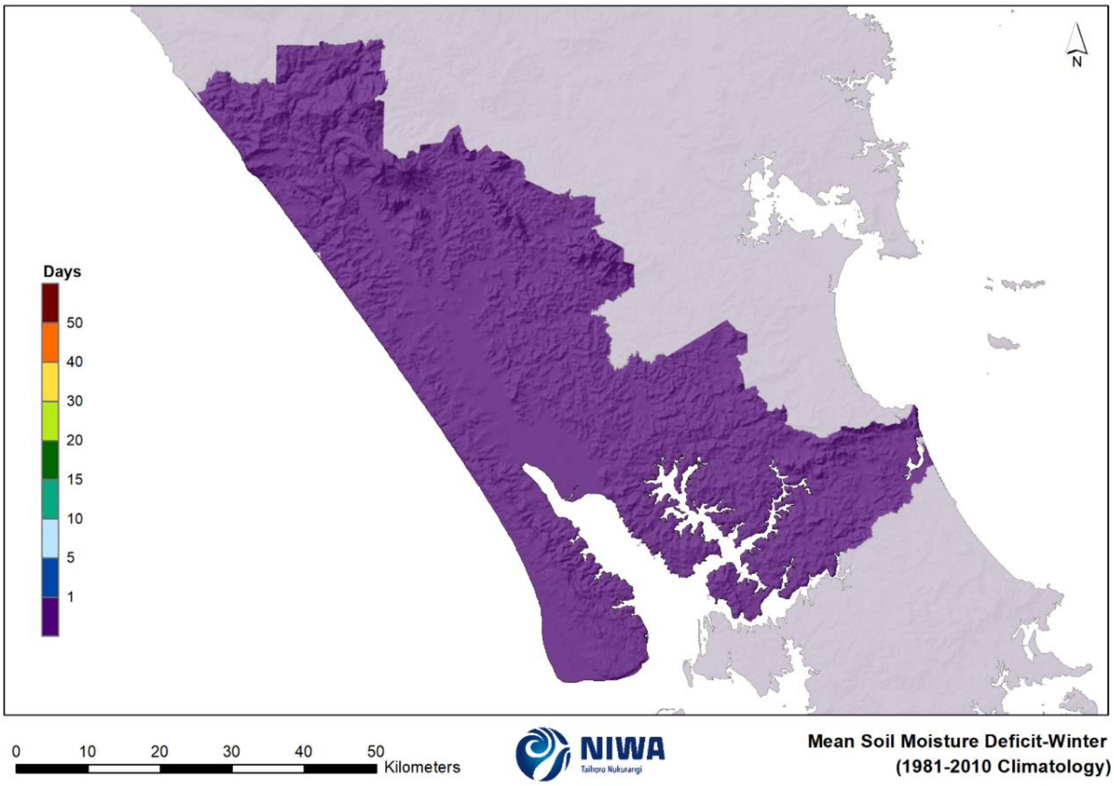

Figure 2-22: Winter mean days of soil moisture deficit. Based on the 30-year average from 1981-2010.

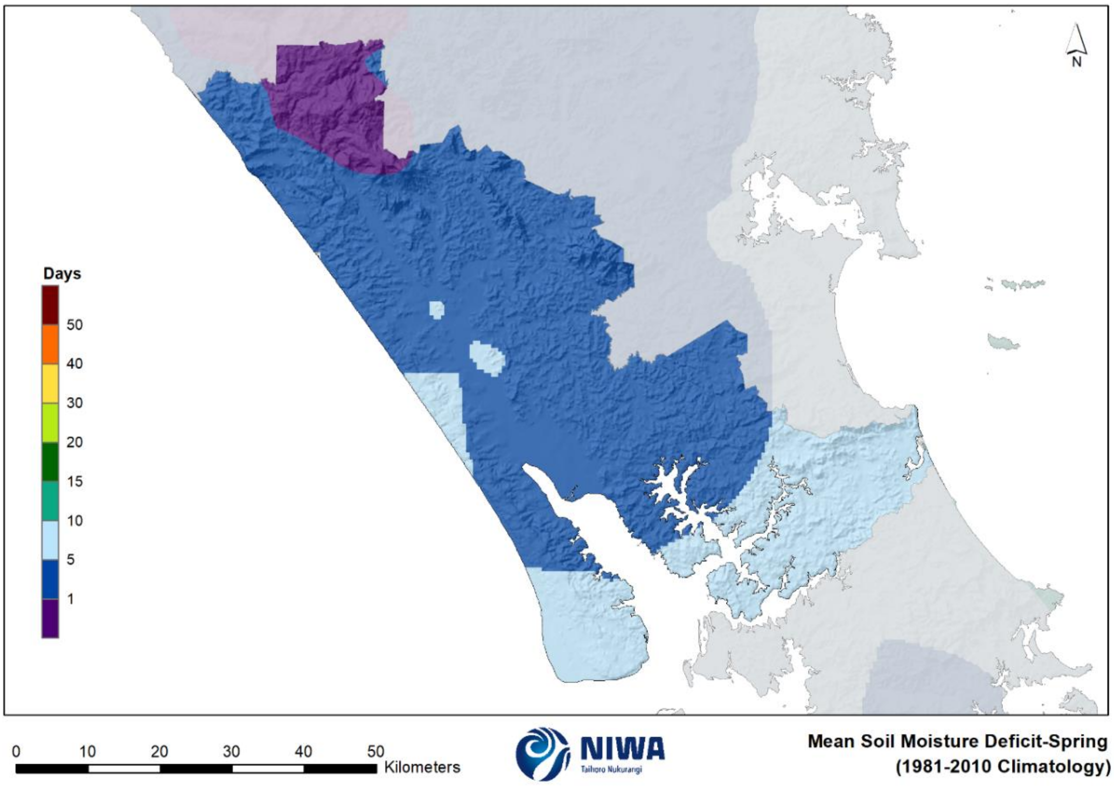

Figure 2-23: Spring mean days of soil moisture deficit. Based on the 30-year average from 1981-2010.

2.4 Sunshine

Key messages

- Median annual sunshine hours in Kaipara typically range between 1,850-1,950 hours.
- Dargaville's highest monthly sunshine hours typically observed in January.

Median annual sunshine hours for Northland are shown in Figure 2-24. For Kaipara District, annual sunshine hours typically range between 1,850-1,950 hours. In Dargaville, highest monthly sunshine hours are typically observed in January (approximately 210 hours), with fewest sunshine hours observed in June (approximately 100 hours) (Chappell, 2013).

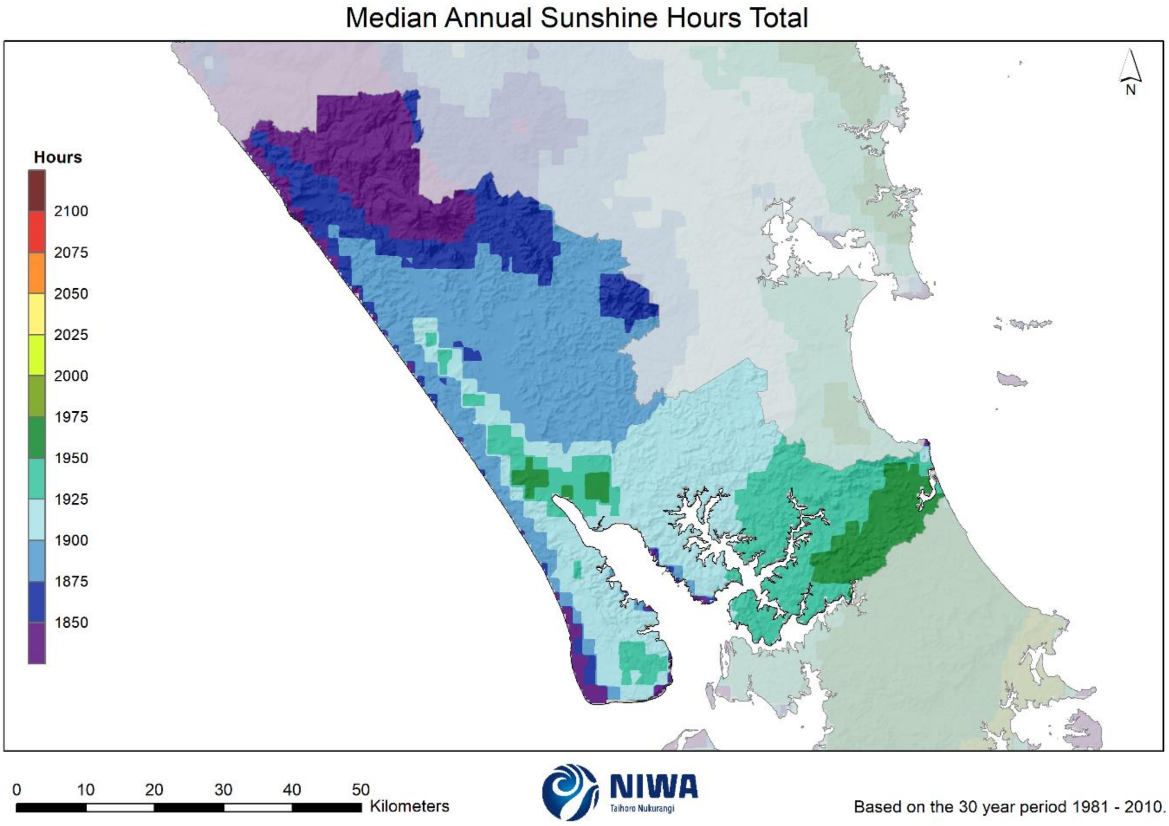

Figure 2-24: Median annual sunshine hours. Based on the 30-year average from 1981-2010.

2.5 Wind

Key messages

- Median annual average wind speed 3-5 m/s for much of Kaipara District.
- Strongest winds in Dargaville are typically from the west or southwest direction.

Median annual average wind speed for Kaipara District is shown in Figure 2-25. Median annual average wind speed for the District is 3-5 m/s. A wind rose for Dargaville is shown in Figure 2-26, illustrating that strongest winds there are typically between the directions of west and southwest.

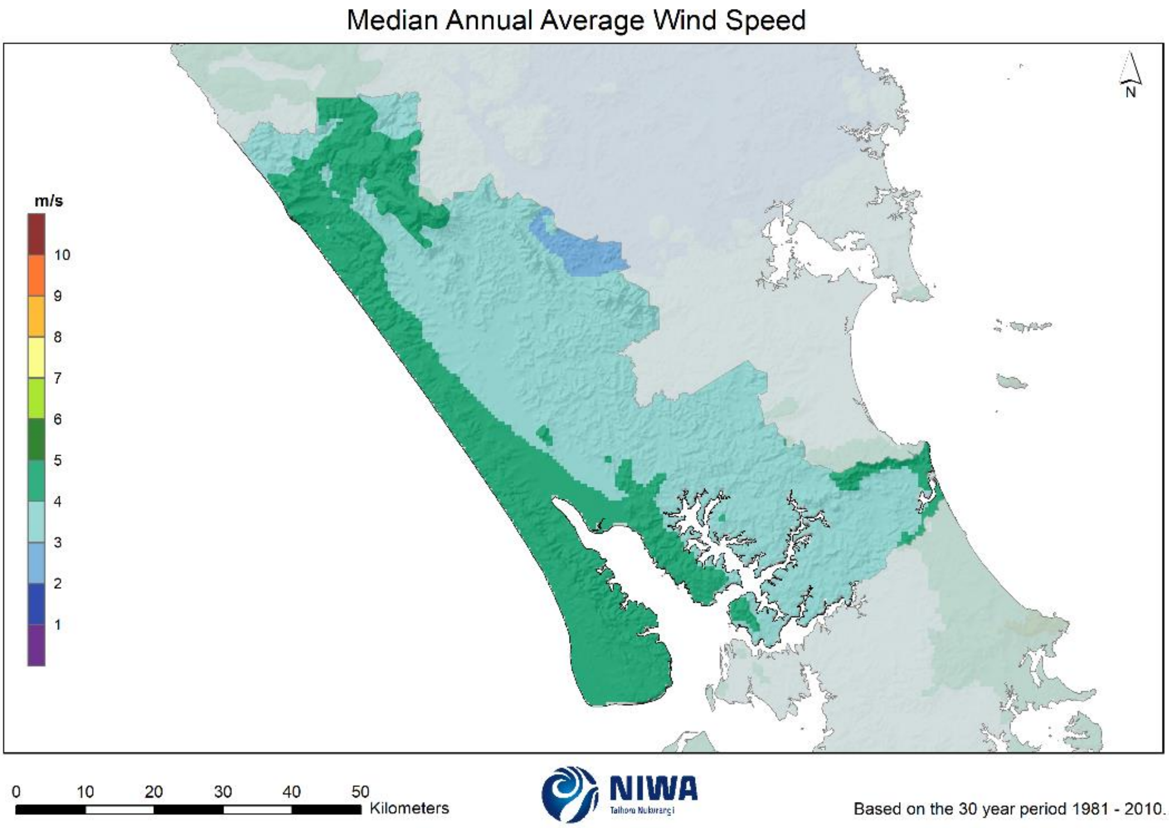

Figure 2-25: Median annual average wind speed (m/s). Based on the 30-year average from 1981-2010.

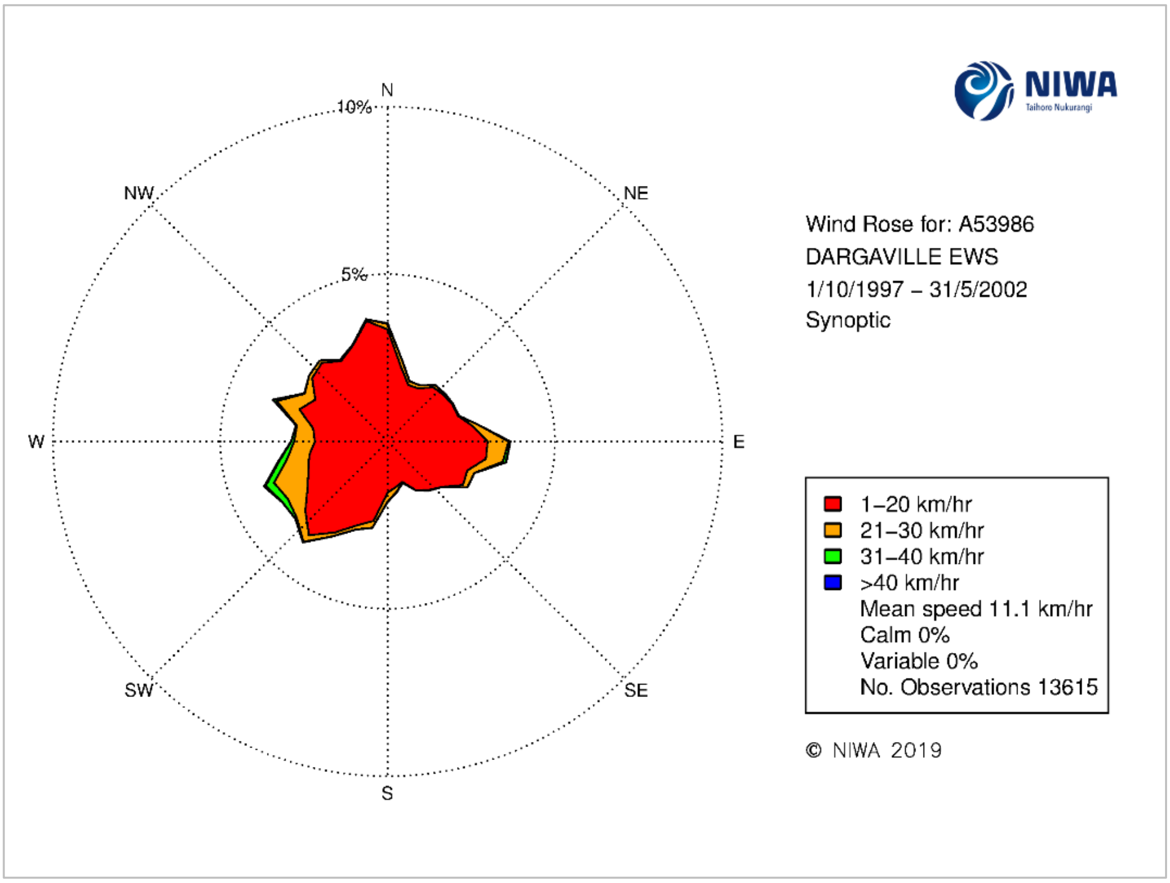

Figure 2-26: Wind rose for Dargaville. Based on data measured from 1997-2002.

3 Climate projections for Kaipara District

The projected future changes presented in this report consider differences between the historical period (based on the 1986-2005 average) and two future time-slices, 2031-2050 (2040) and 2081-2100 (2090). Note, the modelled differences between two time periods should not be attributed solely to climate change, as natural climate variability is also present and may add to or subtract from the climate change effect. The effect of natural variability has been reduced by averaging results from six GCM simulations, but it will still be present.

3.1 Temperature

3.1.1 Average temperature

Key messages

- Projected Kaipara District temperature changes increase with time and greenhouse gas concentrations.
- Future annual and seasonal average warming spans a wide range: 0.5-1.5°C by 2040, and 1.0-3.5°C by 2090.

Annual average temperature is projected to increase by 0.5-1.0°C for all seasons (and annual) by 2040 under RCP4.5 (Figure 3-1). The same is projected for 2040 under RCP8.5, except autumn is projected to warm by 1.0-1.5°C (Figure 3-2). By 2090, most of the region is projected to warm by 1.0-1.5°C under RCP4.5 for all seasons and at the annual scale (Figure 3-3). Under RCP8.5 (Figure 3-4), warming is projected to be around 2.0-3.5°C for most of the region at the annual and seasonal scale.

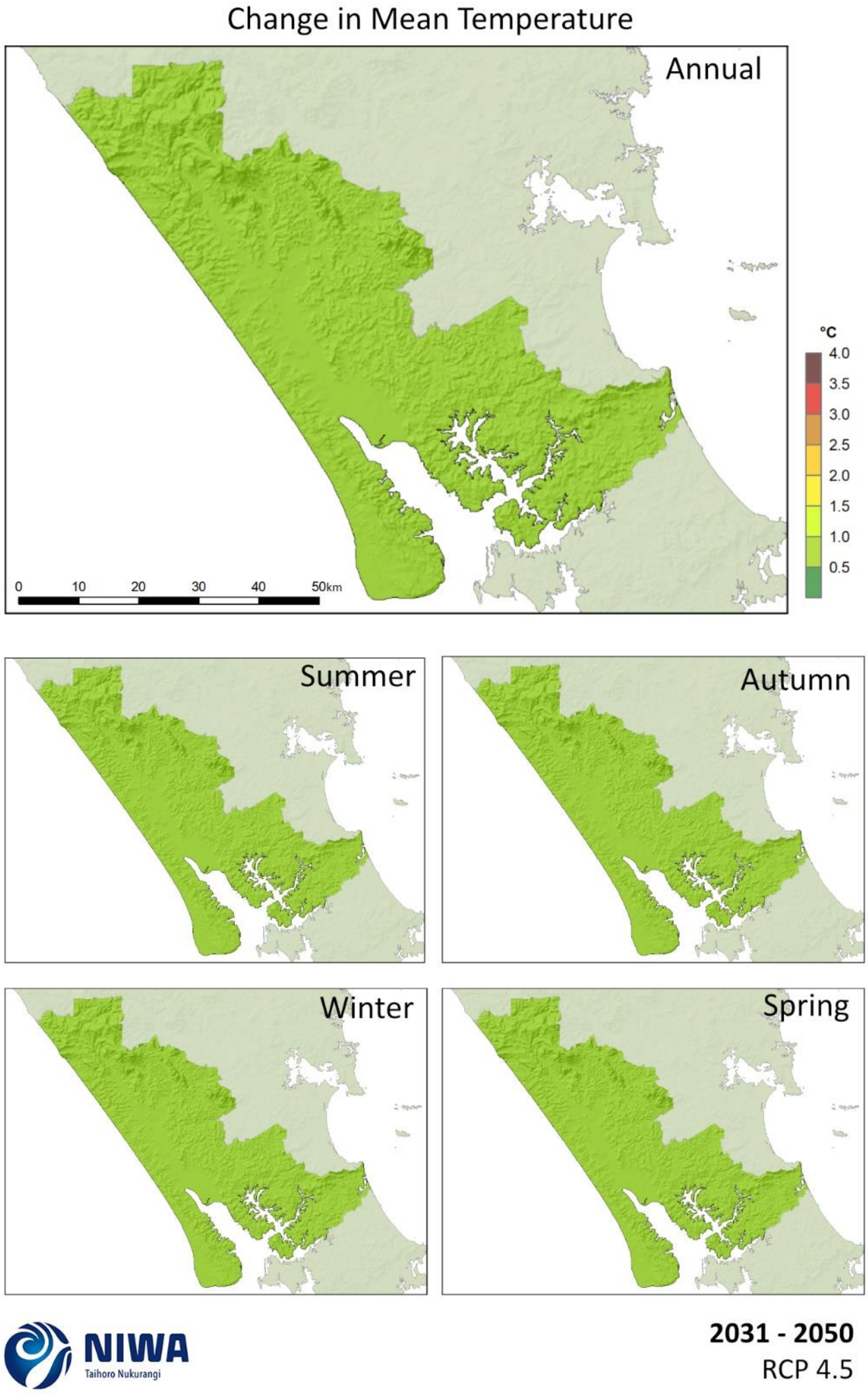

Figure 3-1: Projected annual and seasonal mean temperature changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

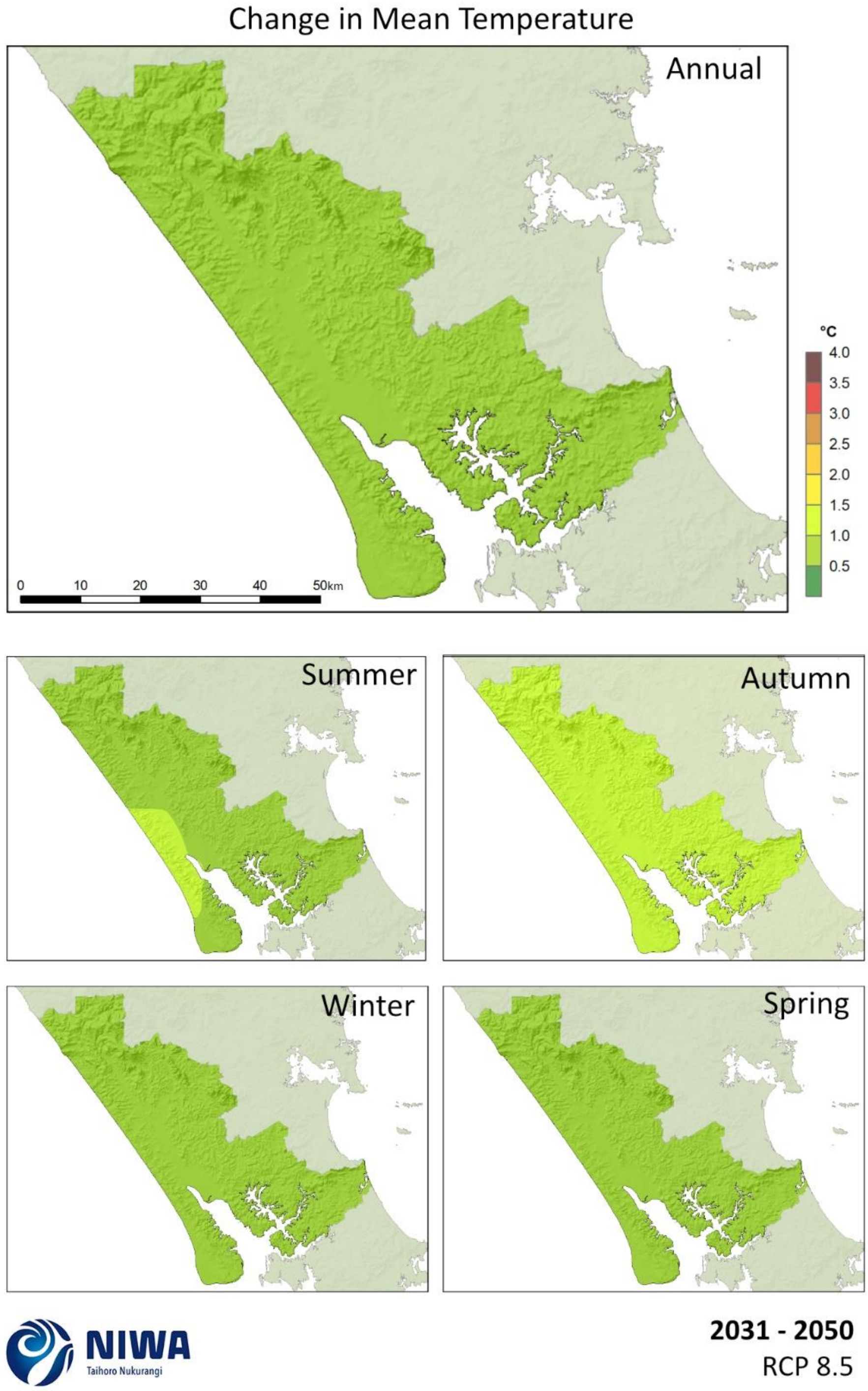

Figure 3-2: Projected annual and seasonal mean temperature changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

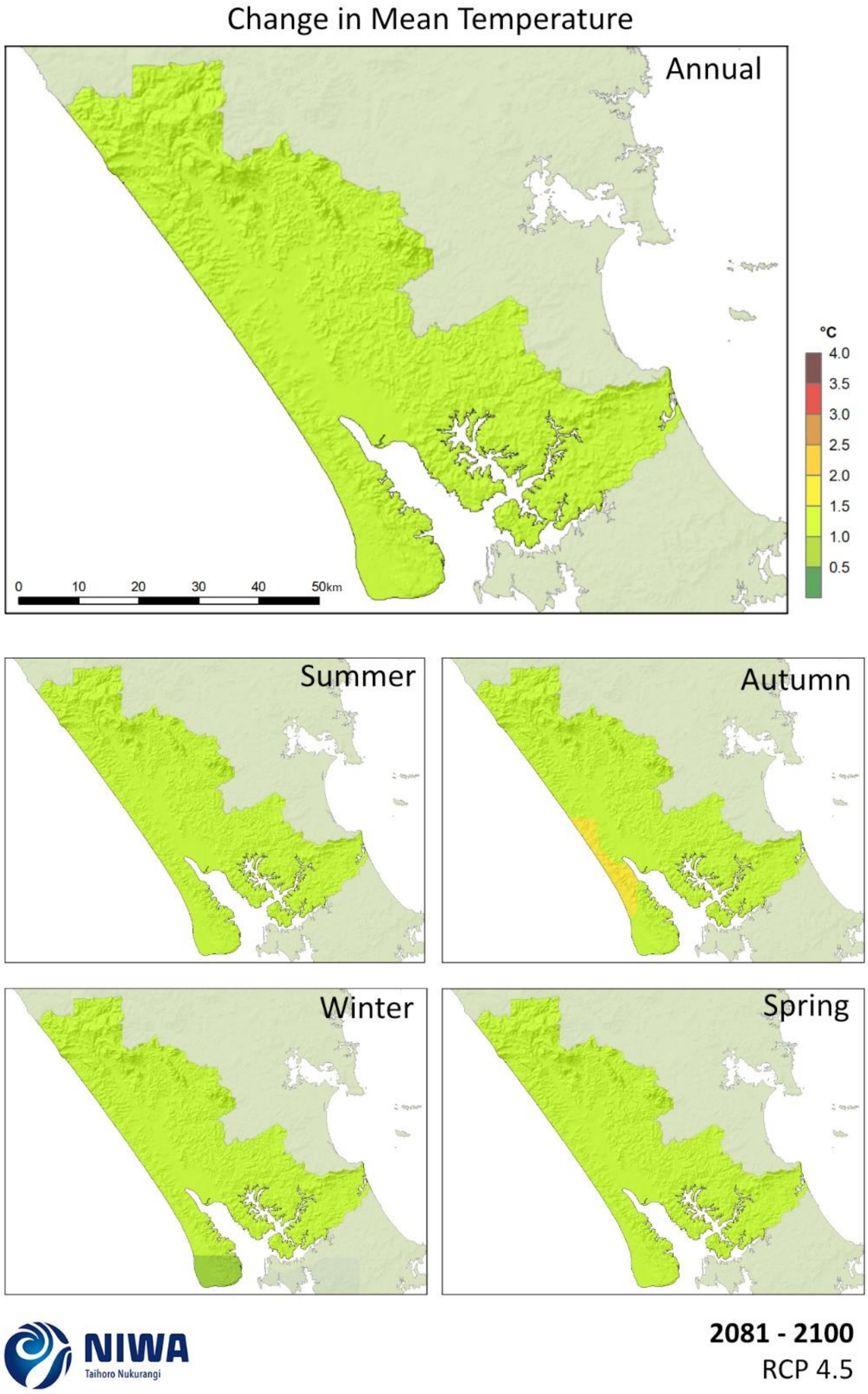

Figure 3-3: Projected annual and seasonal mean temperature changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

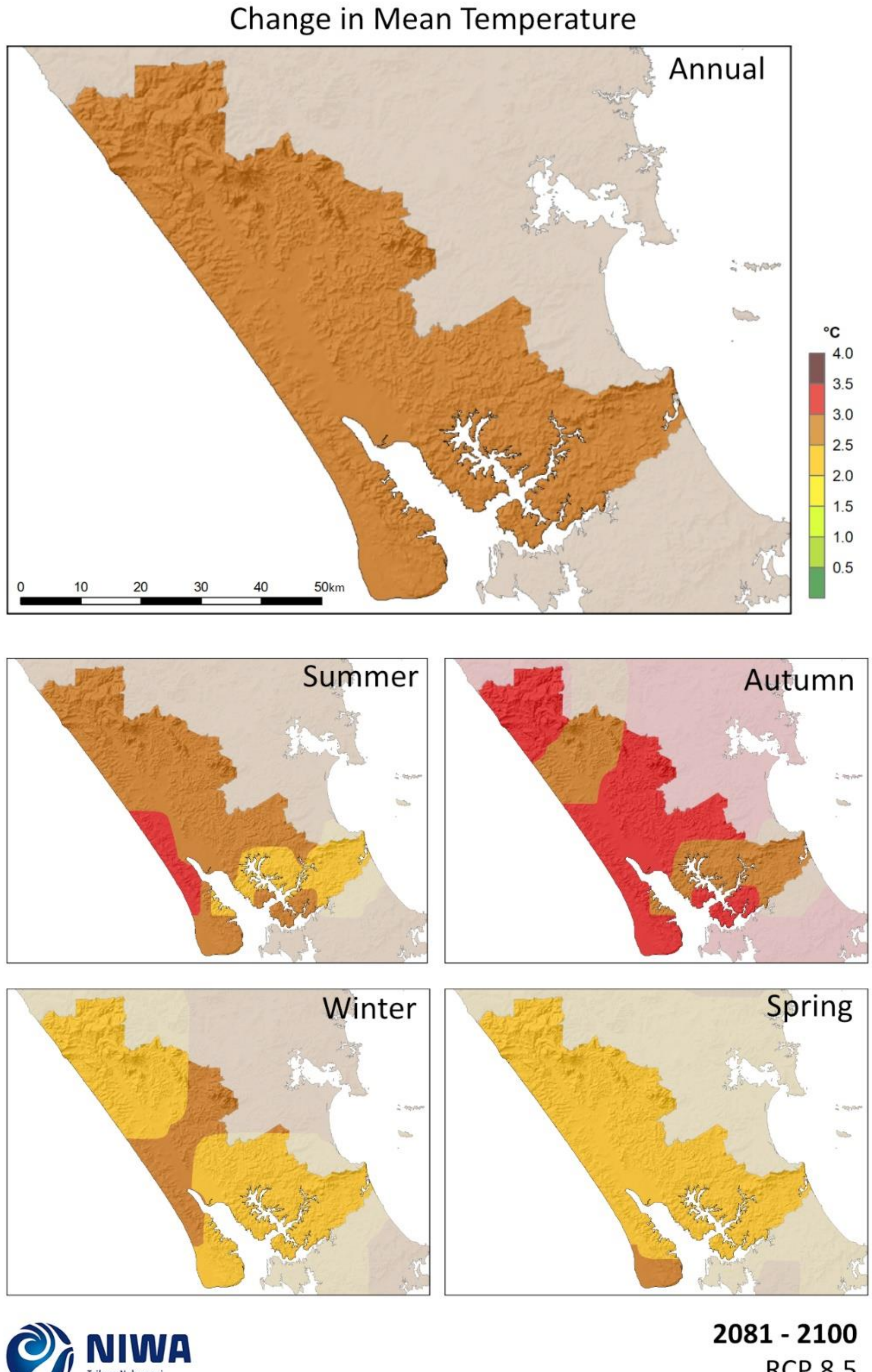

Figure 3-4: Projected annual and seasonal mean temperature changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

3.1.2 Hot days

Key messages

- Parts of Kaipara District are projected to observe a considerable increase in hot days of 60-80 days per year (by 2090 under RCP8.5).
- An increase in annual hot days of 5-20 days is projected for Kaipara District by 2040 under RCP4.5 and RCP8.5.

In this section, future projections of hot days (days above 25°C) were calculated as the difference from modelled historic average number of hot days (based on the 1986-2005 average). In the future, the number of hot days per year shows similar patterns under both RCP4.5 and RCP8.5 by 2040 (Figure 3-5), with increases of around 5-20 days. By 2090, the projected magnitude of changes in hot days are quite different between the two scenarios, although the spatial pattern is similar. Under RCP4.5, 15-40 more hot days per year are projected for most of Kaipara District. In contrast, under RCP8.5 60-80 more hot days per year are projected for the District.

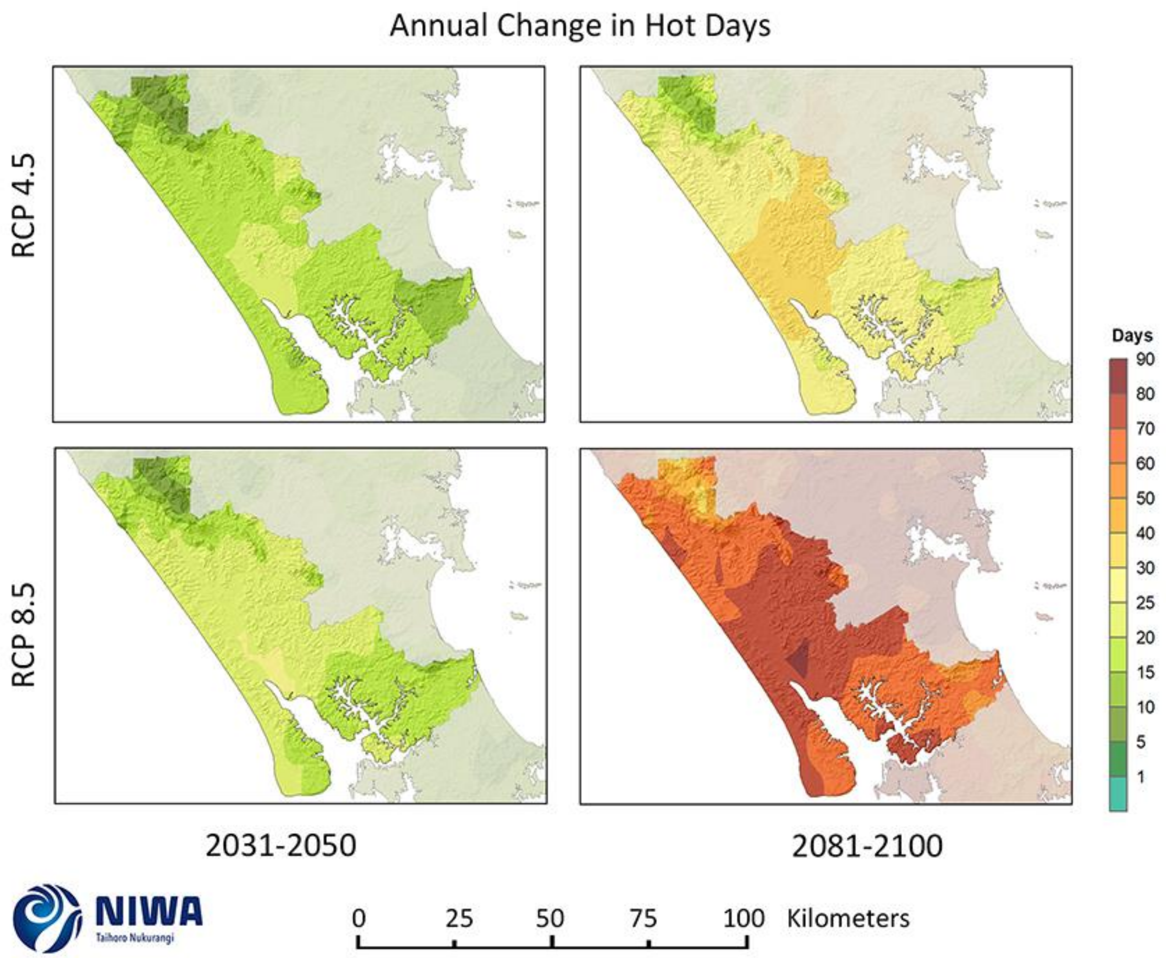

Figure 3-5: Projected annual hot day (maximum temperature >25°C) changes for RCP4.5 and RCP8.5, by 2040 and 2090. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

3.1.3 Extreme hot days

Key messages

- Western parts of Kaipara District are projected to observe an increase in extreme hot days of 10-12 days per year (by 2090 under RCP8.5).
- A minor increase (<2 days) in annual extreme hot days is projected for most of Kaipara District by 2040 under RCP4.5 and RCP8.5.

In this report, an extreme hot day is when the maximum temperature is above 30°C. Future (average over 2031-2050 and 2081-2100) maps for extreme hot days are shown in this section (Figure 3-6). Minor increases in extreme hot days of between 0-1 days are projected by 2040 under RCP4.5 and RCP8.5. In contrast, by 2090 under RCP8.5, western parts of Kaipara District are projected to see a 10-12 day increase in extreme hot days.

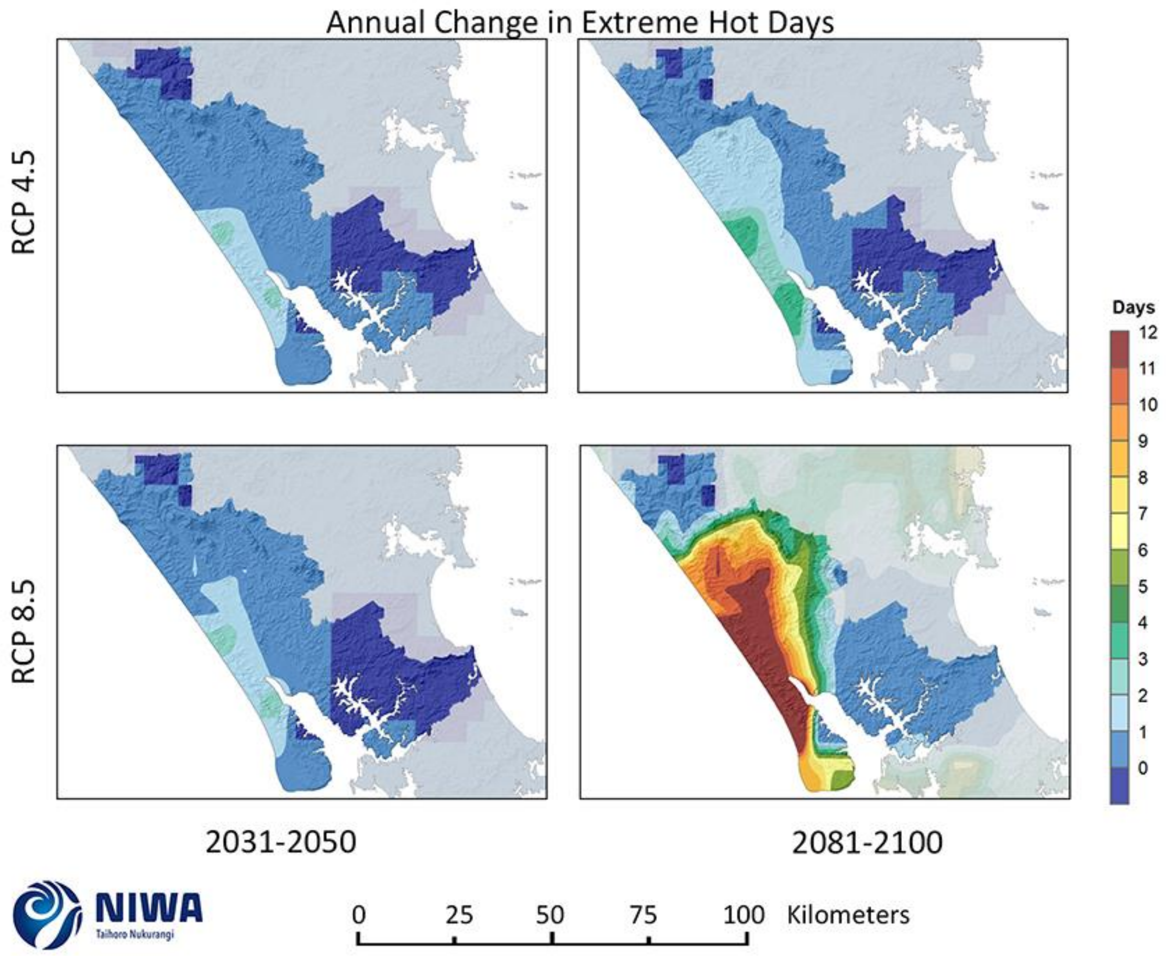

Figure 3-6: Projected annual extreme hot day (maximum temperature >30°C) changes for RCP4.5 and RCP8.5, by 2040 and 2090. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

3.1.4 Heatwave days

Key messages

- Much of Kaipara District is projected to observe an increase in heatwave days of 60-80 days per year (by 2090 under RCP8.5).
- An increase of 10-20 heatwave days is projected for most of Kaipara District by 2040 under RCP4.5 and RCP8.5.

The definition of a heatwave as considered here is a period of three or more consecutive days where the maximum daily temperature exceeds 25°C. This calculation is an aggregation of all days per year that are included in a heatwave (i.e., ≥ three consecutive days with maximum temperature > 25°C), no matter the length of the heatwave. The annual heatwave days are then averaged over the 20-year period of interest (e.g., 2031-2050) to get the average annual heatwave-day climatology (past) and future projections.

Future (average over 2031-2050 and 2081-2100) maps for heatwave days are shown in this section (see Figure 3-7). The future projection maps show the change in the annual number of heatwave-days compared with the historic climatology (in this case 1986-2005).

The number of heatwave days per year shows similar patterns of change under both RCP4.5 and RCP8.5 by 2040, with projected increases of 10-20 days for much of Kaipara District (Figure 3-7). By 2090, the projected magnitude of changes in heatwave days are quite different between the two scenarios. Under RCP4.5, 20-30 more heatwave days are projected for most of Kaipara District. Under RCP8.5, 60-80 more heatwave days per year are projected for most of the area.

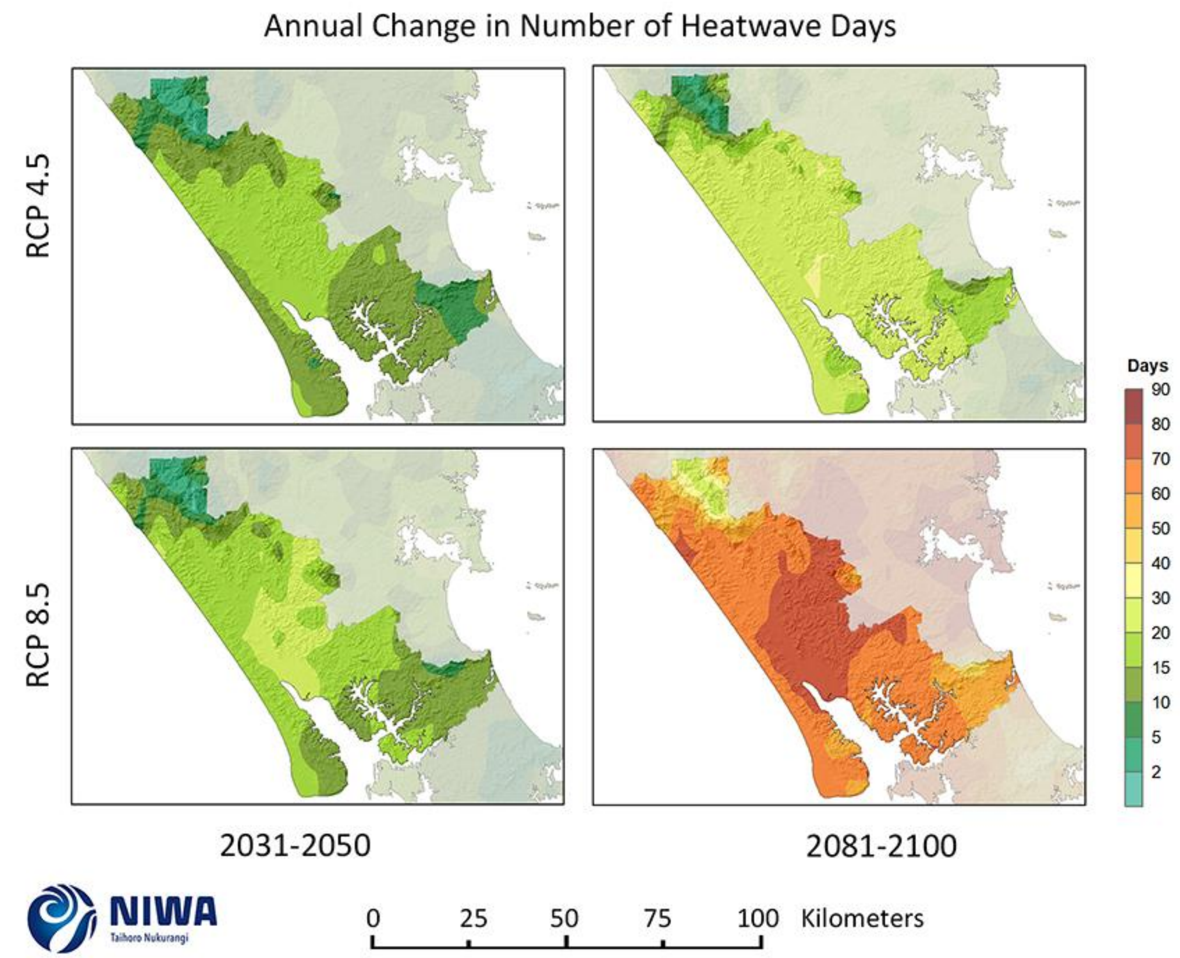

Figure 3-7: Projected annual heatwave day (≥ three consecutive days with maximum temperatures > 25°C) changes for RCP4.5 and RCP8.5, by 2040 and 2090. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

3.1.5 Growing degree days

Key messages

- Most of Kaipara District is projected to observe an increase in growing degree days of 900-1,000 GDD per year (by 2090 under RCP8.5).
- An increase of 250-350 GDD is projected for most of Kaipara District by 2040 under RCP4.5 and RCP8.5.

Future (average over 2031-2050 and 2081-2100) maps for Growing Degree Days (GDD) are shown in this section (see Figure 3-8). The future projection maps show the annual change in GDD compared with the historic period (in this case 1986-2005).

In the future, the number of GDD is projected to increase under all scenarios. By 2040 under RCP4.5, most of the District observes a projected increase of 250-300 GDD per year. By 2040 under RCP8.5, most of the District observes a projected increase of 300-350 GDD per year. By 2090 under RCP4.5, increases of 400-450 GDD per year are projected. By 2090 under RCP8.5, increases of 900-1,000 GDD per year are projected for the majority of Kaipara District.

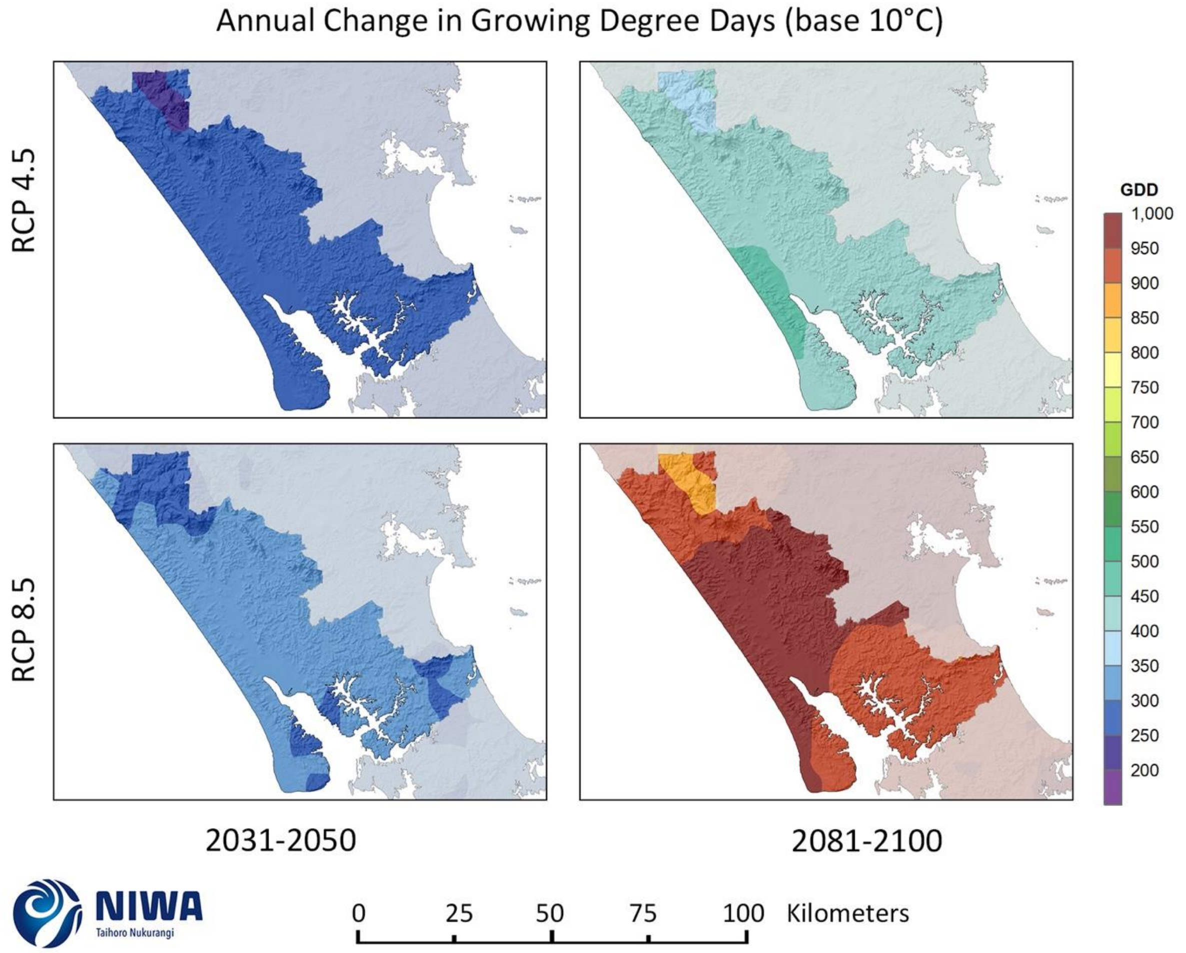

Figure 3-8: Projected annual growing degree-day (base 10°C) changes for RCP4.5 and RCP8.5, by 2040 and 2090. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

3.2 Rainfall and drought

3.2.1 Rainfall

Key messages

- Little change in annual rainfall (±2%) projected for most of Kaipara District by 2040 under both RCP4.5 and RCP8.5, and by 2090 under RCP4.5.
- Annual rainfall projected to decrease by 2-6% in northern inland areas by 2090 under RCP8.5.
- Increases in autumn rainfall between 2-15% are projected for most of the District under all future scenarios.
- Decreases in winter and spring rainfall of 6-15% are projected for many parts of Kaipara District by 2090 under RCP8.5.

This section contains maps showing the future projected change in total rainfall. Future (average over 2031-2050 and 2081-2100) maps show the percentage change in rainfall compared with the historic total (based on the 1986-2005 average).

Kaipara District is generally projected to observe small changes to future annual rainfall. By 2040 under RCP4.5 (Figure 3-9), projected changes to annual rainfall are typically ±2%, with 2-4% more annual rainfall projected for northern coastal areas. By 2040 under RCP8.5 (Figure 3-10), annual rainfall is projected to change by ±2% throughout Kaipara District. At the seasonal scale, increases in autumn rainfall of between 6-15% are projected for much of Kaipara District by 2040 under RCP4.5 (Figure 3-9), with a decrease in summer rainfall of 4-8% projected under this scenario. By 2040 under RCP8.5 (Figure 3-10), increases in autumn rainfall of between 2-8% are projected for much of Kaipara District, with a decrease in spring rainfall of 2-10% projected in most parts.

By 2090 under RCP4.5 (Figure 3-11), annual rainfall changes of ±2% are projected for Kaipara District. By 2090 under RCP8.5 (Figure 3-12), a decrease in annual rainfall of 2-6% is projected for northern and inland parts of Kaipara District. At the seasonal scale, increases in autumn rainfall of between 4-10% are projected for much of Kaipara District by 2090 under RCP4.5 (Figure 3-11Figure 3-9), with a decrease in spring rainfall of 4-10% projected under this scenario. By 2090 under RCP8.5 (Figure 3-12), increases in autumn rainfall of between 6-15% are projected for southern parts of Kaipara District, with a decrease in winter and spring rainfall of 6-15% projected in most parts.

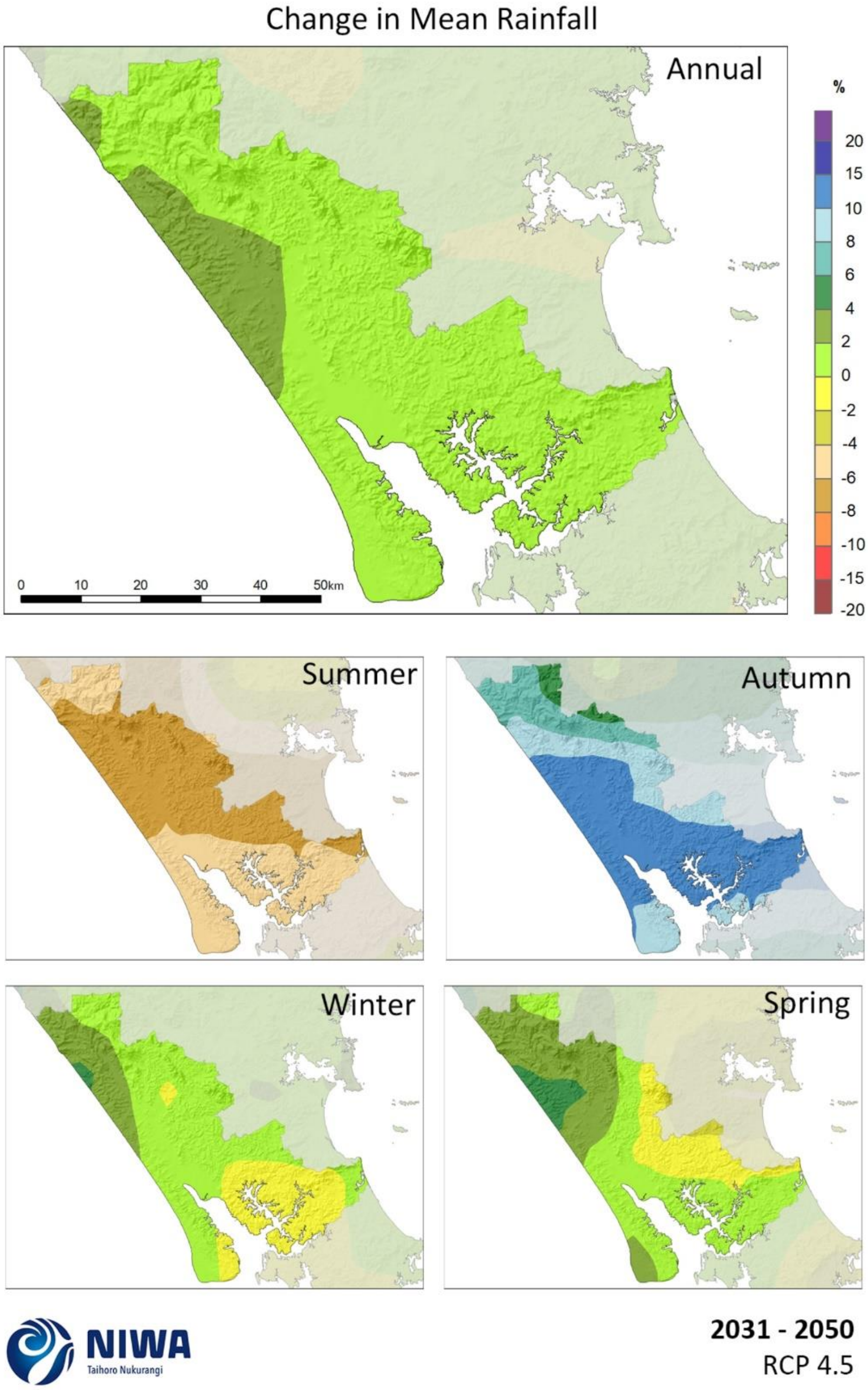

Figure 3-9: Projected annual and seasonal mean rainfall changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

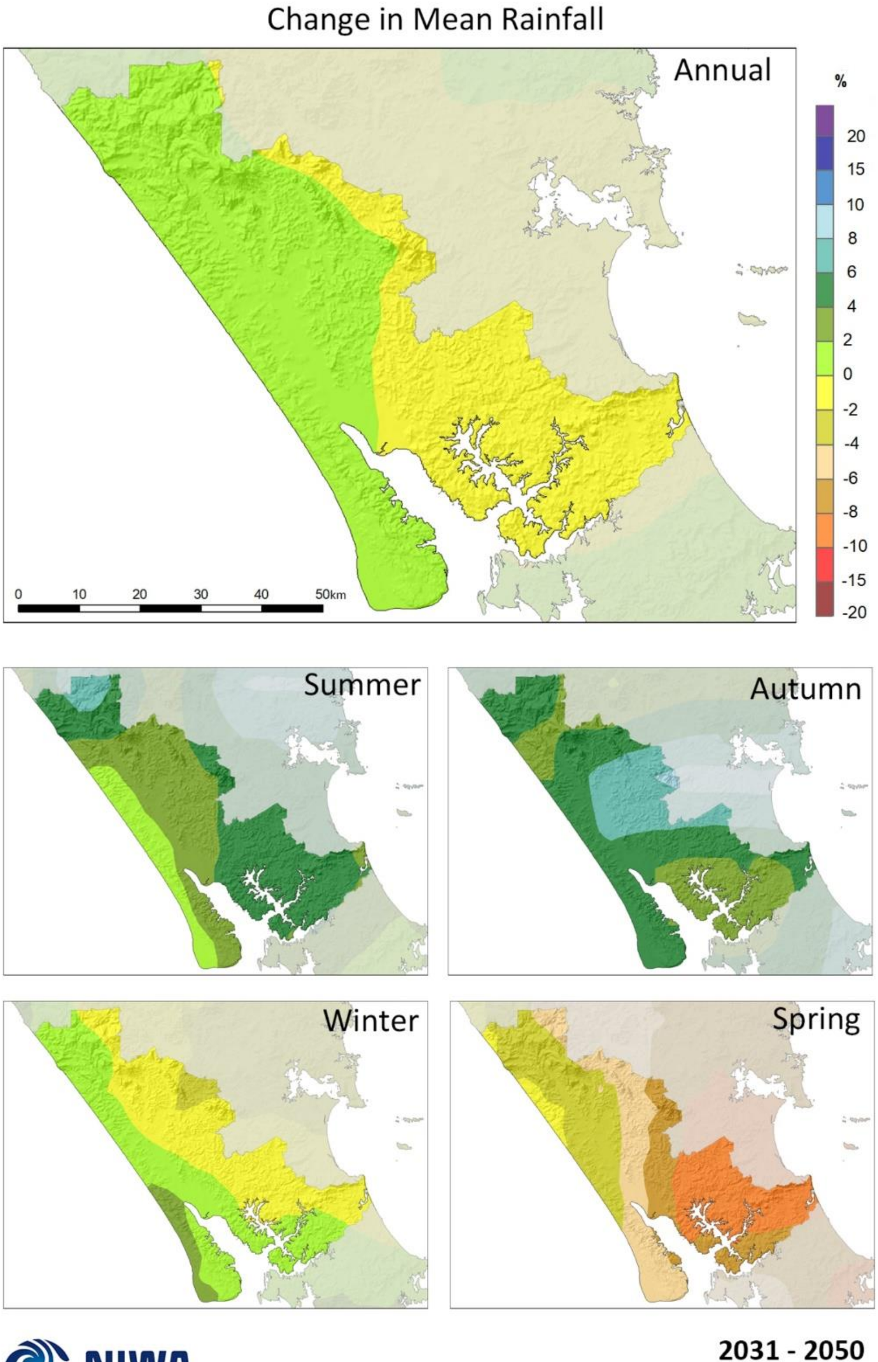

Figure 3-10: Projected annual and seasonal mean rainfall changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

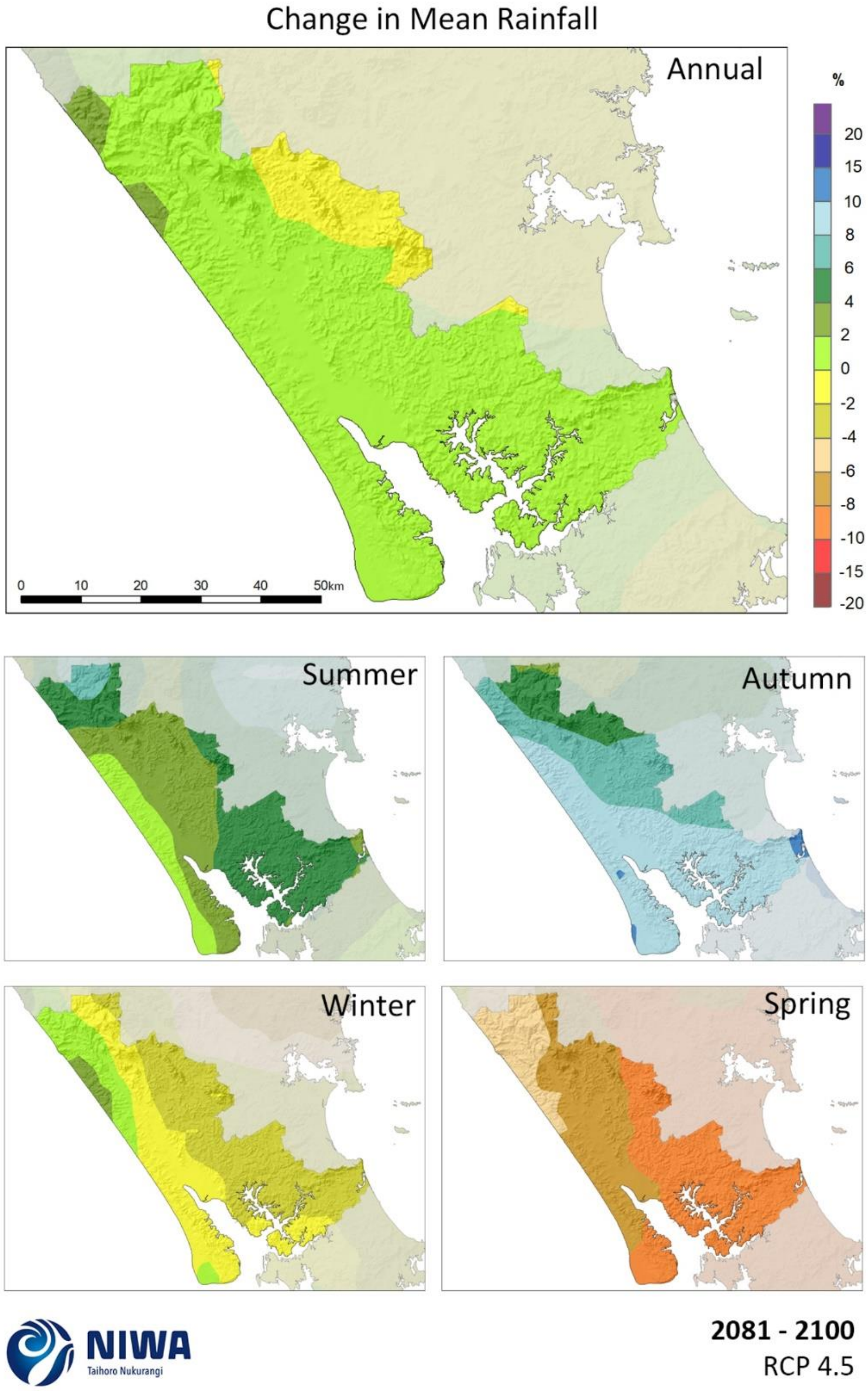

Figure 3-11: Projected annual and seasonal mean rainfall changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

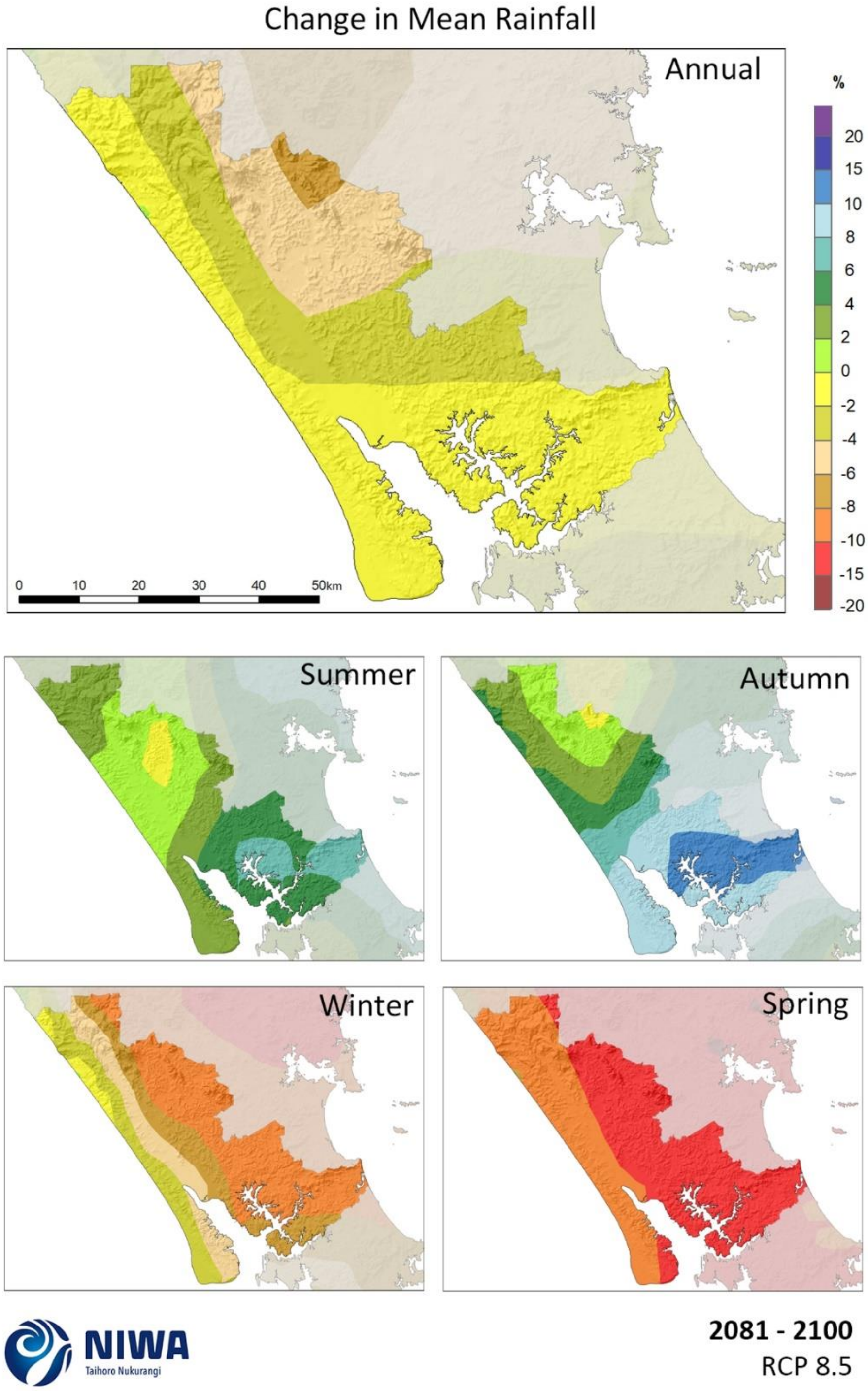

Figure 3-12: Projected annual and seasonal mean rainfall changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

3.2.2 Wet days

Key messages

- Most of Kaipara District is projected to observe a decrease in wet days of 16-22 days per year (by 2090 under RCP8.5).
- A decrease of 4-8 wet days is projected for most of Kaipara District by 2040 under RCP4.5 and RCP8.5.
- By 2090 under RCP8.5, a decrease of 6-10 wet days in spring is projected for most of the district.

The future (average over 2031-2050 and 2081-2100) projection maps in this section show the change in the number of wet days compared with the historic period (based on the 1986-2005 average).

By 2040 under RCP4.5 (Figure 3-13), the annual number of wet days is projected to decrease by 4-8 days for most of Kaipara District. The greatest reduction in seasonal wet days is projected in summer, with 2-4 fewer wet days for most of the District. Under RCP8.5 by 2040 (Figure 3-14), the annual pattern of projected change is similar to RCP4.5; a decrease of 4-8 wet days is projected for much of the District. Under RCP8.5 at 2040, the greatest seasonal change is projected in spring, with 4-6 fewer wet days for most areas.

By 2090 under RCP4.5 (Figure 3-15), the pattern of reduction in wet days is amplified. Approximately 8-12 fewer wet days per year are projected for most of Kaipara District. Very little change is projected for summer (±2 wet days), with 2-6 fewer wet days projected for spring. By 2090 under RCP8.5 (Figure 3-16), a considerable reduction in annual wet days is projected, with 16-22 fewer wet days for most of the District. The greatest seasonal change is projected for spring, with 6-10 fewer wet days for most of the area.

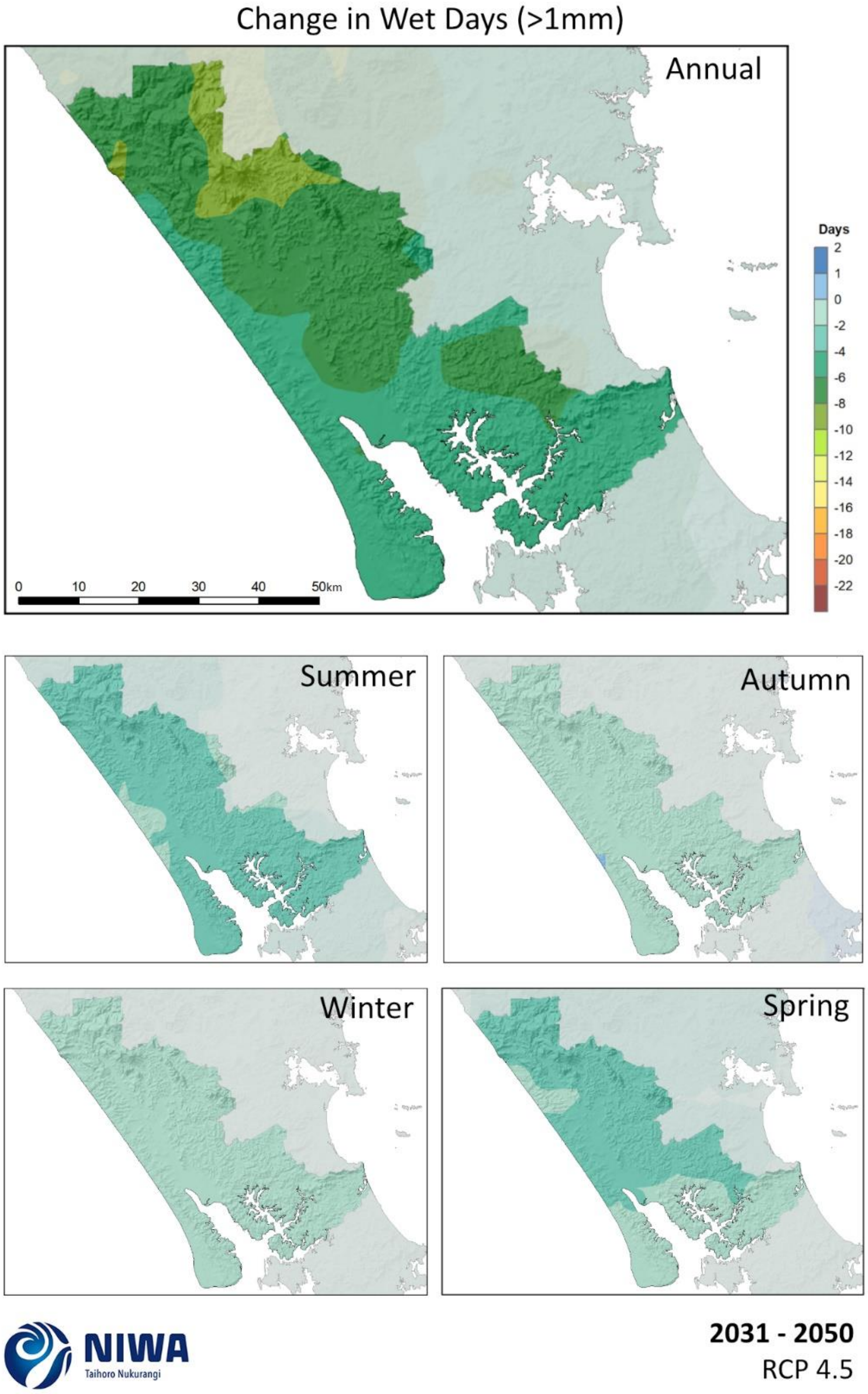

Figure 3-13: Projected annual and seasonal wet day (>1mm rain) changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

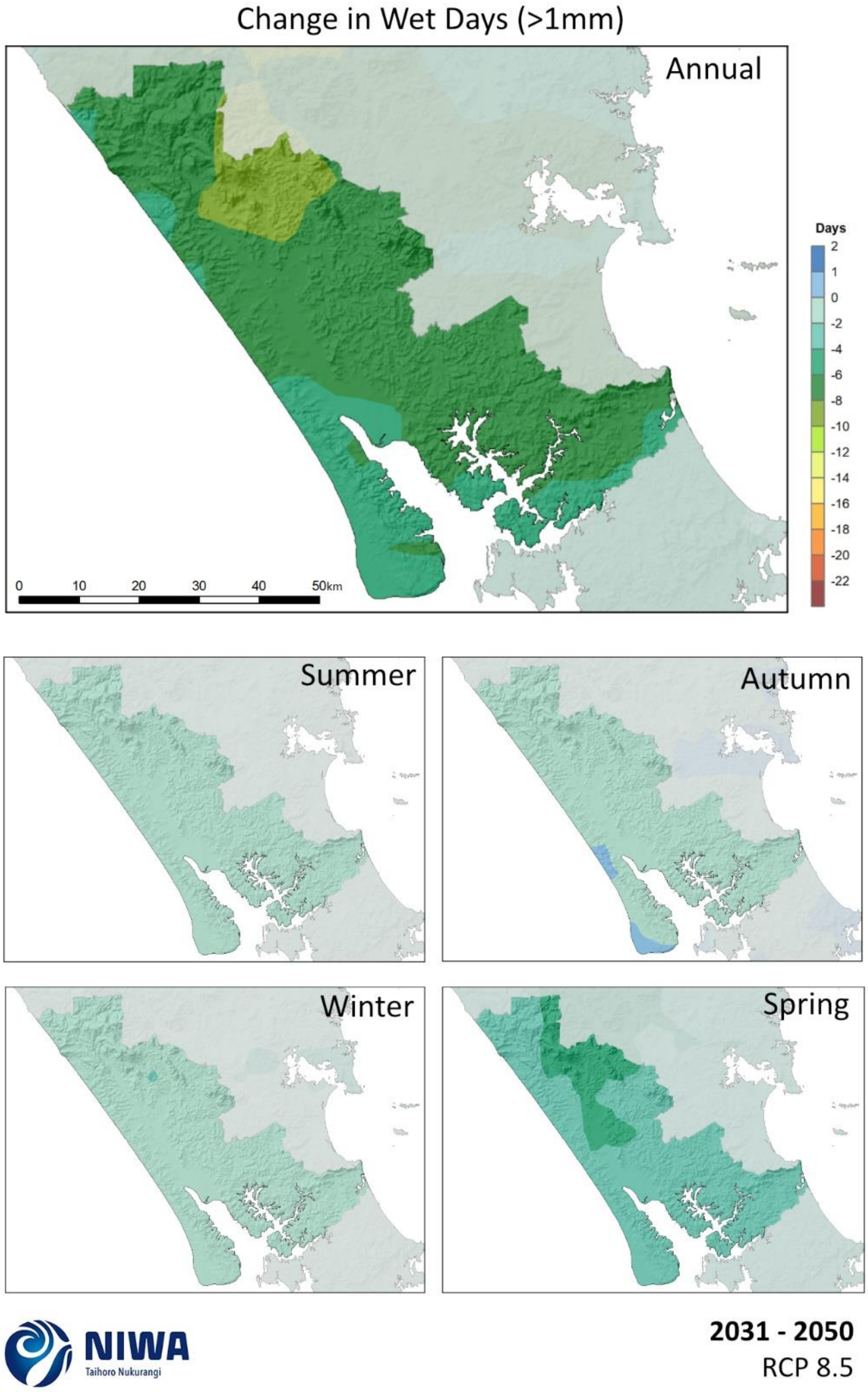

Figure 3-14: Projected annual and seasonal wet day (>1mm rain) changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

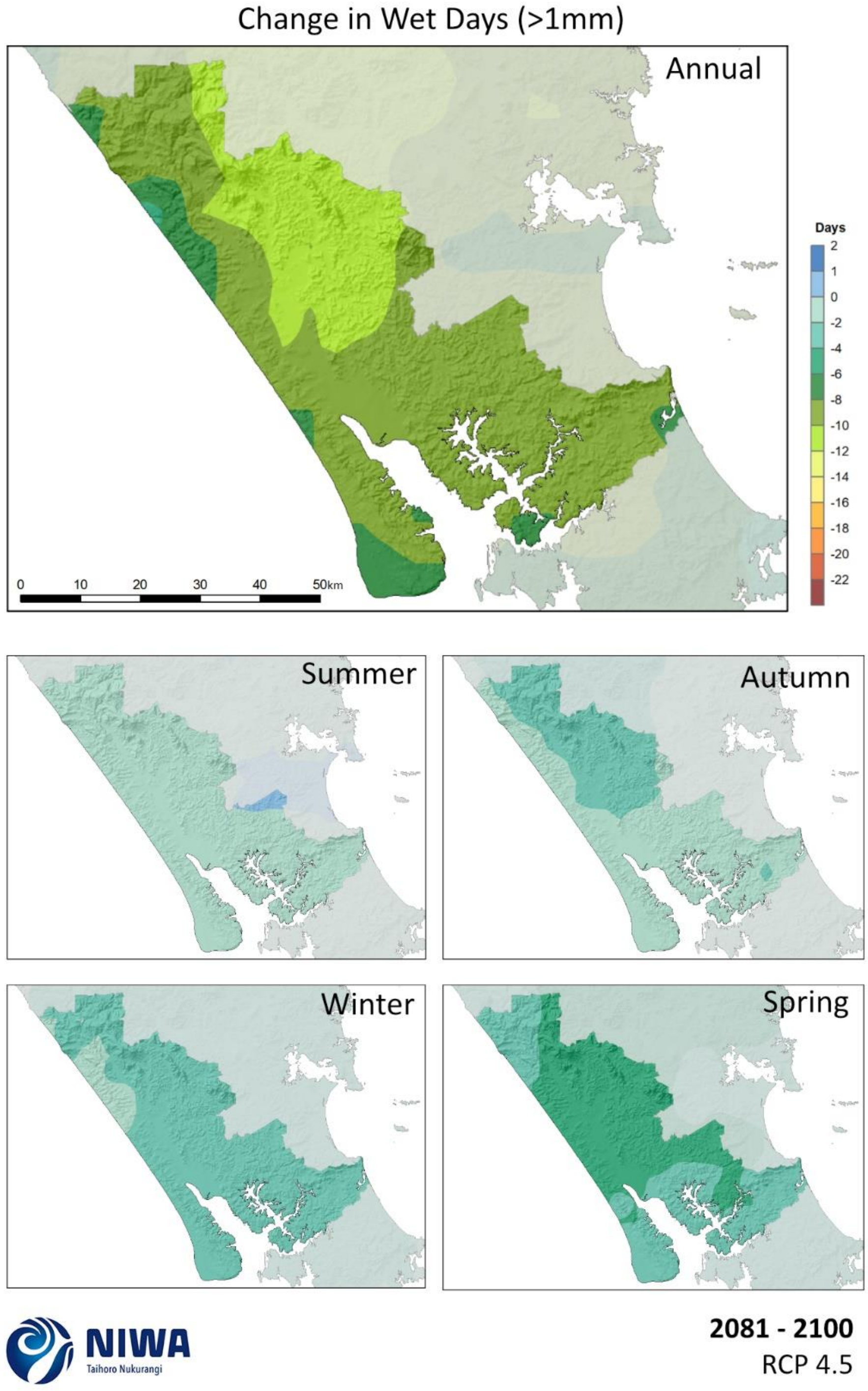

Figure 3-15: Projected annual and seasonal wet day (>1mm rain) changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

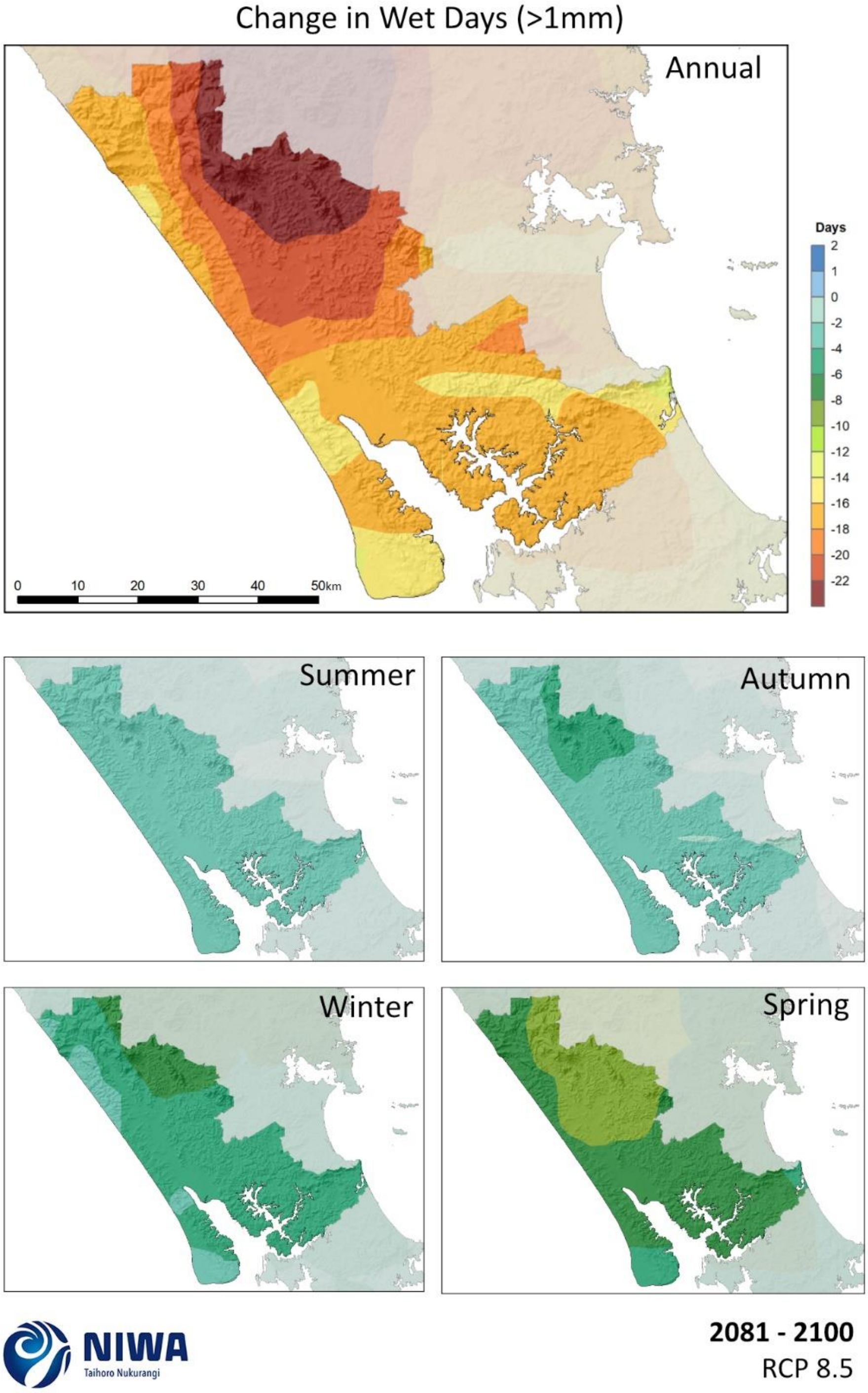

Figure 3-16: Projected annual and seasonal wet day (>1mm rain) changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

3.2.3 Extreme, rare rainfall events (HIRDS v4)

Key messages

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

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

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

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

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

NIWA's High Intensity Rainfall Design System (HIRDS version 4) allows rainfall event totals (depth; measured in mm) at various recurrence intervals to be calculated for any location in New Zealand (Carey-Smith et al., 2018). The rainfall event durations presented in HIRDS range from 10 minutes to 120 hours. HIRDS calculates historic rainfall event totals for given recurrence intervals (based on all available observed data) as well as future potential rainfall event totals for given recurrence intervals based on four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). HIRDS v4 can be freely accessed at https://hirds.niwa.co.nz/, and more background information to the HIRDS methodology can be found at https://www.niwa.co.nz/information-services/hirds/help.

HIRDS rainfall projections for two locations in Kaipara District (Dargaville and Mangawhai) are presented in this section. Three rainfall durations have been chosen: 1-hr, 6-hr and 24-hr. For each rainfall duration there are two tables; the first table presents data for 1:50 year rainfall events, and the second table presents data for 1:100 year rainfall events.

The depth of historic 1:50 and 1:100-year rainfall events are projected to increase in the future under all four climate change scenarios. The most considerable increases are projected at the end of the century (i.e. 2090) under RCP8.5. Short duration rainfall events have the largest relative increases compared with longer duration rainfall events. For example, the depth of a current 1:100-year 1-hour duration rainfall event is projected to increase by approximately 35% by 2090 under RCP8.5 for Kaipara District locations. In contrast, the depth of a current 1:100-year 24-hour duration rainfall event is projected to increase by approximately 22% by 2090 under RCP8.5 for Kaipara District locations.

Table 3-1 (50-year ARI) and Table 3-2 (100-year ARI) show modelled historic and projected rainfall depths for a 1-hour rain event. Projected rainfall depth increases range from 8% (by 2040 and 2090 under RCP2.6) to 35% (by 2090 under RCP8.5).

Table 3-3 (50-year ARI) and Table 3-4 (100-year ARI) show modelled historic and projected rainfall depths for a 6-hour rain event. Projected rainfall depth increases range from 7% (by 2040 and 2090 under RCP2.6) to 29% (by 2090 under RCP8.5).

Table 3-5 (50-year ARI) and Table 3-6 (100-year ARI) show modelled historic and projected rainfall depths for a 24-hour rain event. Projected rainfall depth increases range from 5% (by 2040 and 2090 under RCP2.6) to 22% (by 2090 under RCP8.5).

Table 3-1: Modelled historic and projected rainfall depths (mm) for a 1-hour rain event with a 50-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	**2040**				**2090**			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Dargaville	40.3	43.5	44.3	44.0	44.9	43.5	46.9	49.2	54.4
Mangawhai	56.4	60.9	62.0	61.5	62.8	60.9	65.6	68.8	76.0

Table 3-2: Modelled historic and projected rainfall depths (mm) for a 1-hour rain event with a 100-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	**2040**				**2090**			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Dargaville	44.9	48.5	49.4	49.0	50.1	48.5	52.3	54.8	60.6
Mangawhai	63.0	68.1	69.4	68.8	70.3	68.1	73.4	77.0	85.1

Table 3-3: Modelled historic and projected rainfall depths (mm) for a 6-hour rain event with a 50-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Dargaville	90.5	96.5	98.0	97.4	99.2	96.5	103	107	117
Mangawhai	114	122	124	123	125	122	130	135	147

Table 3-4: Modelled historic and projected rainfall depths (mm) for a 6-hour rain event with a 100-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Dargaville	101	108	109	109	111	108	115	120	131
Mangawhai	128	136	138	137	140	136	145	151	165

Table 3-5: Modelled historic and projected rainfall depths (mm) for a 24-hour rain event with a 50-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Dargaville	153	161	163	162	164	161	169	174	187
Mangawhai	178	187	189	188	191	187	196	203	217

Table 3-6: Modelled historic and projected rainfall depths (mm) for a 24-hour rain event with a 100-year ARI. Time periods: mid-century (2031-2050; "2040") and end-century (2081-2100; "2090"); based on the average of six global climate models under four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5).

	Historic depth (mm)	2040				2090			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Dargaville	171	180	182	181	184	180	189	195	209
Mangawhai	199	209	212	210	213	209	220	227	243

3.2.4 Dry days

Key messages
• Kaipara District is projected to observe an increase in dry days of 16-22 days per year (by 2090 under RCP8.5).
• An increase of 4-8 dry days is projected for most of Kaipara District by 2040 under RCP4.5 and RCP8.5.
• By 2090 under RCP8.5, an increase of 6-10 dry days in spring is projected for most of the area.

A dry day considered here is when < 1 mm of rainfall is recorded. Future (average over 2031-2050 and 2081-2100) maps for dry days are shown in this section. These projection maps show the change in the number of dry days compared with the historic period (based on the 1986-2005 average).

By 2040 under RCP4.5 (Figure 3-17), the annual number of dry days is projected to increase by 4-8 days for most of Kaipara District. The greatest increase in seasonal dry days is projected in summer, with 2-4 more dry days for most of the District. Under RCP8.5 by 2040 (Figure 3-18), the annual pattern of projected change is similar to RCP4.5; an increase of 4-8 dry days is projected for much of the District. Under RCP8.5 at 2040, the greatest seasonal change is projected in spring, with 2-6 more days for most areas.

By 2090 under RCP4.5 (Figure 3-19), the pattern of increase in dry days is amplified. Approximately 8-12 more dry days per year are projected for most of Kaipara District. Under this scenario, around 2-6 more dry days are projected for spring. By 2090 under RCP8.5 (Figure 3-20), a considerable increase in annual dry days is projected, with 16-22 more dry days for most of the District. The greatest seasonal change is projected for spring, with 6-10 more dry days for most of the area.

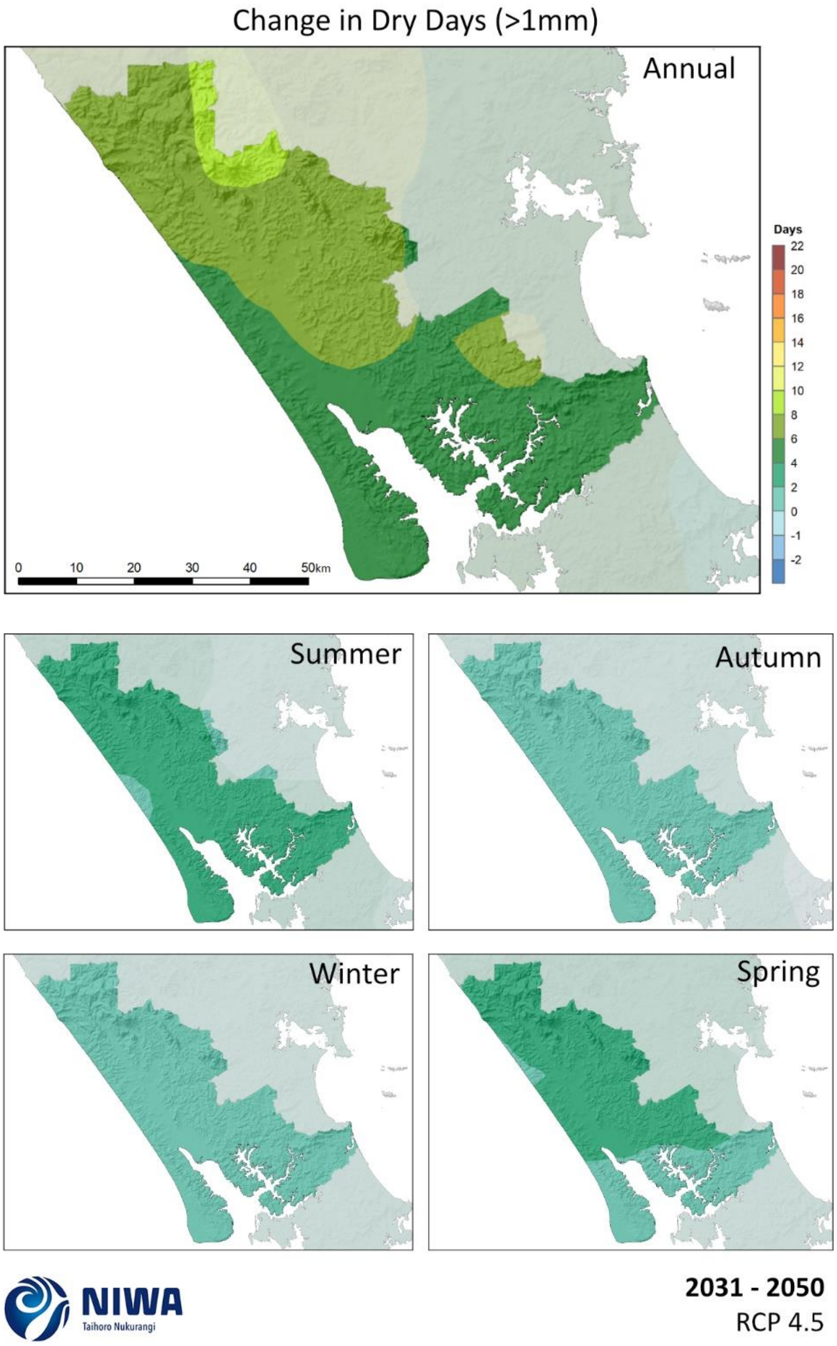

Figure 3-17: Projected annual and seasonal number of dry day (<1mm rainfall) changes by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

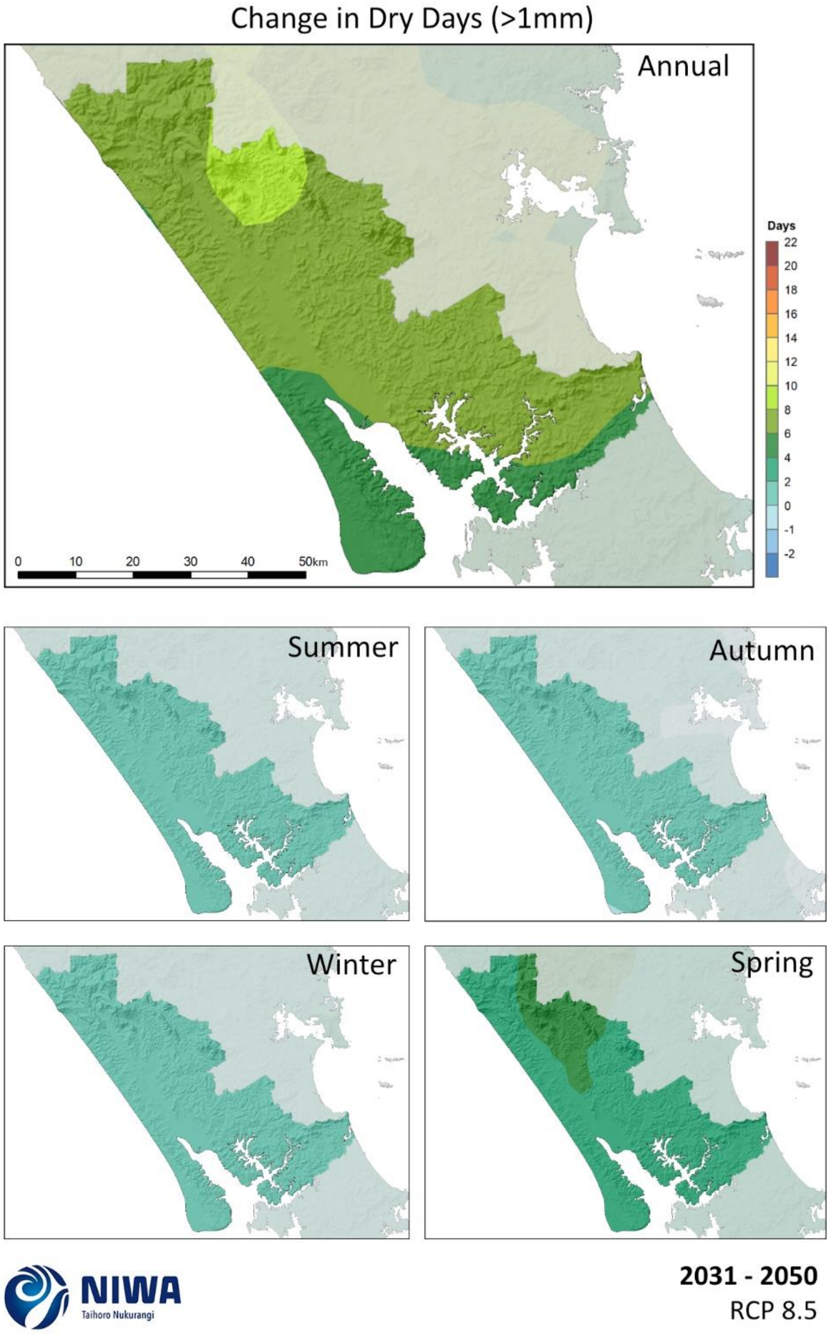

Figure 3-18: Projected annual and seasonal number of dry day (<1mm rainfall) changes by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

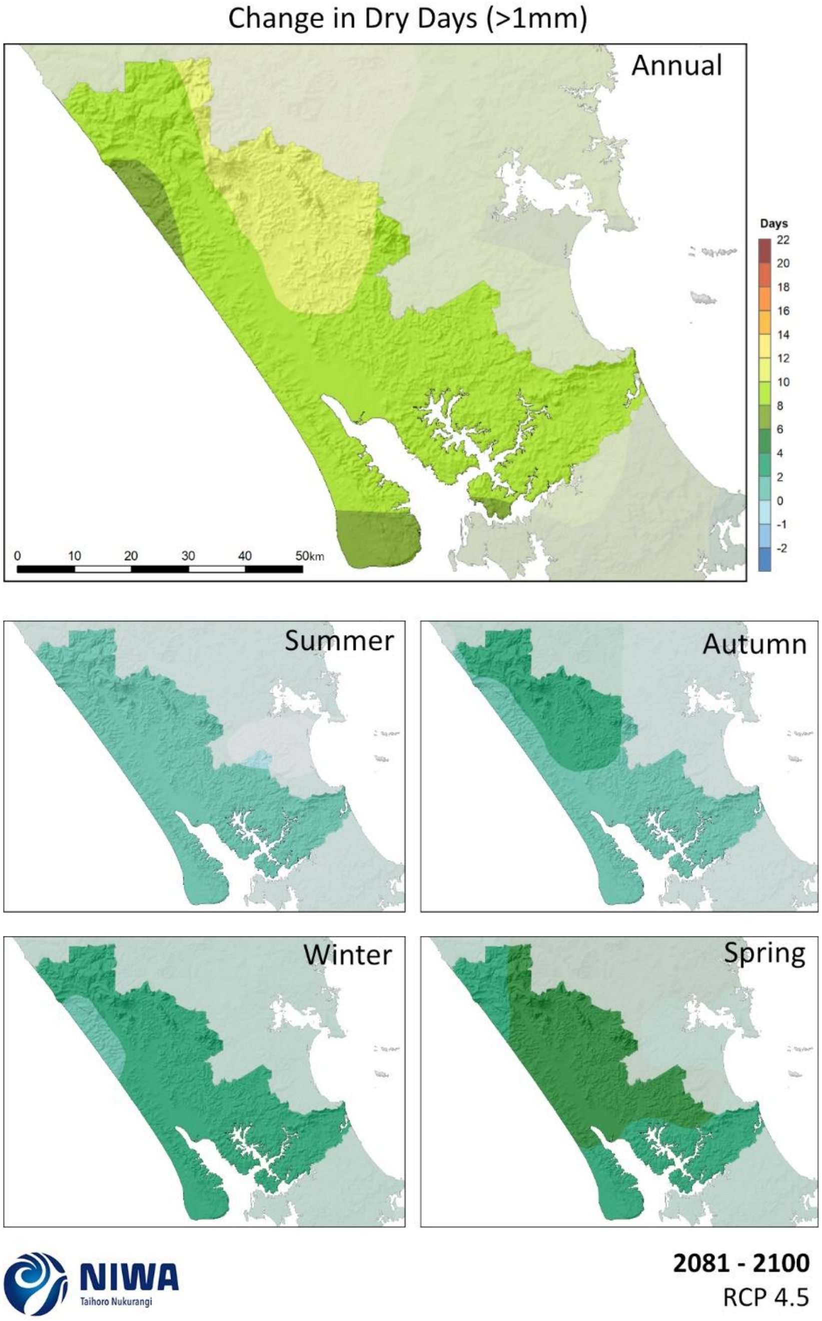

Figure 3-19: Projected annual and seasonal number of dry day (<1mm rainfall) changes by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

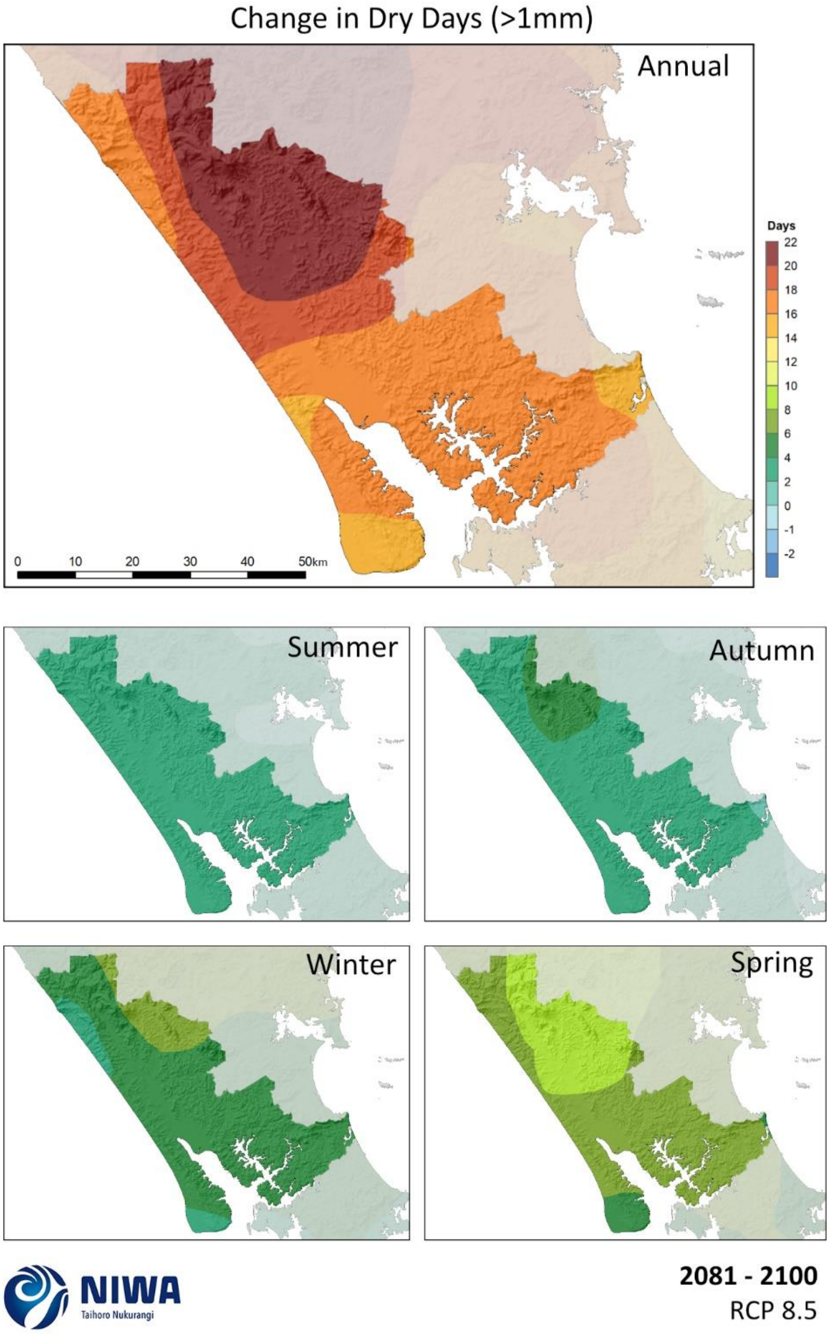

Figure 3-20: Projected annual and seasonal number of dry day (<1mm rainfall) changes by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

3.2.5 Potential evapotranspiration deficit

Key messages
• Kaipara District is projected to observe an increase in the amount of accumulated PED, therefore drought potential is projected to increase.
• Accumulated PED is projected to increase by 120-160 mm per year for most of the District by 2090 under RCP8.5.
• Increases of 80-100 mm of accumulated PED is projected by 2040 under both RCPs.

Potential evapotranspiration deficit (PED) can be used as a measure of meteorological drought[3]. PED and soil moisture deficit (SMD) are similar measures of dryness, but in this report SMD is measured in days (Section 2.3 and Section 3.2.6) and PED is measured in mm of accumulation, so PED is a more sensitive measure of drought intensity than SMD. Evapotranspiration is the process where water held in the soil is gradually released to the atmosphere through a combination of direct evaporation and transpiration from plants. As the growing season advances, the amount of water lost from the soil through evapotranspiration typically exceeds rainfall, giving rise to an increase in soil moisture deficit. As soil moisture decreases, pasture production becomes moisture-constrained and evapotranspiration can no longer meet atmospheric demand.

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

Future (average over 2031-2050 and 2081-2100) maps for PED are shown in this section. The future projection maps show the change in the annual accumulated PED compared with the historic period (in this case 1986-2005), in units of mm.

In the future, the amount of accumulated PED is projected to increase across Kaipara District (Figure 3-21), therefore drought potential is projected to increase. By 2040 under both RCPs, most of the District is projected to experience an increase in annual PED of 80-100 mm. By 2090 under RCP4.5, much of the District is projected to experience an additional 80-100 mm of annual PED, with areas along the northeastern fringes of the District projected to experience an additional 60-80 mm of annual PED. By 2090 under RCP8.5, annual PED is projected to increase by 120-160 mm for most of

[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.

Kaipara District. For northeastern parts of the District, annual PED is projected to increase by 100-120 mm.

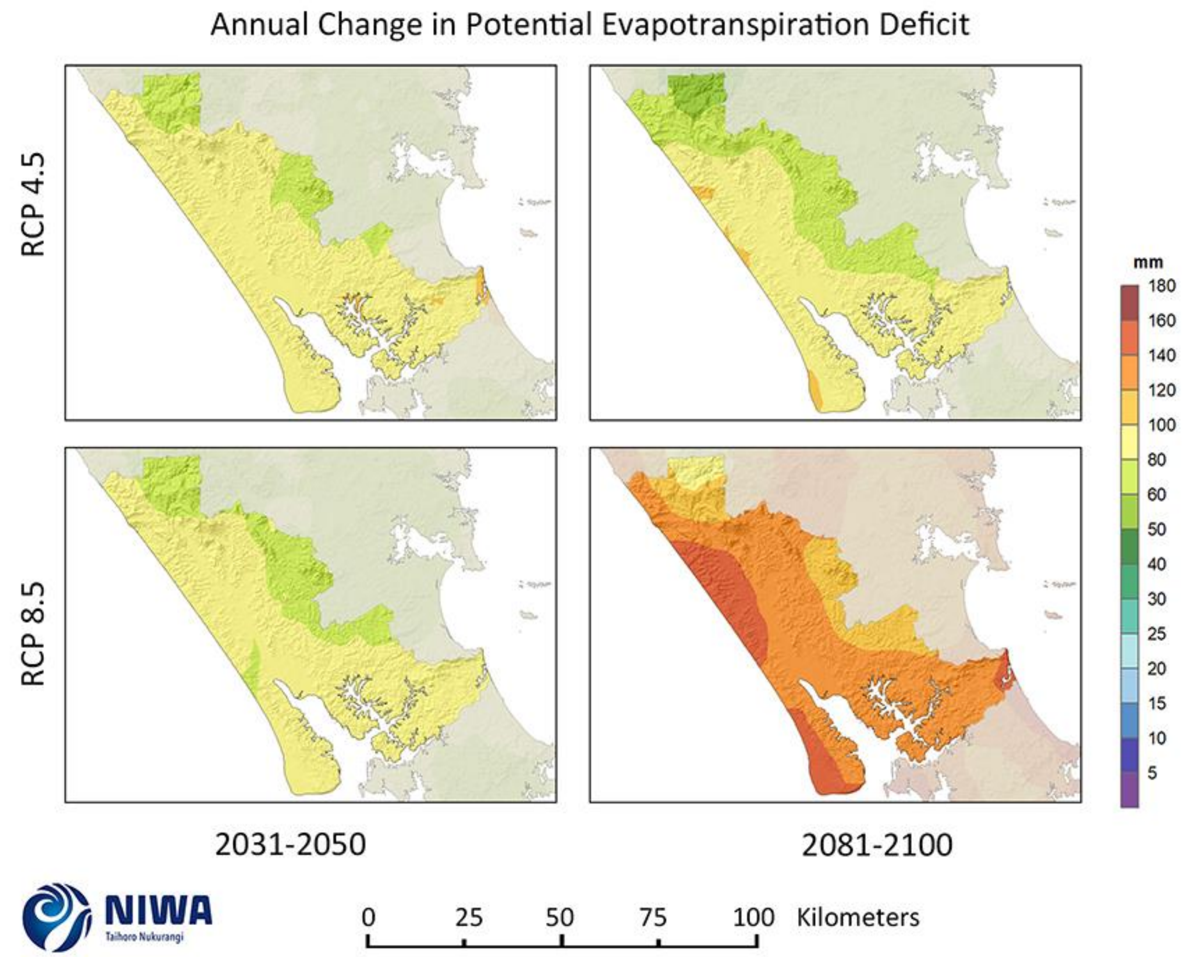

Figure 3-21: Projected annual potential evapotranspiration deficit (PED) accumulation changes for RCP4.5 and RCP8.5, by 2040 and 2090. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

3.2.6 Soil moisture deficit

Key messages

- Kaipara District is projected to observe an increase in days of SMD of 20-35 days per year (by 2090 under RCP8.5).
- An increase of 2-10 days of SMD is projected for most of Kaipara District by 2040 under RCP4.5.
- By 2090 under RCP8.5, an increase of 15-20 days of SMD in spring is projected for most of the District.

Future (average over 2031-2050 and 2081-2100) maps for days of SMD are shown in this section. The future projection maps show the change in the number of days of SMD compared with the historic period (based on the 1986-2005 average).

By 2040 under RCP4.5 (Figure 3-22), annual days of SMD per year are projected to increase by 2-10 days for most of the District. The largest increases are projected for summer (6-10 days). By 2040 under RCP8.5 (Figure 3-23), annual SMD days are projected to increase by 3-15 days for most of Kaipara District.

By 2090 under RCP4.5 (Figure 3-24), increases of 10-15 annual days of SMD are projected for most of Kaipara District. For coastal northwestern parts of the District, increases of 5-10 annual days of SMD are projected. By 2090 under RCP8.5 (Figure 3-25), 20-35 more annual days of SMD days are projected for almost the entire District. The largest increases are projected for spring (10-20 more SMD days for most areas). Some southern parts of Kaipara District are projected to observe a decrease of 1-3 days of SMD during autumn.

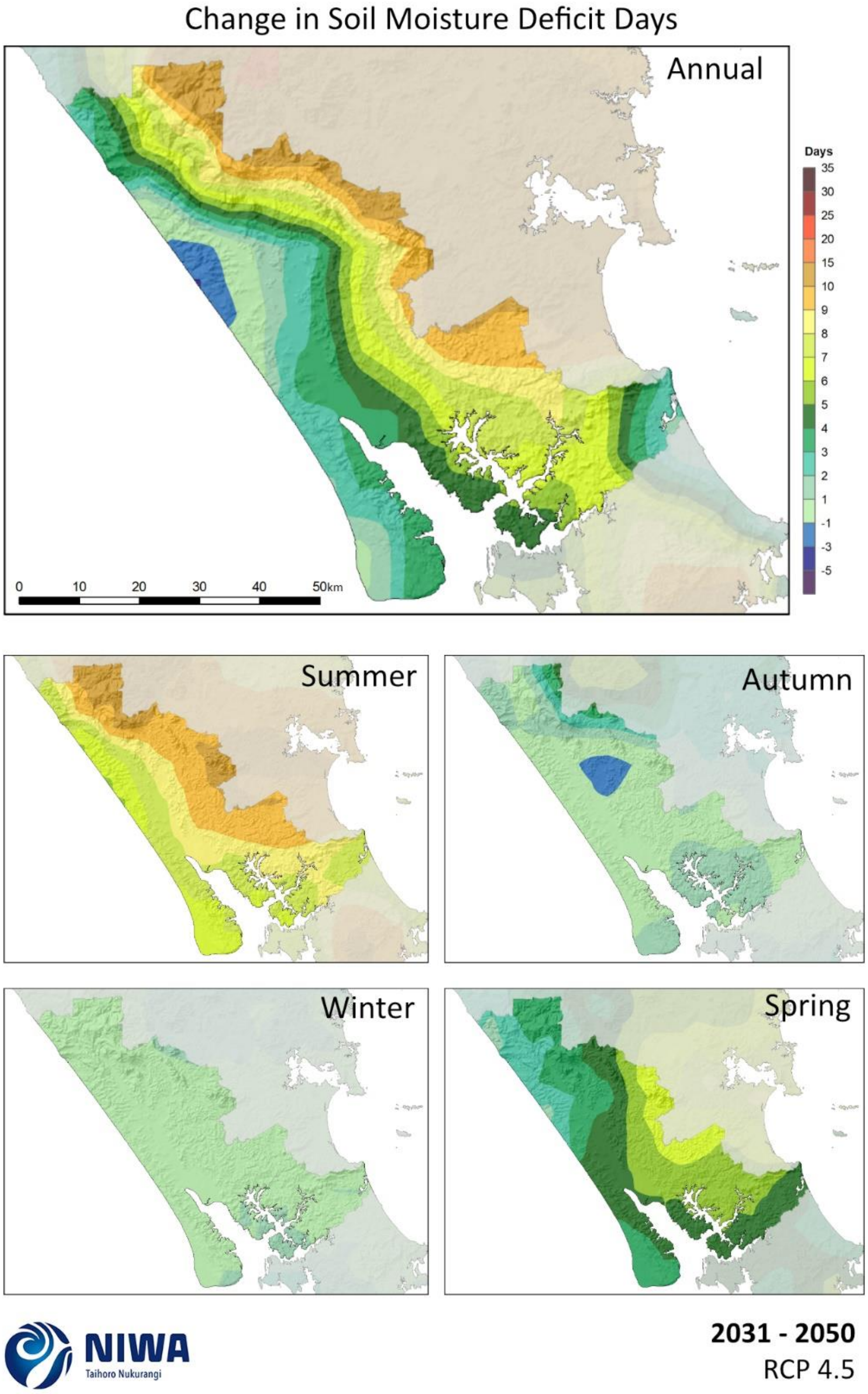

Figure 3-22: Projected change in the number of annual and seasonal soil moisture deficit days by 2040 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

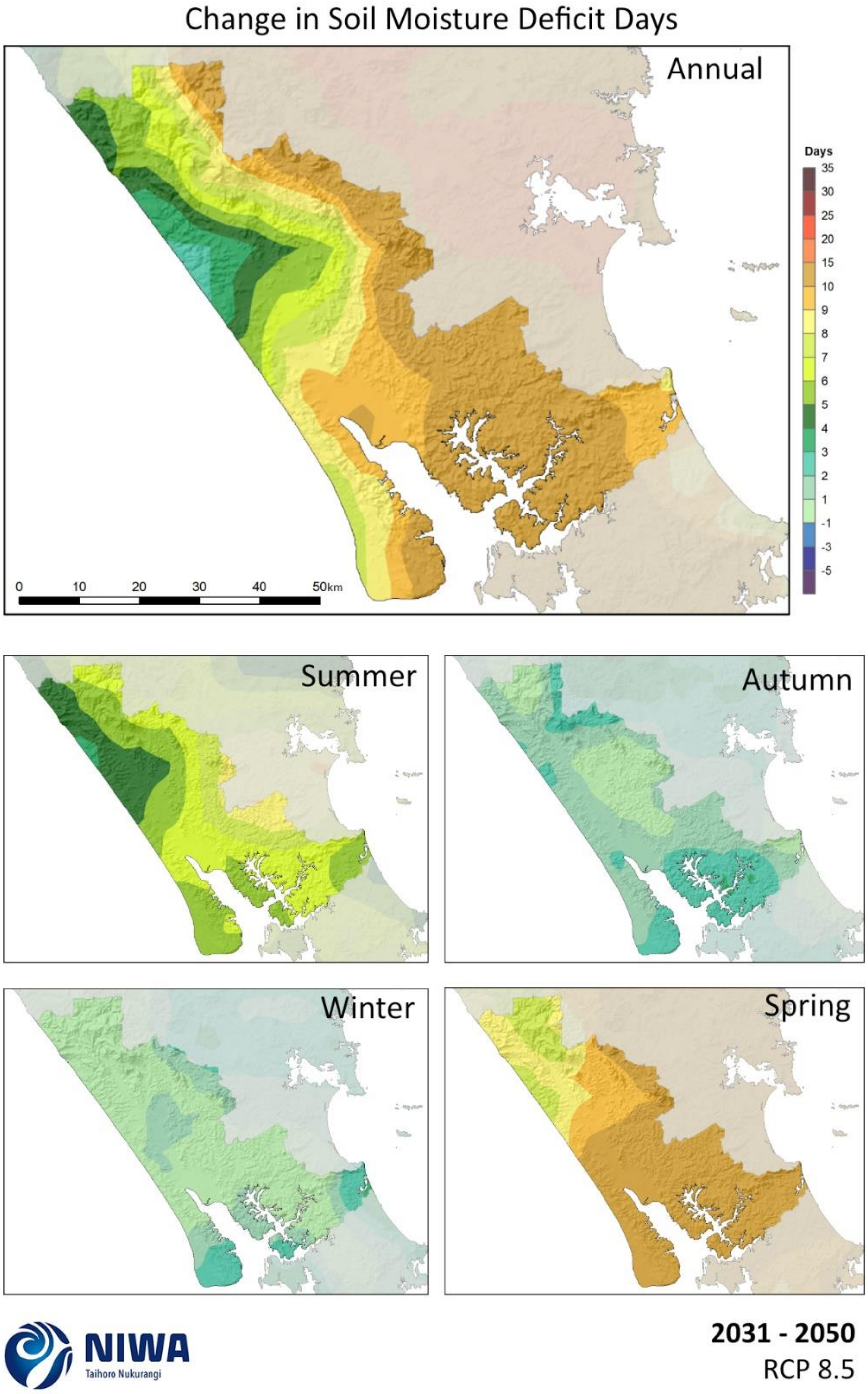

Figure 3-23: Projected change in the number of annual and seasonal soil moisture deficit days by 2040 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

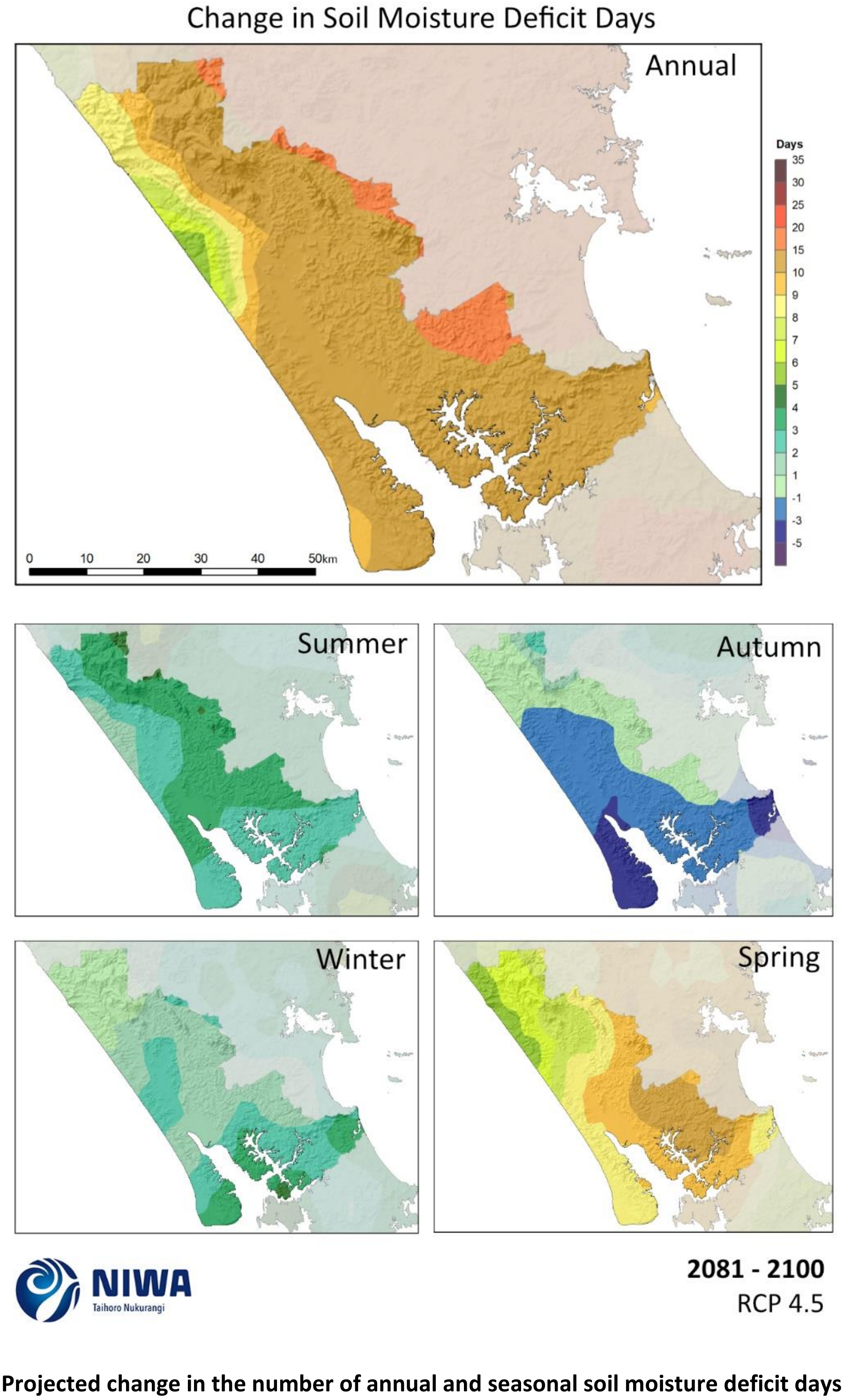

Figure 3-24: Projected change in the number of annual and seasonal soil moisture deficit days by 2090 for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

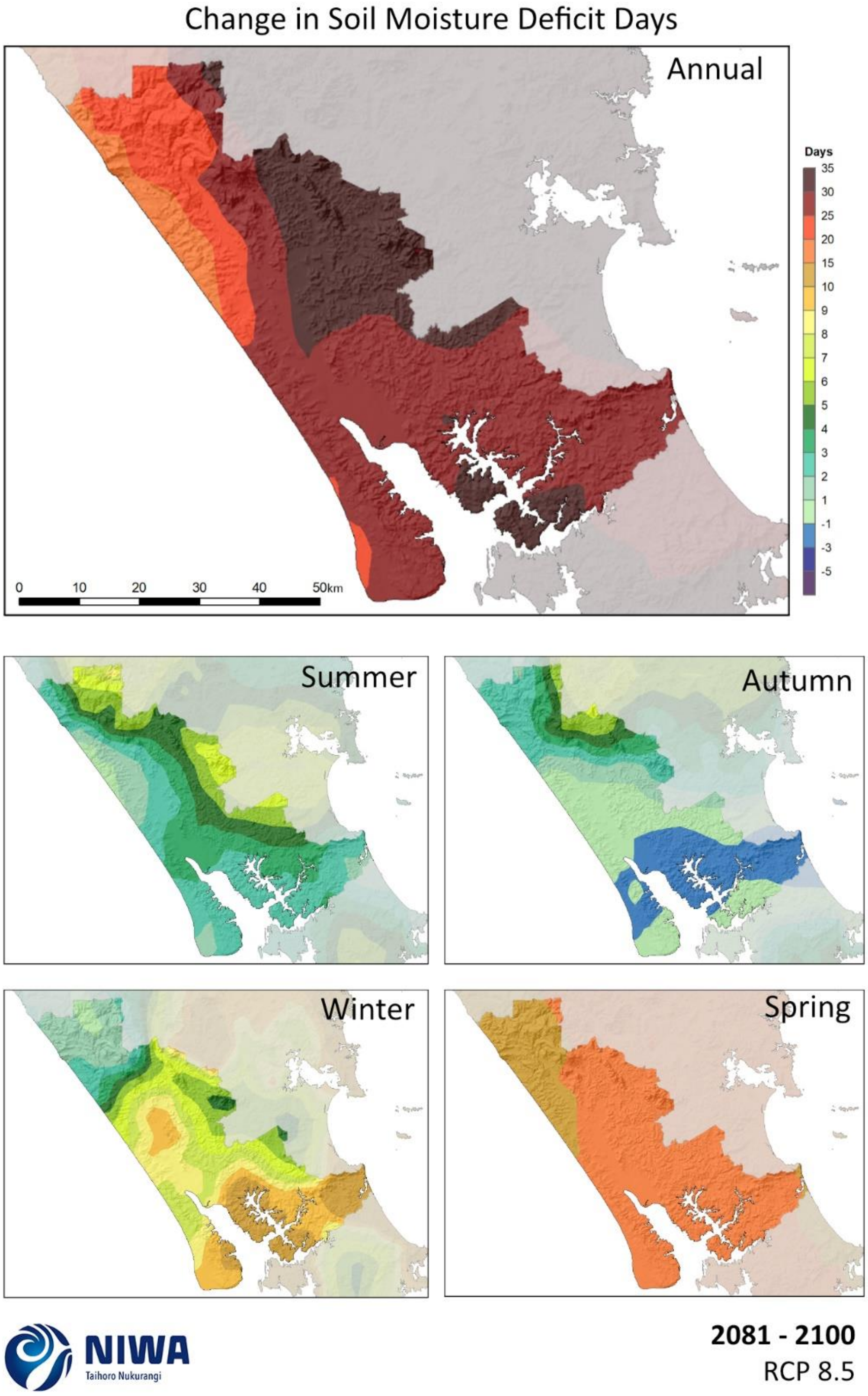

Figure 3-25: Projected change in the number of annual and seasonal soil moisture deficit days by 2090 for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Results are based on dynamical downscaled projections using NIWA's Regional Climate Model. Resolution of projection is 5km x 5km.

3.3 Impacts of sea-level rise

Key messages

- Local sea level trends show a national average rise of 1.8 mm/year from the early 1900s to 2015.
- Adaptation to sea-level rise (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.
- Coastal flooding from extreme sea levels will increase in frequency and magnitude as global climate change forces sea-level rise.
- Extreme sea level events, rare in the recent past (i.e., once per century), are projected to occur at least once per year by 2050 along many of the world's coastlines.
- A large portion of land exposed to 100-year annual recurrence interval extreme sea levels in the Kaipara District is productive land. The total amount of land exposed in the future will depend on the extent of sea-level rise.

3.3.1 Ministry for the Environment coastal hazards and climate change guidance

Updated coastal hazards and climate change guidance has been published by Ministry for the Environment (2017). This section provides a summary of recent sea-level rise (SLR) trends and future projections for New Zealand.

Rising sea level in past decades has already affected 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 roads 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 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[4].

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 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 3-26).

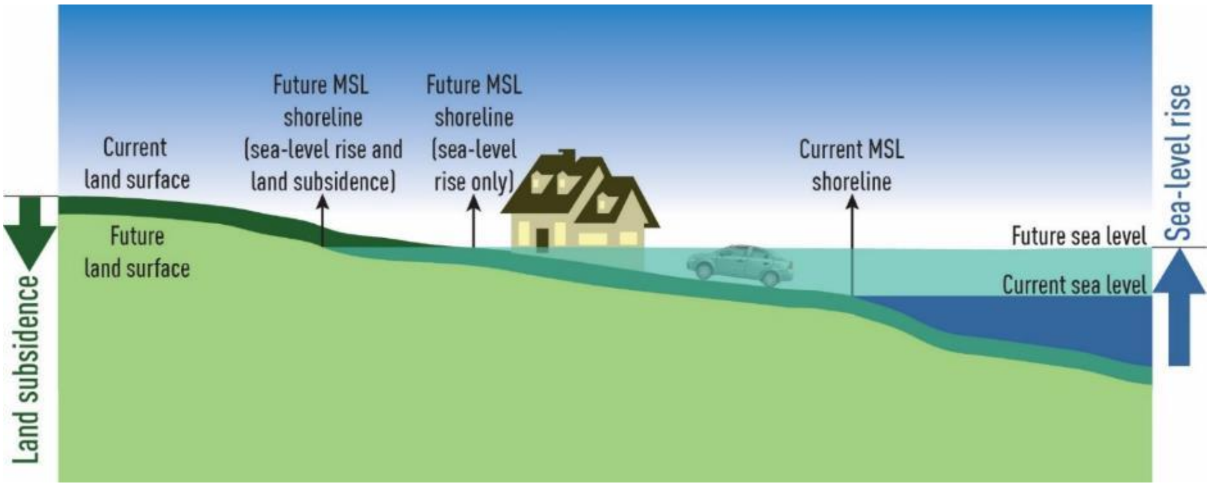

Figure 3-26: Difference in mean sea level (MSL) shoreline between absolute and local (relative) SLR where land subsidence occurs.

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 3-27, based on updates of the data from Church and White (2011).

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

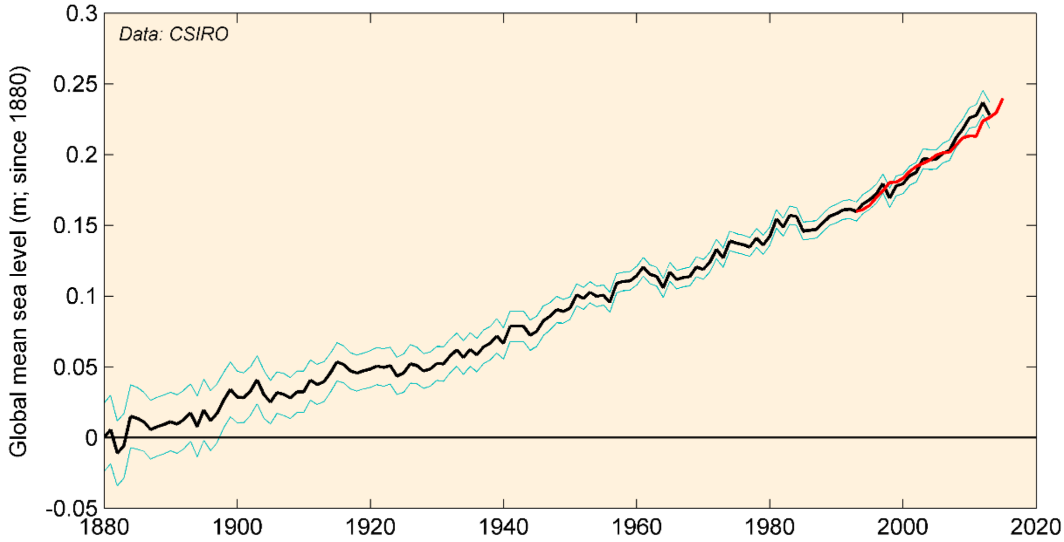

Figure 3-27: Cumulative changes in global mean sea level (MSL) since 1880, based on a reconstruction of long-term tide gauge measurements to end of 2013 (black) and recent satellite measurements to end 2015 (red). Lighter lines are the upper and lower bounds of the likely range (± 1 standard deviation) 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 SLR 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).

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 3-28. 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 SLR scenario is being followed (because there is little difference at present between scenarios -Figure 3-28).

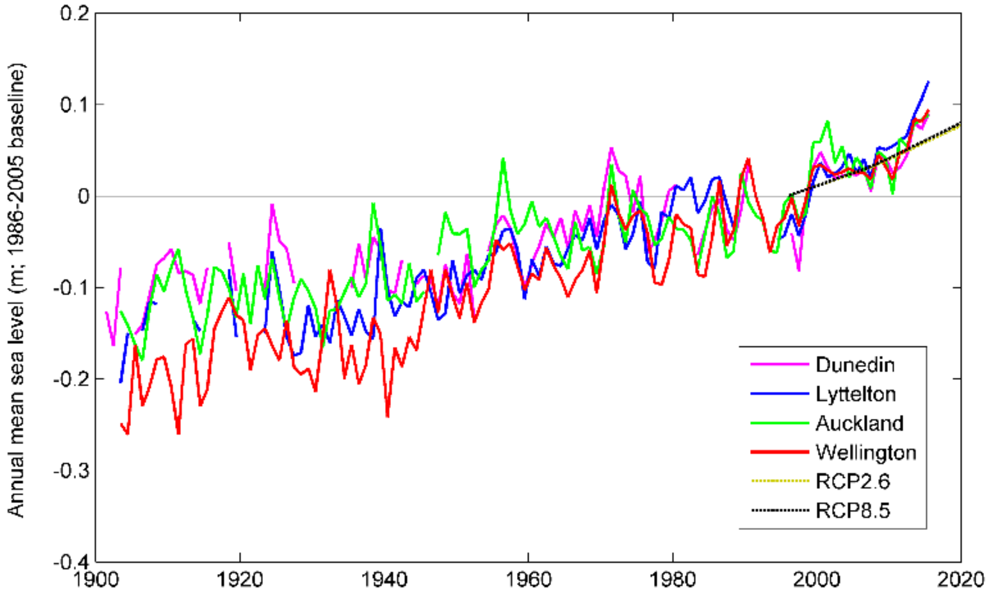

Figure 3-28: Change in annual local MSL for the four main ports from 1900–2015, and initial global-mean SLR projections for RCP2.6 and RCP8.5 to 2020 (dashed lines). Relative to the average MSL over the baseline period 1986–2005 (used for IPCC AR5 projections of SLR, with mid-point at 1996). (Source 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, 2013a).

Local sea-level or RSLR trends over the past 60-100 years with standard deviations were analysed at 10 gauge sites by Hannah and Bell (2012), with an average rise of 1.7 mm/year from early last century up to 2008. The trends were updated to 2015 (except for Whangarei), as shown in Figure 3-29, with the national average rate now closer to 1.8 mm/year.

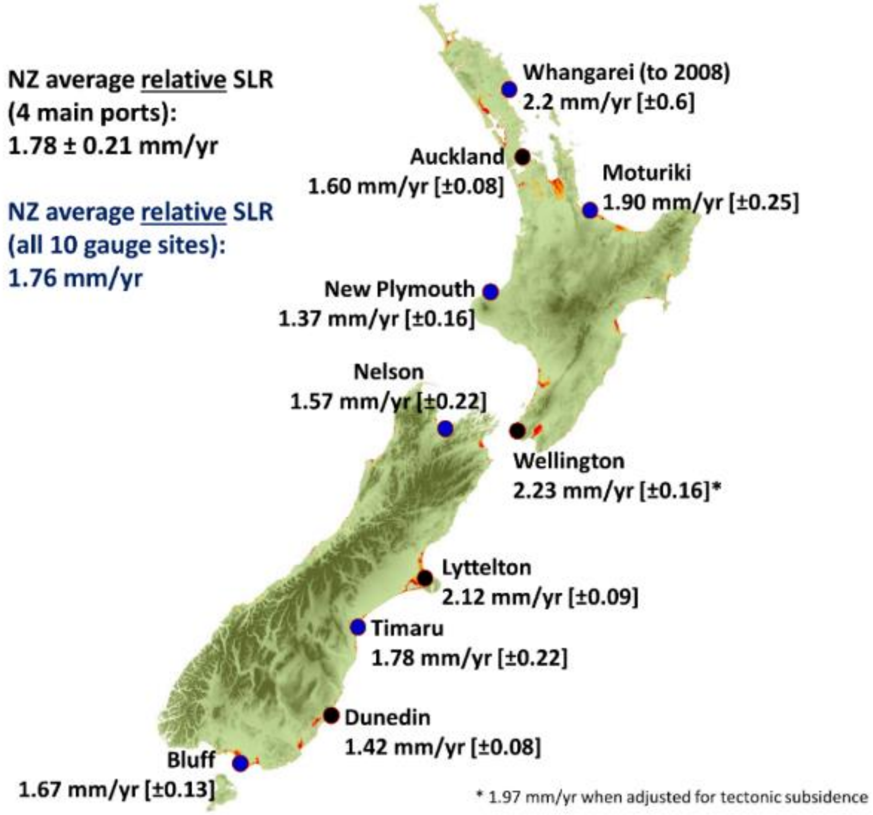

Figure 3-29: Historic long-term RSLR rates for the 20th century up to and including 2015 (excluding Whangarei), determined from longer sea-level gauge records at the four main ports. Note: Standard deviations of the trend are listed in the brackets. Sources: analysis up to end of 2008 from Hannah and 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 3-26).

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 Northland was vertically stable within ±1 mm/yr. 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.

Future major earthquake displacements for a particular locality are deeply uncertain (both when and by how much). Unlike the ongoing SLR, 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).

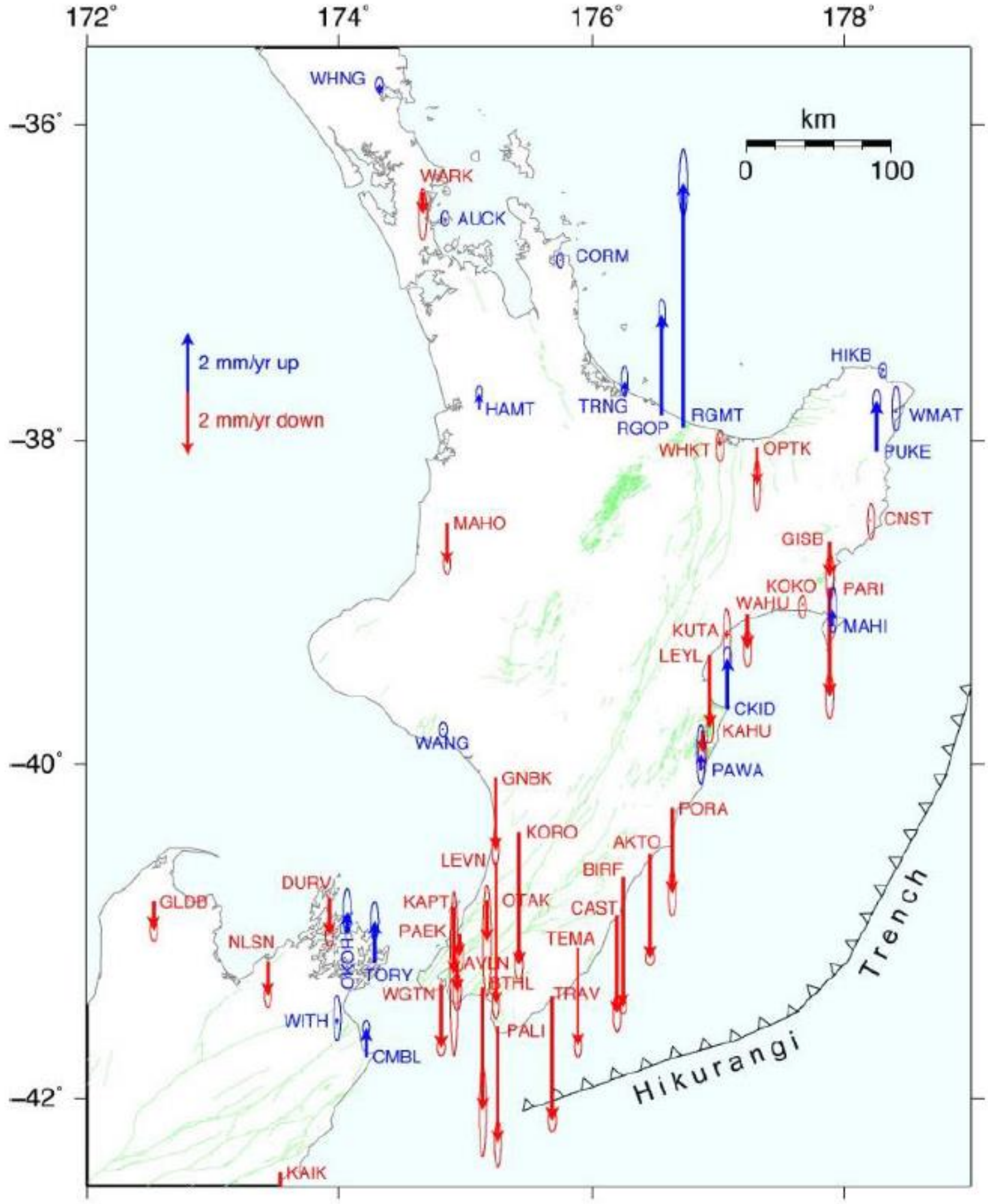

Figure 3-30: Average vertical land movements (mm/yr) for near-coastal continuous GPS sites across central New Zealand regions. Source: Beavan and Litchfield (2012).

Projections for sea-level rise

The primary climate driver for SLR is global and regional surface temperature, which is strongly influenced by greenhouse gas concentrations. 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 3-31. 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 3-28).

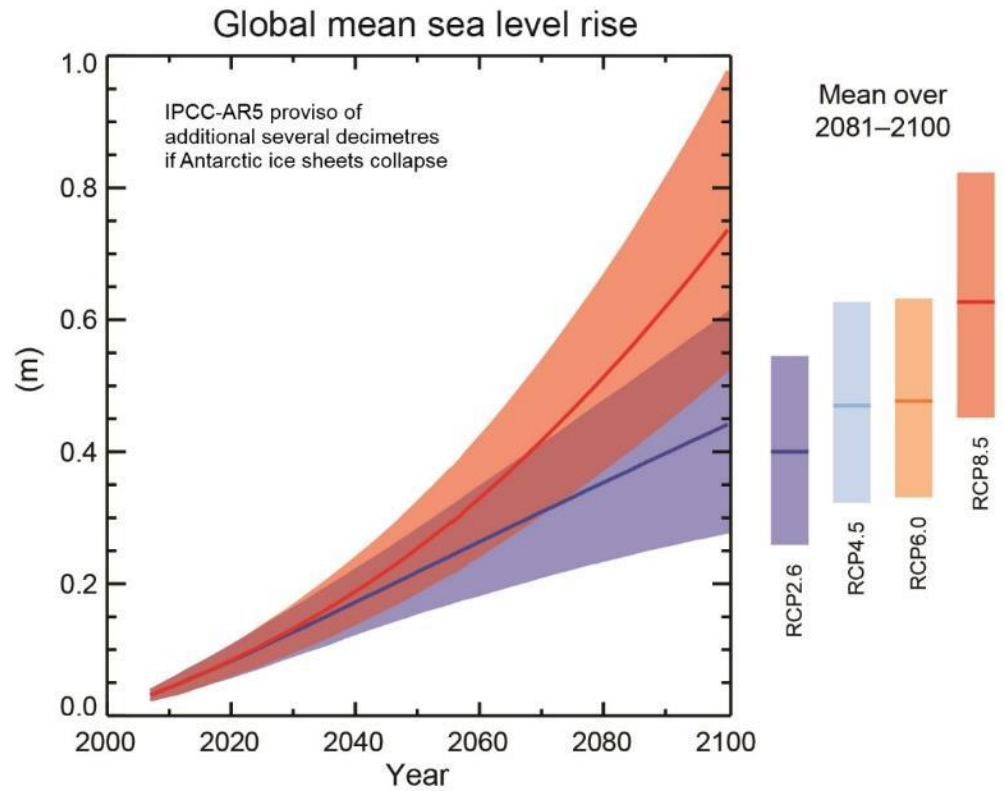

Figure 3-31: IPCC AR5 projections of global-average MSL rise (metres, relative to a base MSL of 1986-2005) covering the range of scenarios from RCP2.6 to RCP8.5. The heavy line shows the median estimate for that RCP, while the shaded area covers the "likely range" projections for the RCP, with a 33% 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 3-31) during this century. While the contribution cannot be precisely quantified, there is *medium confidence* that it would not exceed several tenths of a metre[5] of SLR by 2100.

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

- It is *virtually certain* that global mean SLR will continue for many centuries beyond 2100, with the amount of rise dependent on future emissions.
- The threshold for the loss of the Greenland ice sheet over a millennium or more, and an associated SLR of up to 7 metres, is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) of global warming with respect to pre-industrial temperatures.
- Abrupt and irreversible ice loss 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 3-32, 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 2130, to align with the planning timeframe of at least 100 years stipulated in the New Zealand Coastal Policy Statement 2010 (Stephens, 2017).

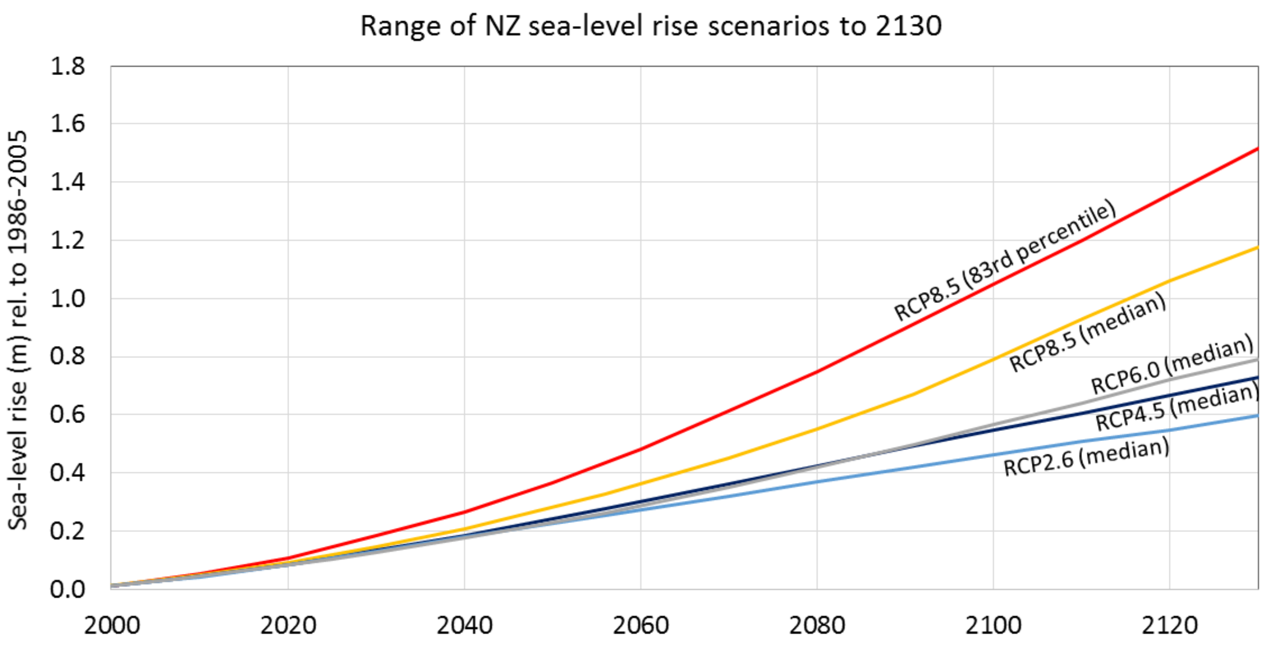

Figure 3-32: SLR scenarios for New Zealand seas, based on a set of median projections for all four RCPs (based on Church et al., 2013b) plus a higher 83rd percentile RCP8.5 projection (based on (Kopp et al., 2014)). The M next to the RCP on the plot stands for median. Note: for New Zealand seas, SLR 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 may be reached is shown in for all scenarios in Table 3-7 (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 3-7: 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

3.4 Areas exposed to coastal inundation and river flooding

Maps of areas exposed to 100-year annual recurrence interval extreme sea levels (ESL_{100}) and sea-level rise (SLR) in the Kaipara District are presented in Figure 3-33. A detailed description of the methodology to calculate extreme sea levels and map coastal flooding from ESL_{100} is presented by Paulik et al. (2020).

A static, "bathtub" approach was applied to map ESL_{100} flooding scenarios at a 10 m horizontal resolution onto LiDAR and satellite Digital Elevation Models (DEMs). On coastal land around Dargaville and Mangawhai with LiDAR DEM coverage (Figure 3-34), ESL_{100} flooding is mapped for present-day mean sea level (MSL) and thereafter at 0.5 m increments up to 2 m above MSL. On other coastlines, a lower-resolution satellite derived MERIT DEM (Yamazaki et al., 2017), supported ESL_{100} flood mapping only for 3 m SLR above MSL. This was applied for flood mapping due to lower resolution topography (vertical errors >2 m) from the MERIT DEM. Northland Regional Council has recently has now made available full regional LIDAR coverage which will make it possible to update the LIDAR DEM maps in the future.

Kaipara District's land area present-day exposure to ESL_{100} flooding is 18.5 km^2 along coastlines with LiDAR DEM coverage (Figure 3-34). Production land cover encompasses most of this area (16.7 km^2), while built-land covers less than 1 km^2. A 1 m SLR could expose a further 8.4 km^2 land area, mostly production land. A 3 m SLR (top map - Figure 3-33), ESL_{100} flooding identified from the combined LiDAR and MERIT DEMs reaches 328.8 km^2. (The respective DEM contribution equates to 36.8 km^2 from the LiDAR dataset and 292 km^2 from the MERIT dataset). Production land area covers 264.1 km^2 (80%) of the district's exposure to ESL_{100} flooding at 3 m SLR. In summary, a large portion of land exposed to 100-year annual recurrence interval extreme sea levels in the Kaipara District is productive land. The total amount of land exposed in the future will depend on the extent of sea level rise.

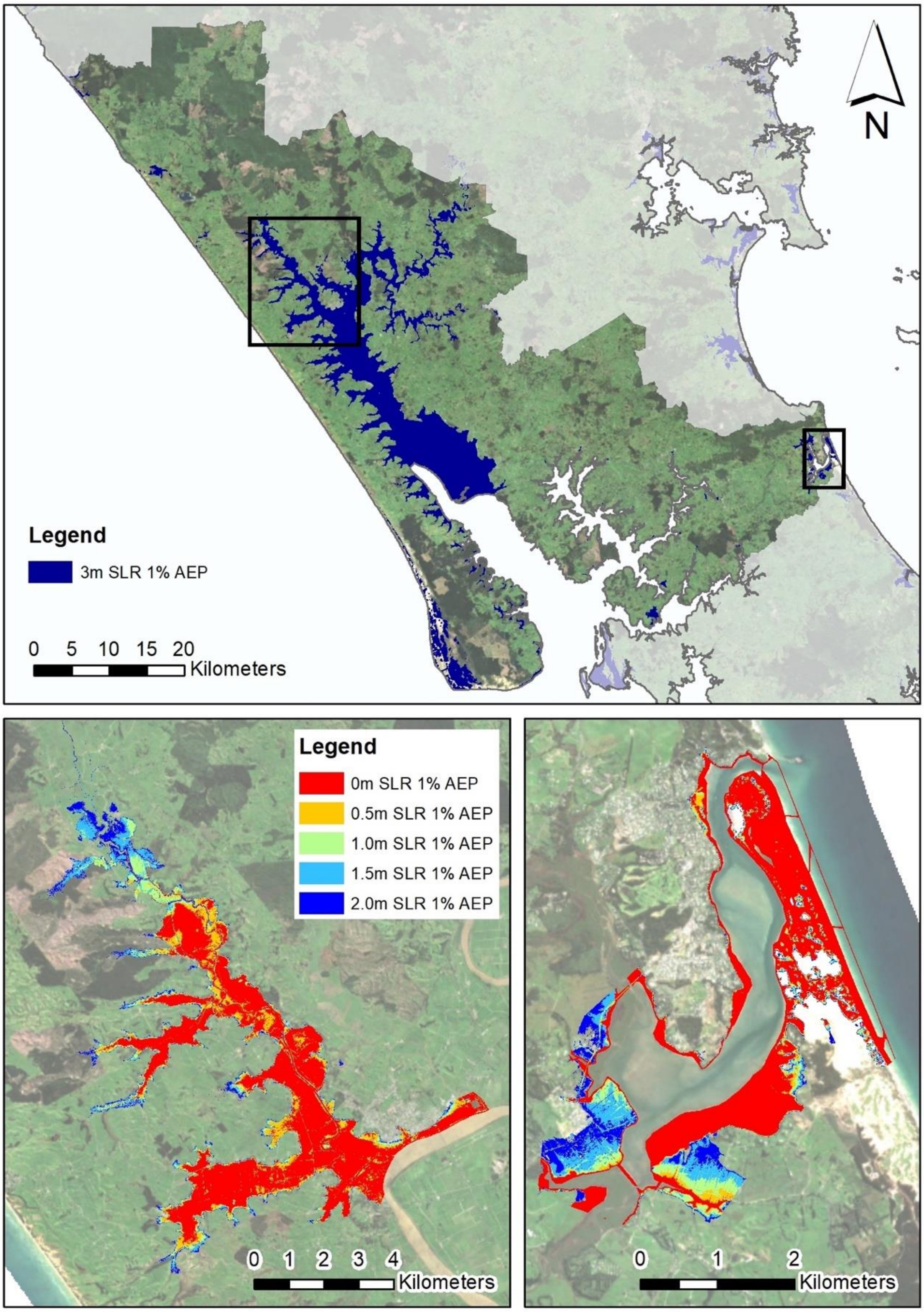

Figure 3-33: Maps of areas exposed to 100-year annual recurrence interval extreme sea levels (ESL_{100}) and sea-level rise (SLR) in the Kaipara District. The top map shows ESL_{100} flood mapping for 3 m SLR above mean sea level based on MERIT digital elevation data. The lower maps show ESL_{100} flood mapping for coastal land around Dargaville and Mangawhai where there was higher resolution LiDAR DEM coverage.

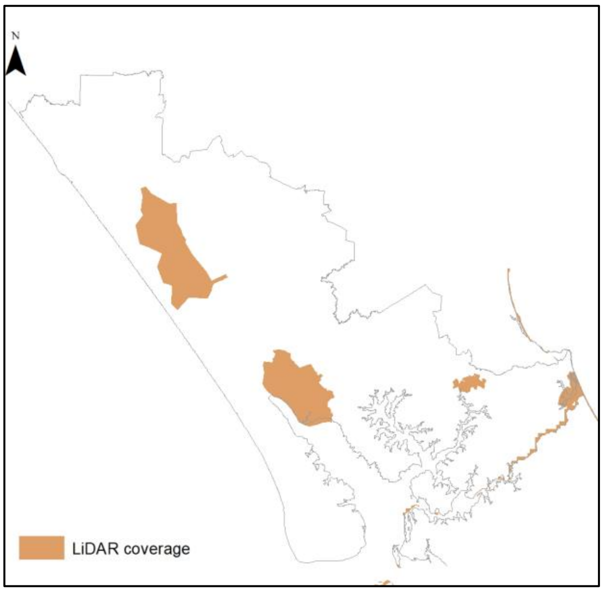

Figure 3-34: High Resolution DEM LiDAR coverage in Kaipara District.

3.5 Hydrological impacts of climate change

Key messages

- Mean annual discharge generally decreases by mid-century across the Kaipara District. By late century, mean discharge decrease is accentuated in the north-eastern area of the district with increasing greenhouse gas concentrations.
- Mean annual low flow generally decreases by late century, with decreases exceeding 20% in many areas of the district.
- High flow (expressed as Q5% flow) changes are expected to generally decrease with increasing greenhouse gas concentrations, with decreases exceeding 20% in many areas of the district.
- Floods (characterised by the Mean Annual Flood (annual peak flood)) are expected to become larger for many parts of the district under high radiative forcing scenarios. Under RCP4.5, flood peaks are expected to increase by mid-century while decreasing by the end of the century.

3.5.1 Methodology

Hydrological impacts of climate change were generated by coupling one-way climate change projections used in this study with NIWA's TopNet model. TopNet is a spatially semi-distributed, time-stepping model of water balance, that is used commonly in New Zealand for catchment, regional and national scale hydrological modelling. The model is driven by time-series of precipitation and temperature, and additional weather elements where available. More details about the methods used in hydrological modelling are found in Appendix F. As part of the Collins and Zammit (2016) drawn upon for this report, the hydrological modelling was set up with the following specificities:

- TopNet was run continuously from 1971 to 2100, with the spin-up period 1971 excluded from the analysis. The climate inputs were stochastically disaggregated from daily to hourly time steps.
- The simulation results comprise time-series of modelled river flow for each computational sub-catchment, and for each of the six GCMs and two RCPs considered.
- Hydrological projections are presented as the average for two future periods: 2036-2056 (termed 'mid-century') and 2086-2099 (termed 'late-century'). All maps show changes relative to the baseline climate (1986-2005 average).
- The period analysed are slightly different from the corresponding time slices of the atmospheric modelling because the modelling was done before this project was initiated. We do not expect that the conclusions drawn would be substantively different if the periods were aligned.
- Hydrological projections were analysed for the following hydrological statistics:
  - Mean annual discharge;
  - Mean annual low flow;
  - The Q5% flow[6]; and
  - The mean annual flood[7] (MAF).

3.5.2 Mean annual discharge

The projected future differences in the annual discharge for RCP4.5 and RCP8.5 at two future time periods are presented in Figure 3-35. At the annual scale, mean discharge generally decreases by mid-century across the Kaipara District. By late century, the decrease in mean discharge is accentuated in the north-eastern area of the district with increasing greenhouse gas concentrations.

[6] Q5: Flow that is exceeded 5 percent of the time.
[7] The mean of the series of each year's highest daily mean flow (m^3/s).

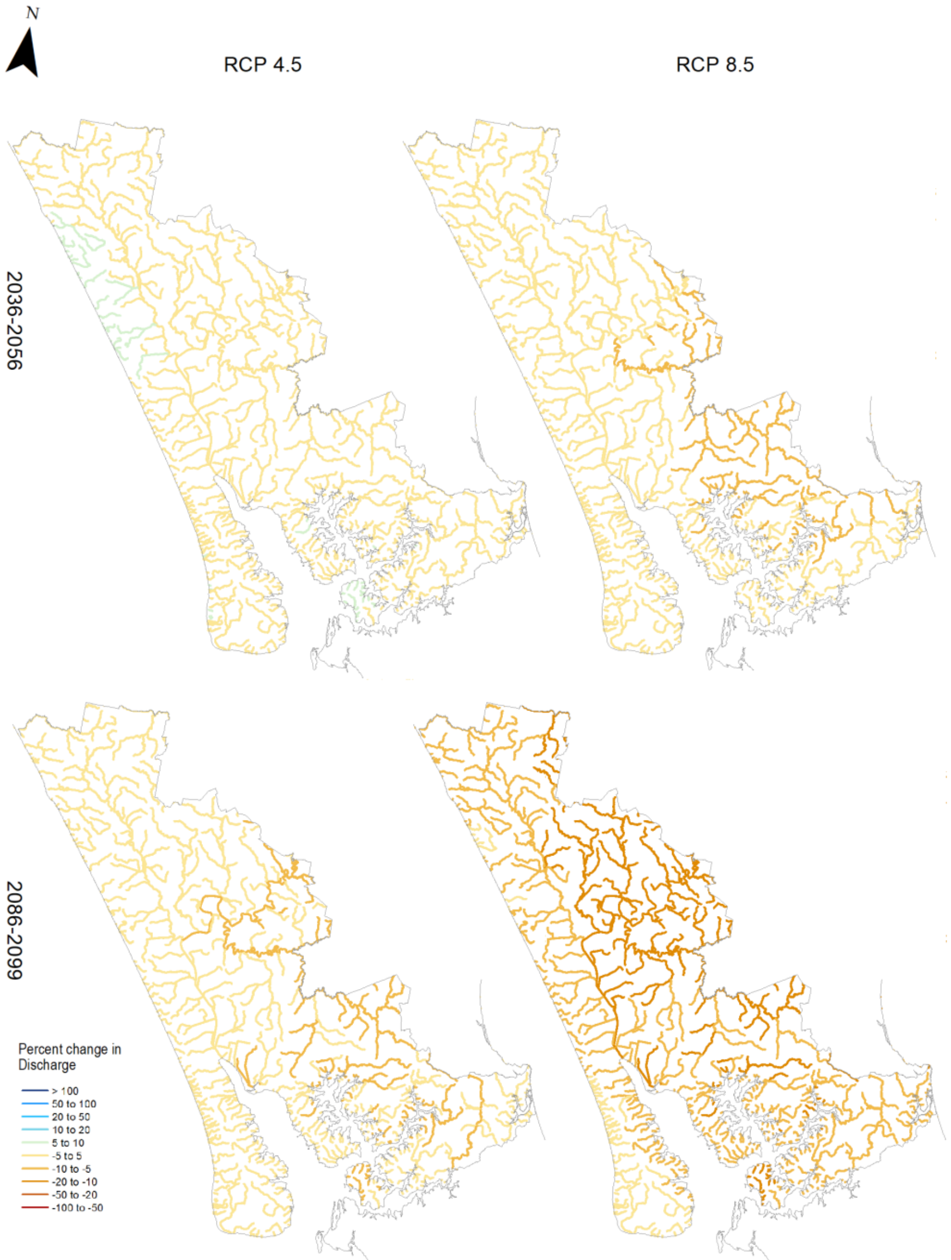

Figure 3-35: Percent changes in multi-model median of the mean discharge across Kaipara District for mid (top) and late-century (bottom). Climate change scenarios: RCP4.5 (left panels) and RCP8.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

3.5.3 Mean annual low flow

Mean annual low flow (MALF) is defined as the mean of the lowest 7-day average flows in each year of a projection period. Median changes in the MALF are presented for RCP4.5 and RCP8.5 at two time periods in Figure 3-36. At the annual scale, MALF generally decreases by mid-century across the district, although decreases are projected to be less severe under the higher greenhouse gas scenario. By late century, decrease in MALF tends to be more severe across the Kaipara District, with decreases exceeding 20% in many areas of the region.

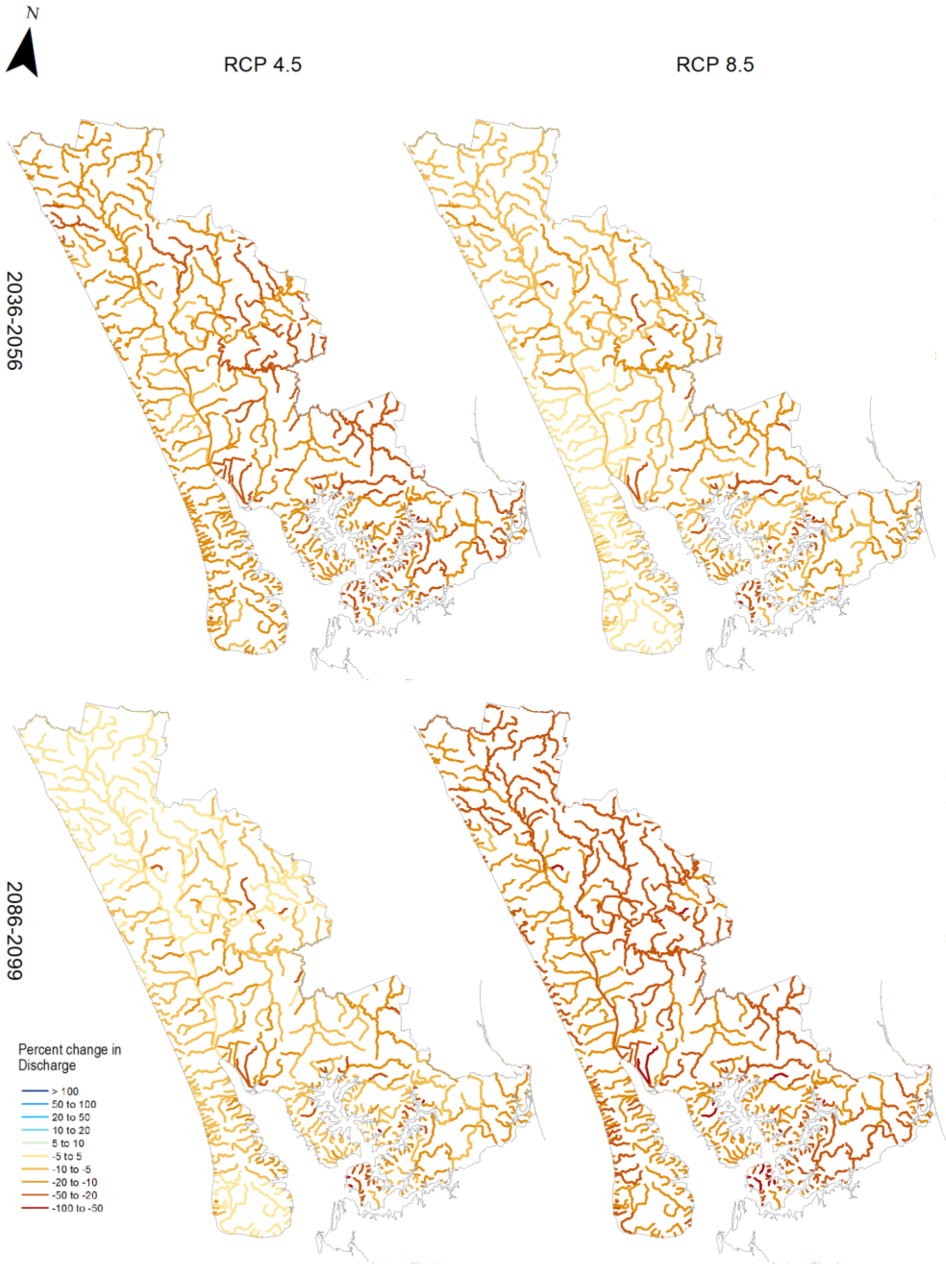

Figure 3-36: Percent changes in multi-model median of the mean annual low flow across Kaipara District for mid (top) and late-century (bottom). Climate change scenarios: RCP4.5 (left panels) and RCP8.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

3.5.4 High flow

The projected future differences in the Q5% flows (flow that is exceeded 5 percent of the time) for RCP4.5 and RCP8.5 at two time periods are presented in Figure 3-37. At the annual scale, Q5% generally decreases by mid-century across the district, although decreases are projected to be less severe under the higher greenhouse gas scenario. By late century, decrease in Q5% tends to be more severe across the Kaipara District, with decreases exceeding 20% for most of the district. These projections of decreasing high flows may seem counterintuitive with rainfall intensities generally projected to increase with more warming. However, the result here is linked with the limitation of climate models, in that they are not able to correctly reproduce ex-tropical cyclone tracks and other intense storms (where much of Kaipara's extreme rainfall is derived from). Because of this, further research and modelling is required to understand future changes to high flows.

Figure 3-37: Percent changes in multi-model median Q5% across Kaipara District for mid (top) and end of century (bottom). Climate change scenarios: RCP4.5 (left panels) and RCP8.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

3.5.5 Mean annual flood

The projected future differences in the mean annual flood (MAF; the mean of the series of each year's highest daily mean flow) for RCP4.5 and RCP8.5 at two time periods are presented in Figure

3-38. While there are some pockets of little change or decreasing MAF, in general Kaipara District is projected to experience an increase in MAF, with some increases exceeding 50% (by late-century under RCP8.5). There is difference among the RCPs during the mid-century period, with lower radiative forcing scenarios generating increase in MAF, while higher radiative forcing scenarios generating decrease in MAF (exceeding 25% in some catchments). By late-century, the areas under a large decrease in MAF by mid-century tends to experience increases in MAF especially under the higher radiative forcing scenario.

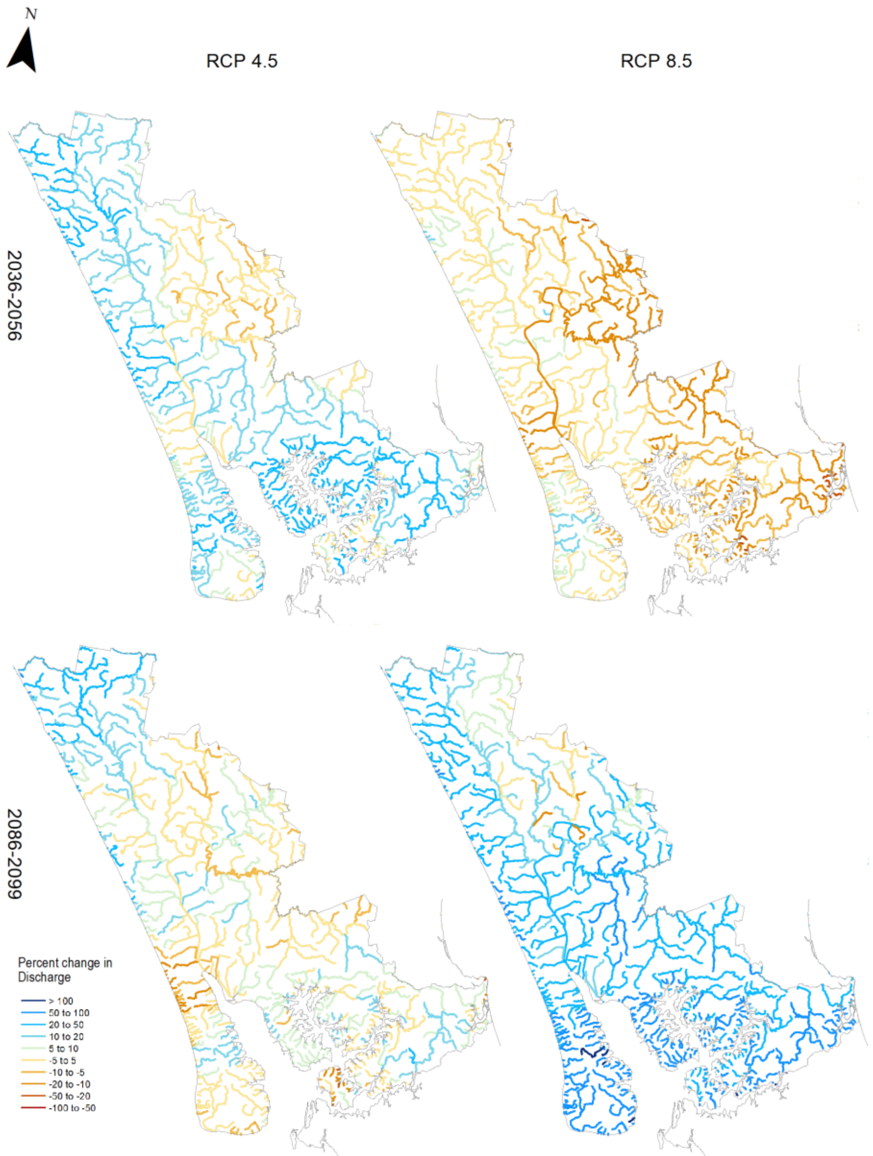

Figure 3-38: Percent changes in multi-model median of MAF across Kaipara District for mid (top) and end of century (bottom). Climate change scenarios: RCP4.5 (left panels) and RCP8.5 (right panels). Time periods: mid-century (2036-2056) and end-century (2086-2099).

The increase in MAF is a change that is largely consistent with the changes to rainfall presented in Ministry for the Environment (2018), especially regarding the 99th percentile of daily rainfall. Analysis of flow records indicates that MAF has a strong correspondence with observed mean annual rainfall

(Henderson et al., 2018). It is noteworthy that flood design standards for significant infrastructure are usually made based on events with annual exceedance probabilities much smaller than that represented by MAF. Analysis of RCM rainfall projections undertaken for the High Intensity Rainfall Design project (Carey-Smith et al., 2018), has shown that events with small annual exceedance probability are projected to increase ubiquitously across the country in a way that scales with increasing temperatures. As such, MAF should not be considered a comprehensive metric for the possible impact of climate change on New Zealand flooding.

3.6 Impacts on horticulture

Climate change will likely impact the horticulture industry in Kaipara District, particularly through changes to temperature and rainfall.

Increasing temperatures will impact all types of crops, as plant phenological development may occur at a faster rate. Different stages of plant growth (e.g. bud burst, flowering, and fruit development) may happen at different times, which may affect the harvested crop. For example, the hottest summer on record for New Zealand in 2017/18 saw wine grapes in multiple New Zealand regions ripen faster than usual (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[8].

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 varieties that are not able to currently be grown in Kaipara District. However, future warmer temperatures may create issues for horticulture in the District. Increasing risk from pests (plants and animals) and diseases is a concern. Currently, many pests are limited by New Zealand's relatively cool 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 Kaipara District.

Increases in extreme rainfall event magnitudes may impact horticulture in several different ways. Slips on hill country land 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 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.

Increased prevalence of drought and longer dry spells in Kaipara District will likely have impacts on water availability for irrigation and other horticultural uses. Low river flows are likely to decline in the District, 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 Kaipara District, which may further impact plant growth and increase the need for irrigation.

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

4 Summary and conclusions

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

Present-day climatic conditions in Kaipara District were characterised using a combination of data based on the most recent climate-normal period (30-year average from 1981-2010; i.e. the "climatology") and all available data. Climatology data were typically used when calculating the average, or typical present-day values for each climate variable. All available data were used when calculating extreme values, such as Dargaville's highest temperature on record. The following list summarises the present-day climate of Kaipara District:

1. The annual average temperature is between 14.8°C to 15.4°C for most of Kaipara District. Summer average temperature is between 18.5°C to 19.5°C, and winter average temperature is between 11.0°C to 12.0°C.

2. Dargaville's average daily maximum temperature is 24.4°C in February, and the average daily minimum temperature is 7.2°C in July. On average, Dargaville observes 32 hot days (daily maximum temperature >25°C) and 3 frost days (daily minimum temperature <0°C) per year.

3. Annual average growing degree days (base 10°C) is between 1,700 GDD to 2,000 GDD for most of Kaipara District.

4. Kaipara District's annual total rainfall averages between 1,100-1,400 mm. Summer is typically the driest season (225-300mm), and winter is the wettest season (350-500mm).

5. Dargaville averages 140 wet days (i.e., days where the total precipitation is at least 1 mm) per year.

6. Kaipara District observes an average of 40-60 days of soil moisture deficit each year.

7. The median annual sunshine for Kaipara District is 1,850-1,950 hours.

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

Changes to Kaipara District's future climate are likely to be significant. The following list summarises the projections of different climate and hydrological variables in Kaipara District:

1. The projected Kaipara District temperature changes increase with time and greenhouse gas concentrations. Future annual average warming spans a wide range: 0.5-1.5°C by 2040, and 1.0-3.5°C by 2090.
2. Changes in extreme temperatures reflect the changes in the average annual signal. The average number of hot days and heatwave days is expected to increase with time and scenario. The number of hot days and heatwave days is projected to increase by 60-80 days by 2090 under RCP8.5.
3. Growing degree days are projected to increase throughout Kaipara District. By 2040 under RCP4.5, an increase of 250-300 GDD is projected, and by 2090 under RCP8.5 an increase of 900-1,000 GDD is projected.
4. Projected changes in rainfall show variability across Kaipara District. Annual rainfall is expected to slightly decrease in northern inland areas by 2090 under RCP8.5 (2-6%), while little change to annual rainfall in Kaipara District is projected under remaining scenarios (±2%). Seasonally the largest increases are projected during autumn, with 2-15% increases projected for most of the District under all future scenarios. Winter and spring rainfall are projected to decrease by 6-15% by 2090 under RCP8.5.
5. The number of wet days is projected to decrease for Kaipara District at each future period and for both RCPs. By 2090 under RCP8.5, 16-22 fewer wet days are projected for the District. Consequently, the annual number of dry days are projected to increase in future throughout Kaipara District.
6. Extreme, rare rainfall events are projected to become more severe in the future. Short duration rainfall events have the largest relative increases compared with longer duration rainfall events. The depth of a current 1:100-year 1-hour duration rainfall event is projected to increase by approximately 35% by 2090 under RCP8.5.
7. Kaipara District is projected to observe an increase in the amount of accumulated PED, therefore drought potential is projected to increase. Accumulated PED is projected to increase by 120-160 mm per year by 2090 under RCP8.5.
8. Kaipara District will likely observe an increase in days of soil moisture deficit. By 2040 under RCP4.5, an increase of 2-10 days of SMD is projected. By 2090 under RCP8.5, an increase of 20-35 days of SMD is projected.
9. Projected climate changes will bring challenges (e.g. higher PED resulting in increased demand for water resources) and opportunities (e.g. warmer temperatures more suitable to warm climate crops) to the horticulture industry of Kaipara District.
10. Coastal flooding from extreme sea levels will increase in frequency and magnitude as global climate change forces sea-level rise.

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

- Mean annual discharges generally decrease by mid-century across the Kaipara District. By late century, mean discharge decrease is accentuated in the north-eastern area of the district with increasing greenhouse gas concentrations.
- Mean annual low flow generally decreases by late century, with decreases exceeding 20% in many areas of the district.
- High flow (expressed as Q5% flow) changes are expected to generally decrease with increasing greenhouse gas concentrations, with decreases exceeding 20% in many areas of the district.
- Floods (characterised by the Mean Annual Flood (annual peak flood)) are expected to become larger for many parts of the district under high greenhouse gas concentrations. Under RCP4.5, flood peaks are expected increase by mid-century while decreasing by the end of the century.

5 Glossary of abbreviations and terms

Adaptation	The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.
Anomaly	The deviation of a variable from its value averaged over a reference period.
Anthropogenic	Human-induced; man-made. Resulting from or produced by human activities.
Anthropogenic emissions	Emissions of greenhouse gases, greenhouse gas precursors, and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use changes, livestock production, fertilization, waste management, and industrial processes.
AOGCM	Atmosphere-ocean global climate model – a comprehensive climate model containing equations representing the behaviour of the atmosphere, ocean and sea ice and their interactions.
AR5	5th Assessment Report of IPCC – published in 2013/14 covering three Working Group Reports and a Synthesis Report.
Atmosphere	The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium and radiatively active greenhouse gases such as carbon dioxide (0.035% volume mixing ratio) and ozone. In addition, the atmosphere contains the greenhouse gas water vapour, whose amounts are highly variable but typically around 1% volume mixing ratio. The atmosphere also contains clouds and aerosols.
Available Water Capacity (AWC)	The amount of water in the soil 'reservoir' that plants can use.
Baseline/reference	The baseline (or reference) is the state against which change is measured. A baseline period is the period relative to which anomalies are computed.
BCC-CSM1.1	The Beijing Climate Centre Climate System Model version 1.1. A fully coupled global climate-carbon model. Part of CMIP5.
Bias correction	Procedures designed to remove systematic climate model errors.
Business as Usual (BAU)	Business as usual projections assume that operating practices and policies remain as they are at present. Although baseline scenarios could incorporate some specific features of BAU scenarios (e.g., a ban on a specific technology), BAU scenarios imply that no practices or policies other than the current ones are in place. RCP8.5 is known as the 'business as usual' climate change scenario.

Carbon dioxide (CO2)	A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas and coal of burning biomass, of land use changes and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1.
CESM1-CAM5	The Community Earth System Model, version 5 of the Community Atmosphere Model primarily developed at the National Center for Atmospheric Research in the USA. Part of CMIP5.
Climate	Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, rainfall and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.
Climate change	Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.
Climate change scenario	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.

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

CMIP5	Coupled Model Inter-comparison Project, Phase 5, which involved coordinating and archiving climate model simulations based on shared model inputs by modelling groups from around the world. This project involved many experiments with coupled atmosphere-ocean global climate models, most of which were reported on in the IPCC Fifth Assessment Report, Working Group I. The CMIP5 dataset includes projections using the Representative Concentration Pathways.
Confidence	The validity of a finding based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement. Confidence is expressed qualitatively.
DEM	Digital elevation model.
Diurnal temperature range	The difference between the maximum and minimum temperature during a 24-hour period.
Downscaling (statistical, dynamical)	Deriving local climate information (at the 5 kilometre grid-scale in this report) from larger-scale model or observational data. Two main methods exist – statistical and dynamical. Statistical methods develop statistical relationships between large-scale atmospheric variables (e.g., circulation and moisture variations) and local climate variables (e.g., rainfall variations). Dynamical methods use the output of a regional climate/weather model driven by a larger-scale global model.
Drought (meteorological, hydrologic)	A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term; therefore, any discussion in terms of rainfall deficit must refer to the rainfall-related activity that is under discussion. For example, shortage of rainfall during the growing season impinges on crop production or ecosystem function in general (due to soil moisture drought, also termed agricultural drought), and during the runoff and percolation season primarily affects water supplies (hydrological drought). Storage changes in soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in rainfall. A period with an abnormal rainfall deficit is defined as a meteorological drought. A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.
Emission scenario	A plausible representation of the future development of emissions of substances that act as radiative forcing factors (e.g., greenhouse gases, aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships.

Ensemble	A collection of model simulations characterizing a climate prediction or projection. Differences in initial conditions and model formulation result in different evolutions of the modelled system and may give information on uncertainty associated with model error and error in initial conditions in the case of climate forecasts and on uncertainty associated with model error and with internally generated climate variability in the case of climate projections.
ENSO	El Niño-Southern Oscillation. A natural global climate phenomenon involving the interaction between the tropical Pacific and the atmosphere, but has far-reaching effects on the global climate, especially for countries in the Pacific rim. ENSO is the strongest climate signal on time scales of one to several years, characteristically oscillating on a 3-7-year timescale. The quasi-periodic cycle oscillates between El Niño (unusually warm ocean waters along the tropical South American coast and west-central equatorial Pacific) and La Niña (colder-than-normal ocean waters off South America and along the central-east equatorial Pacific).
Eustatic sea-level rise	Absolute level of sea-level rise, measured relative to the centre of the earth. In contrast to relative sea-level rise which is measured relative to the land nearby.
Evapotranspiration	The combined process of evaporation from the Earth's surface and transpiration from vegetation.
Flood	The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.
GCM	Global climate model. These days almost all GCMs are AOGCMs (atmosphere-ocean global climate models). See also climate model.
GFDL-CM3	The Coupled physical model version 3, developed by the Geophysics Fluid Dynamics Laboratory at NOAA in the USA. Part of CMIP5.
GISS-E2-R	The E2-R climate model developed by NASA Goddard Institute for Space Studies in the USA. Part of CMIP5.

Greenhouse effect	The radiative effect of all infrared-absorbing constituents in the atmosphere. Greenhouse gases, clouds, and (to a small extent) aerosols absorb terrestrial radiation emitted by the Earth’s surface and elsewhere in the atmosphere. These substances emit infrared radiation in all directions, but, everything else being equal, the net amount emitted to space is normally less than would have been emitted in the absence of these absorbers. This is because of the decline of temperature with altitude in the troposphere and the consequent weakening of emission. An increase in the concentration of greenhouse gases increases the magnitude of this effect; the difference is sometimes called the enhanced greenhouse effect. The change in a greenhouse gas concentration because of anthropogenic emissions contributes to an instantaneous radiative forcing. Surface temperature and troposphere warm in response to this forcing, gradually restoring the radiative balance at the top of the atmosphere.
Greenhouse gas (GHG)	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth’s surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary greenhouse gases in the Earth’s atmosphere. Moreover, there are many entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO2, N2O and CH4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).
HadGEM2-ES	Climate model developed by the UK Met Office Hadley Centre, from the UK Unified Model. Part of CMIP5.
HAT	Highest Astronomical Tide. The highest tidal level which can be predicted to occur under average meteorological conditions over 18 years. Sometimes called the maximum high water.
Humidity	*Specific* humidity is the ratio of the mass of water vapour to the total mass of the system (water plus air) in a parcel of moist air. *Relative* humidity is the ratio of the vapour pressure to the saturation vapour pressure (the latter having a strong dependence on temperature).
Hydrologic drought	Hydrologic drought occurs when low water supply becomes evident, especially in streams, reservoirs, and groundwater levels, usually after an extended period of meteorological drought.

Industrial Revolution	A period of rapid industrial growth with far reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of fossil fuels and emission of, in particular, fossil carbon dioxide.
IPCC	Intergovernmental Panel on Climate Change. This body was established in 1988 by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) to objectively assess scientific, technical and socioeconomic information relevant to understanding the scientific basis of risk of human induced climate change, its potential impacts and options for adaptation and mitigation. Its latest reports (the Fifth Assessment) were published in 2013/14 (see www.ipcc.ch/).
IPO	Interdecadal Pacific Oscillation – a long timescale oscillation in the ocean–atmosphere system that shifts climate in the Pacific region every one to three decades.
Mean annual flood (MAF)	The mean of the series of each year's highest daily mean flow.
Mean annual low flow (MALF)	The mean of the lowest 7-day average flows in each year of a projection period.
Mean discharge	The average annual streamflow or discharge of a river.
Mean sea level (MSL)	The surface level of the ocean at a point averaged over an extended period such as a month or year, or the average level which would exist in the absence of tides. Mean sea level is often used as a national datum to which heights on land are referred. Mean sea level changes with the averaging period used, due to climate variability and long-term sea-level rise.
MFE	Ministry for the Environment.
Mitigation (of climate change)	A human intervention to reduce the sources or enhance the sinks of greenhouse gases.
Model spread	The range or spread in results from climate models, such as those assembled for Coupled Model Intercomparison Project Phase 5 (CMIP5). Does not necessarily provide an exhaustive and formal estimate of the uncertainty in feedbacks, forcing or projections even when expressed numerically, for example, by computing a standard deviation of the models' responses. To quantify uncertainty, information from observations, physical constraints and expert judgement must be combined, using a statistical framework.
NIWA	National Institute of Water and Atmospheric Research Ltd.
NorESM1-M	The Norwegian Earth System Model. Part of CMIP5.

Ozone	Ozone, the triatomic form of oxygen (O_3), is a gaseous atmospheric constituent. In the troposphere, it is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Tropospheric ozone acts as a greenhouse gas. In the stratosphere, it is created by the interaction between solar ultraviolet radiation and molecular oxygen (O_2). Stratospheric ozone plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.
Paris agreement	The Paris Agreement aims to respond to the global climate change threat by keeping a global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C.
PED	Potential evapotranspiration deficit. PED can be thought of as the amount of water needed to be added as irrigation, or replenished by rainfall, to keep pastures growing at levels that are not constrained by a shortage of water.
Percentiles	The set of partition values which divides the total population of a distribution into 100 equal parts, the 50th percentile corresponding to the median of the population.
PET	Potential evapotranspiration. The amount of evaporation that would occur if a sufficient water source were available.
Precipitation	Describes all forms of moisture that falls from clouds (rain, sleet, hail, snow, etc). 'Rainfall' describes just the liquid component of precipitation.
Pre-industrial	Conditions at or before 1750. See also Industrial revolution.
Projection	A numerical simulation (representation) of future conditions. Differs from a forecast; whereas a forecast aims to predict the exact time-dependent conditions in the immediate future, such as a weather forecast a future cast aims to simulate a time-series of conditions that would be typical of the future (from which statistical properties can be calculated) but does not predict future individual events.
Radiative forcing	A measure of the energy absorbed and retained in the lower atmosphere. More technically, radiative forcing is the change in the net (downward minus upward) irradiance (expressed in W/m^2, and including both short-wave energy from the sun, and long-wave energy from greenhouse gases) at the tropopause, due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the sun.

Regional Climate Model (RCM)	A numerical climate prediction model run over a limited geographic domain (here around New Zealand), and driven along its lateral atmospheric boundary and oceanic boundary with conditions simulated by a global climate model (GCM). The RCM thus downscales the coarse resolution GCM, accounting for higher resolution topographical data, land-sea contrasts, and surface characteristics. RCMs can cater for relatively small-scale features such as New Zealand's Southern Alps.
Relative sea-level rise (RSLR)	A tide gauge records a combined signal of the vertical change (positive or negative) in the level of both the sea and the land to which the gauge is affixed; or relative sea level change, which is typically referred to as relative sea-level rise.
Representative Concentration Pathways (RCPs)	Representative concentration pathways. They describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. The four RCPs, RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively)
Resolution	In climate models, this term refers to the physical distance (metres or degrees) between each point on the grid used to compute the equations. Temporal resolution refers to the time step or time elapsed between each model computation of the equations.
SAM	Southern Annular Mode. Represents the variability of circumpolar atmospheric jets that encircle the Southern Hemisphere that extend out to the latitudes of New Zealand. Positive phases of SAM are associated with relatively settled weather in New Zealand, whereas negative phases are associated with unsettled weather over the country.
Scenario	In common English parlance, a 'scenario' is an imagined sequence of future events. The IPCC Fifth Assessment describes a 'climate scenario' as: A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. The word 'scenario' is often given other qualifications, such as 'emission scenario' or 'socio-economic scenario'. For the purpose of forcing a global climate model, the primary information needed is the time variation of greenhouse gas and aerosol concentrations in the atmosphere.
Sea surface temperature (SST)	The sea surface temperature is the subsurface bulk temperature in the top few metres of the ocean, measured by ships, buoys and drifters.
Seven-station series	This refers to seven long-term temperature records used to assess New Zealand's warming on the century time-scale. The sites are located in Auckland, Wellington, Masterton, Nelson, Hokitika, Lincoln, and Dunedin.

Simulation	Simulation is the imitation of the operation of a real-world process or system over time. The act of simulating something first requires that a model be developed; this model represents the key characteristics, behaviours and functions of the selected physical or abstract system or process. The model represents the system itself, whereas the simulation represents the operation of the system over time.
SLR	Sea-level rise.
SOI	Southern Oscillation Index, representing seesaws of atmospheric pressure in the tropical Pacific, one pole being at Tahiti and the other at Darwin, Australia. Extreme states of this index are indicative of El Niño or La Niña events in the equatorial Pacific. Typically, El Niño events produce more south-westerly flow than usual over New Zealand and associated cooler conditions, with more rainfall in western parts and frequently drought conditions in the east. La Niña events produce more high pressures over the South Island and warmer north-easterly airflow over the North Island, sometimes with drought conditions in the South Island.
Soil moisture deficit (SMD)	A day of soil moisture deficit is considered in this report to be when soil moisture is below 75 mm of available soil water capacity. SMD is calculated based on incoming daily rainfall (mm), outgoing daily potential evapotranspiration (PET, mm), and a fixed available water capacity (the amount of water in the soil 'reservoir' that plants can use) of 150 mm. Evapotranspiration (ET) is assumed to continue at its potential rate until about half of the water available to plants is used up, whereupon it decreases, in the absence of rain, as further water extraction takes place. ET is assumed to cease if all the available water is used up.
Solar radiation	Electromagnetic radiation emitted by the Sun with a spectrum close to the one of a black body with a temperature of 5770 K. The radiation peaks in visible wavelengths. When compared to the terrestrial radiation it is often referred to as shortwave radiation.
Spatial and temporal scales	Climate may vary on a large range of spatial and temporal scales. Spatial scales may range from local (less than 100,000 km2), through regional (100,000 to 10 million km2) to continental (10 to 100 million km2). Temporal scales may range from seasonal to geological (up to hundreds of millions of years).
TopNet	A semi-distributed hydrological model for simulating catchment water balance and river flow, developed by NIWA.
Trend	In this report, the word trend designates a change, generally monotonic in time, in the value of a variable.

Uncertainty	A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts).
VCSN	Virtual Climate Station Network. Made up of observational datasets of a range of climate variables: maximum and minimum temperature, rainfall, relative humidity, solar radiation, and wind. Daily data are interpolated onto a 0.05° longitude by 0.05° latitude grid (approximately 4 kilometres longitude by 5 kilometres latitude), covering all New Zealand (11,491 points). Primary reference to the spline interpolation methodology is Tait et al (2006).

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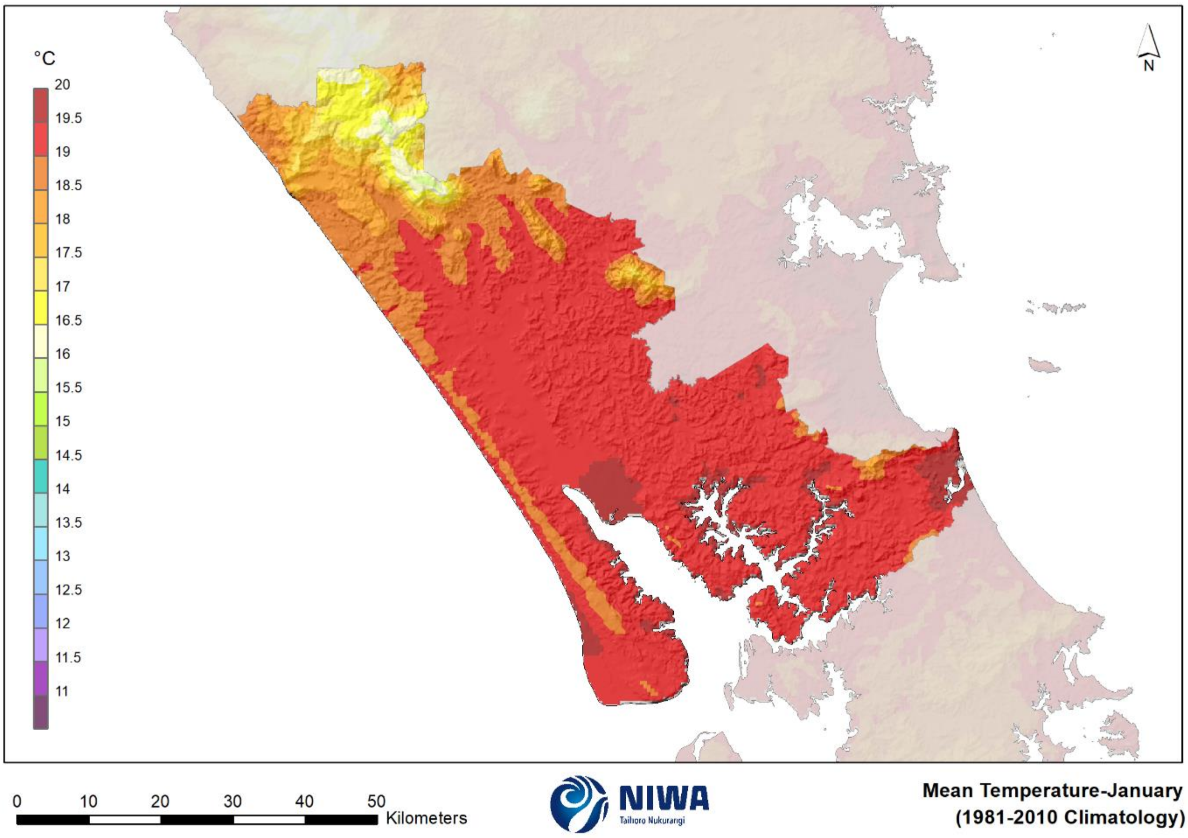
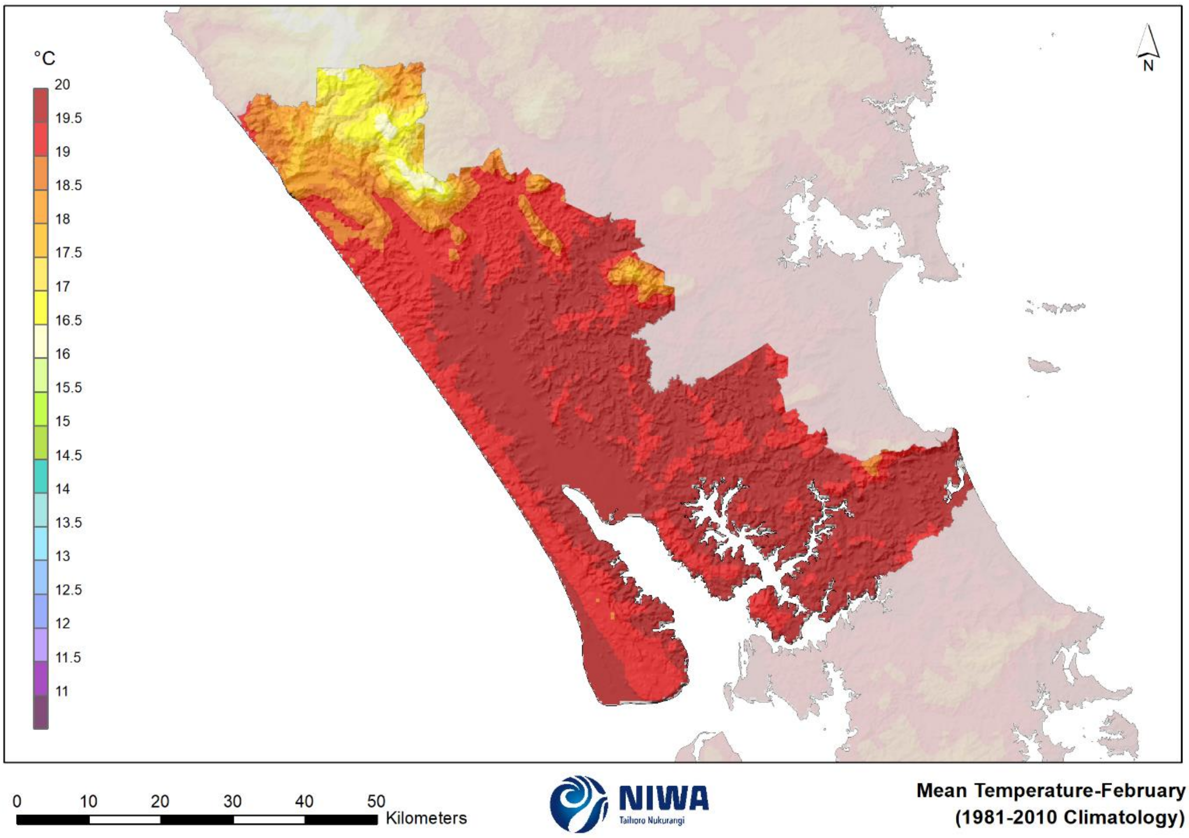
Appendix A Monthly average temperature maps

Monthly average temperature maps for Kaipara District are included sequentially (i.e. January to December) below.

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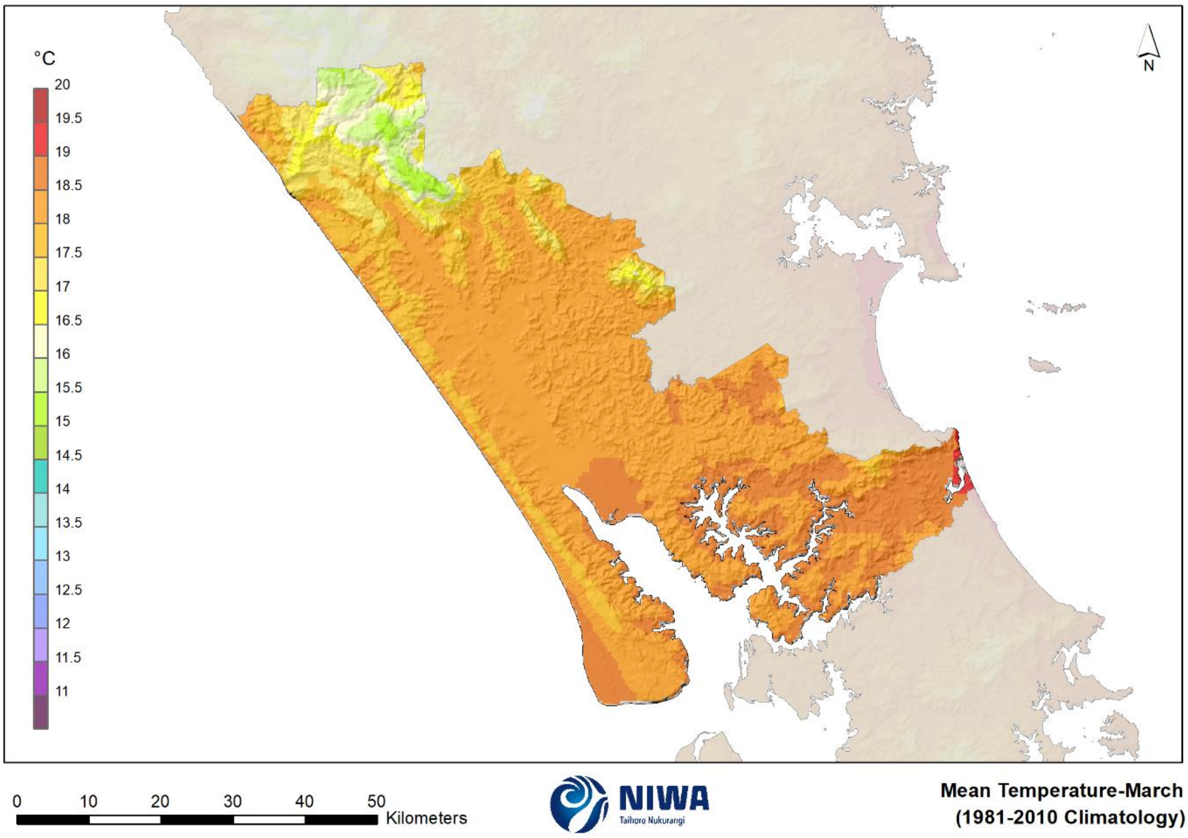
NIWA
Taihoro Nukurangi
Mean Temperature-February
(1981-2010 Climatology)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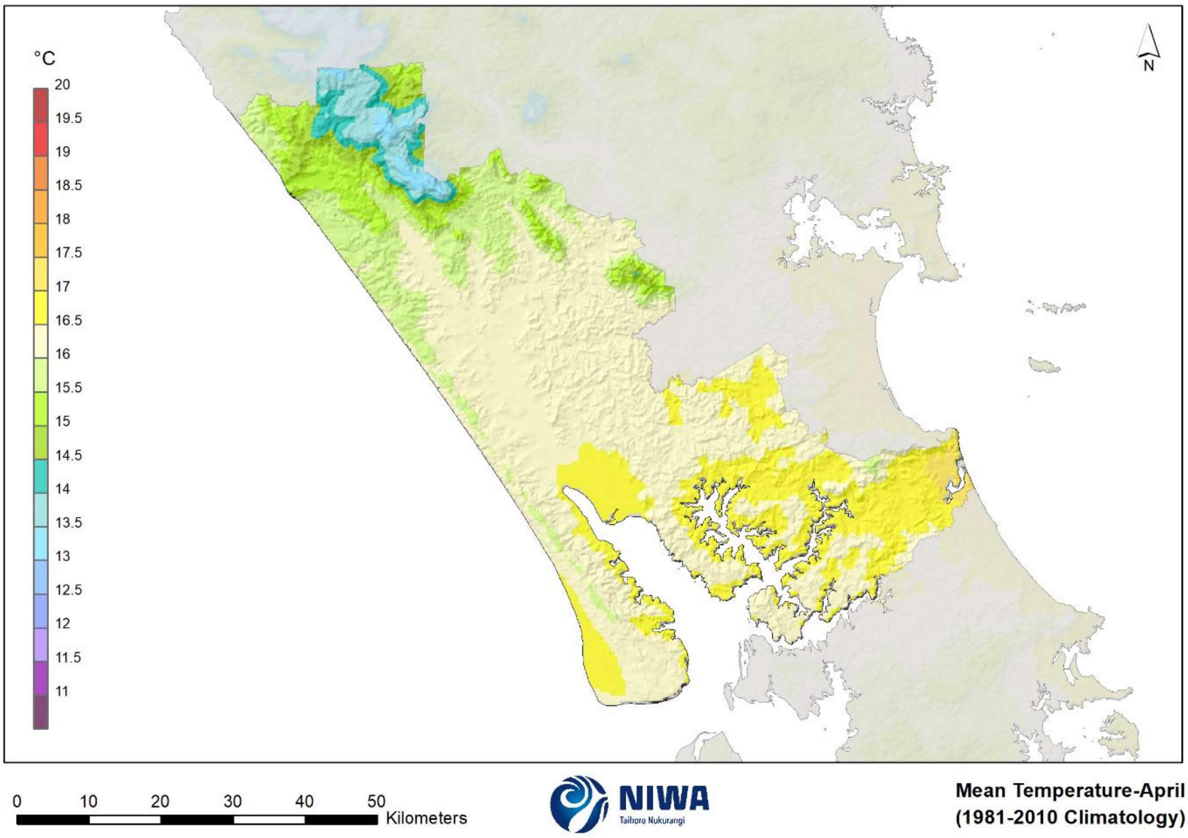
NIWA
Taihoro Nukurangi
Mean Temperature-March
(1981-2010 Climatology)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NIWA
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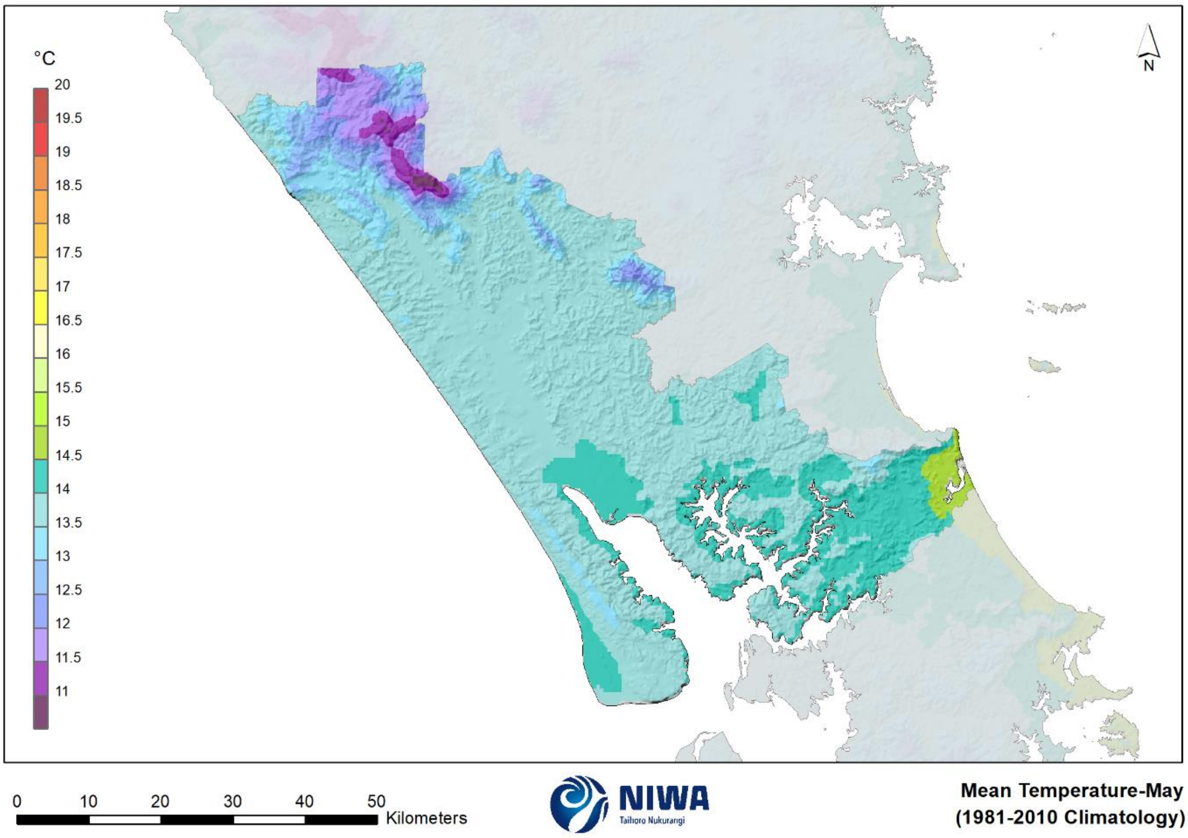
Mean Temperature-April
(1981-2010 Climatology)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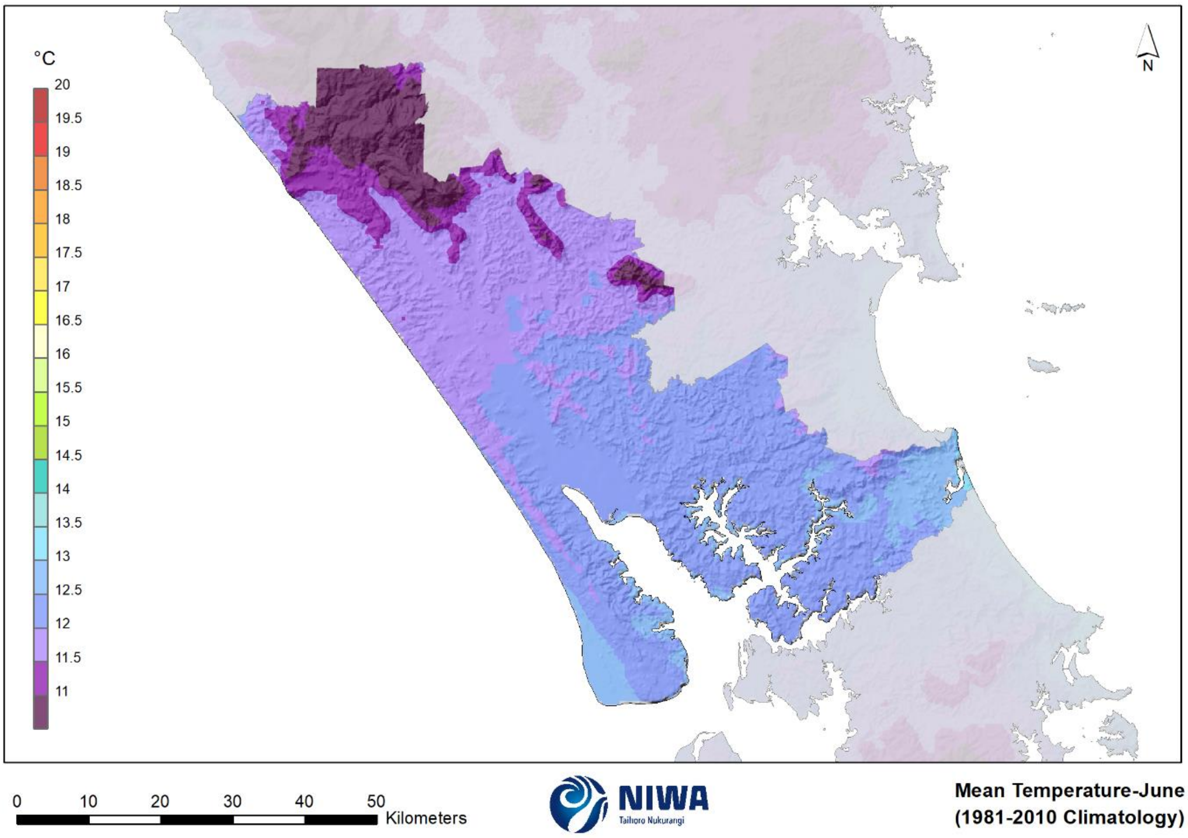
Taihoro Nukurangi
Mean Temperature-May
(1981-2010 Climatology)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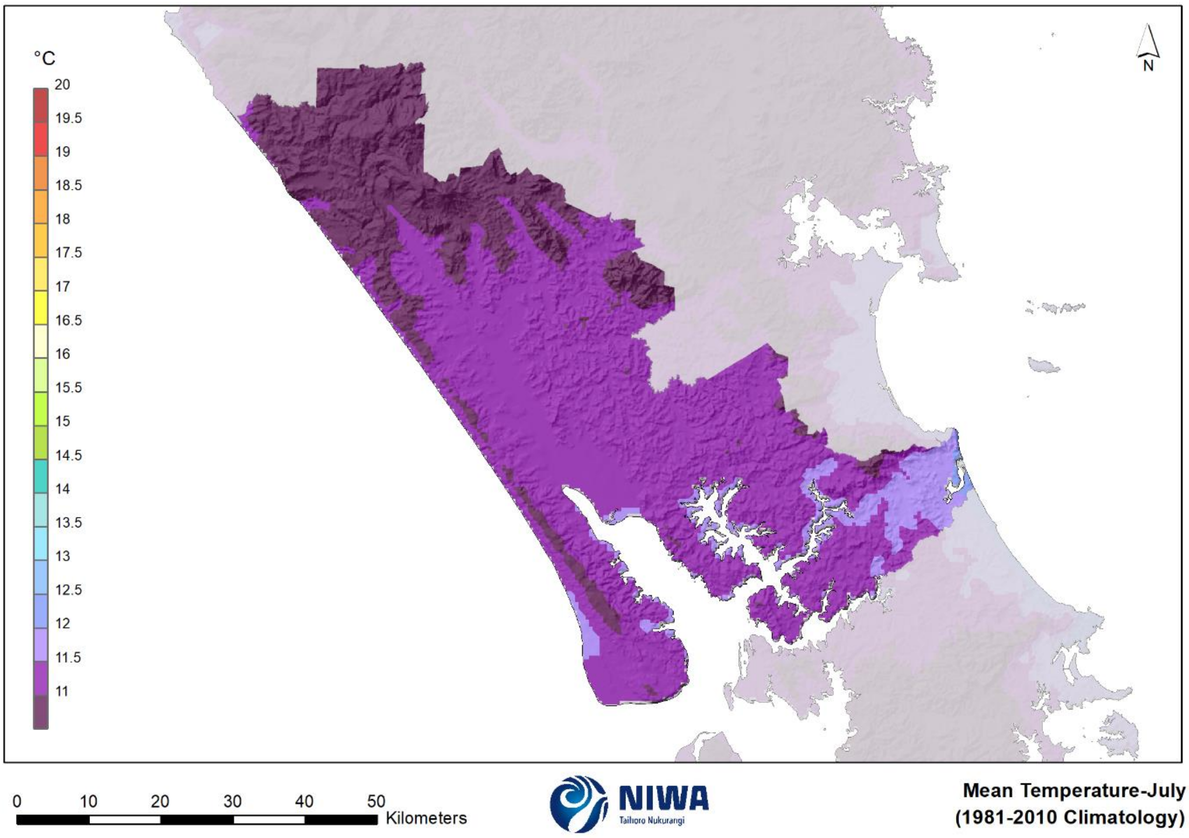
NIWA
Taihoro Nukurangi
Mean Temperature-June
(1981-2010 Climatology)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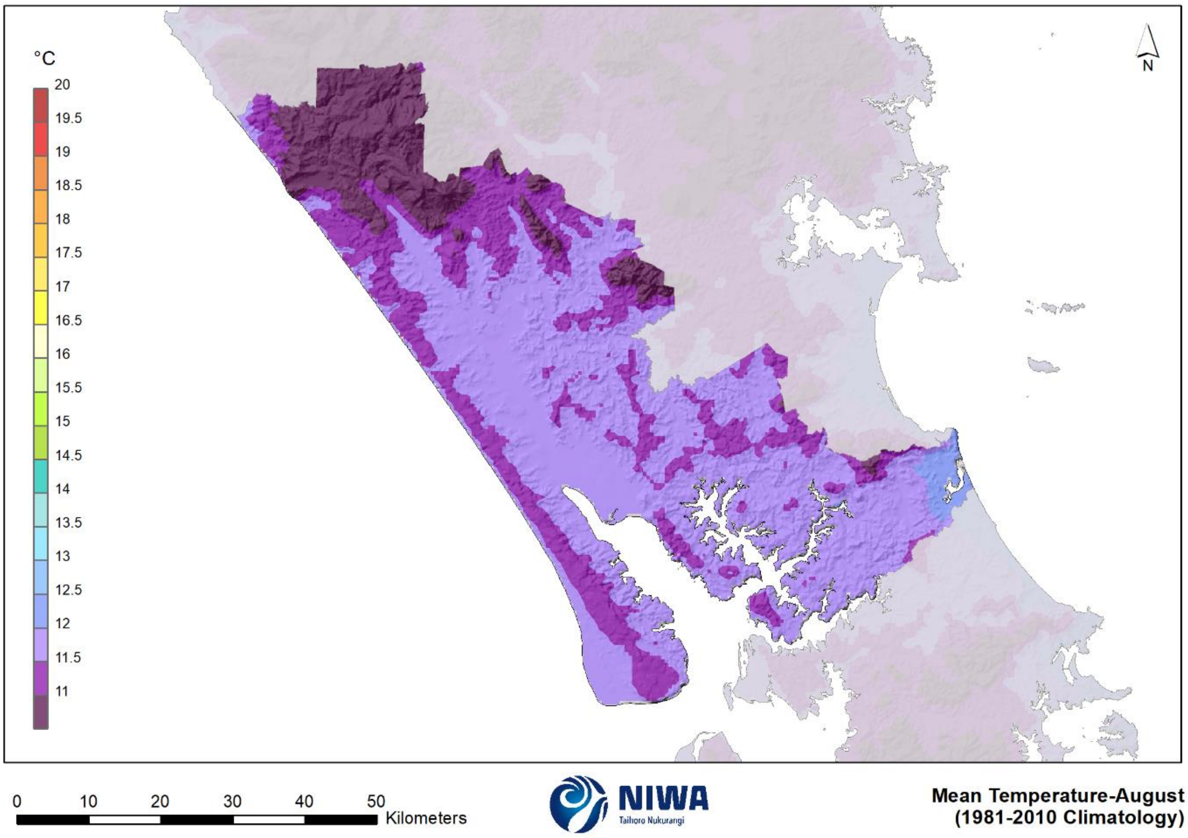
NIWA
Taihoro Nukurangi
Mean Temperature-July
(1981-2010 Climatology)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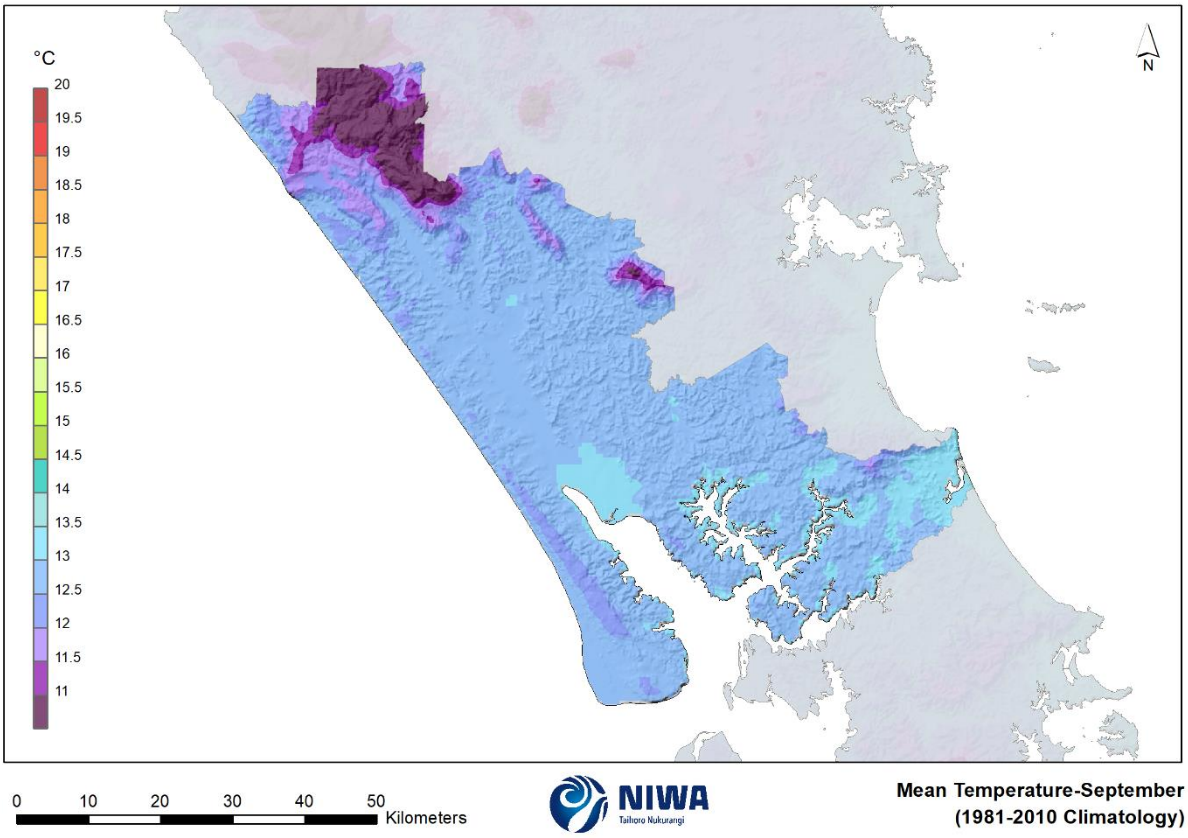
NIWA
Taihoro Nukurangi
Mean Temperature-August
(1981-2010 Climatology)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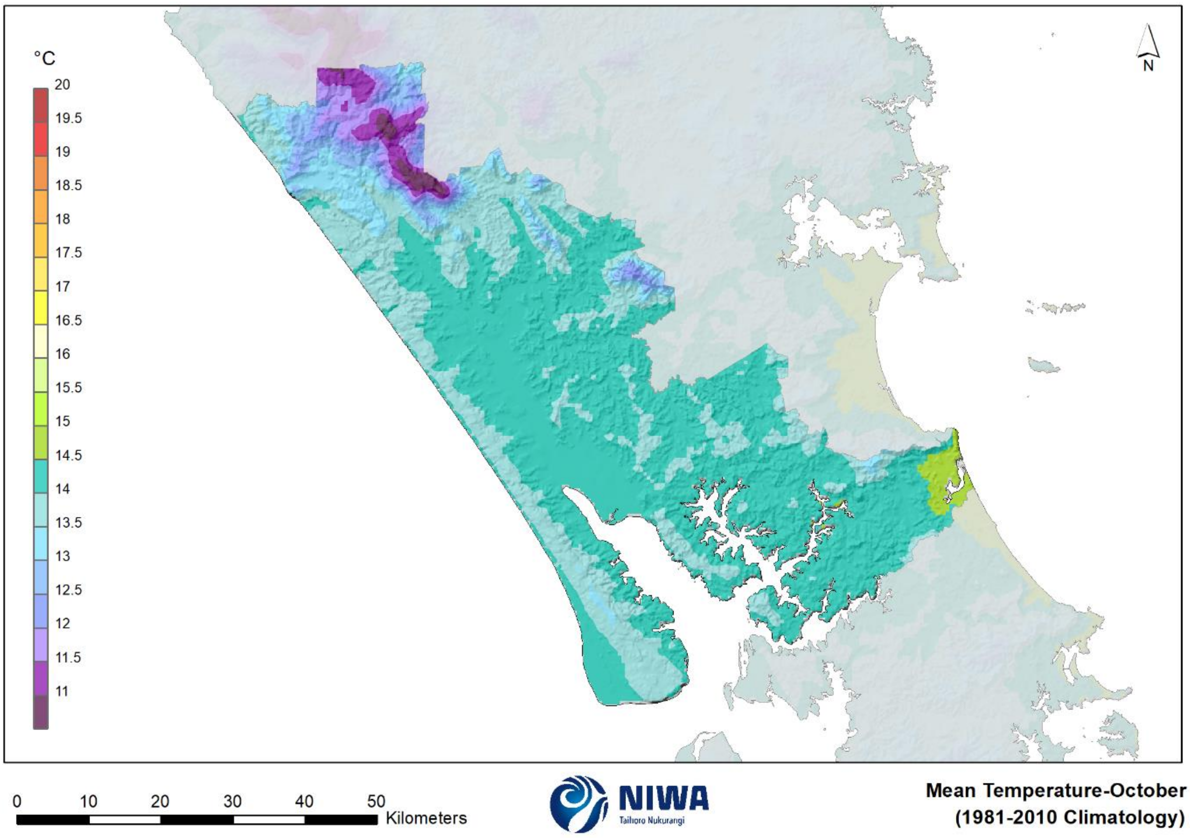
NIWA
Taihoro Nukurangi
Mean Temperature-September
(1981-2010 Climatology)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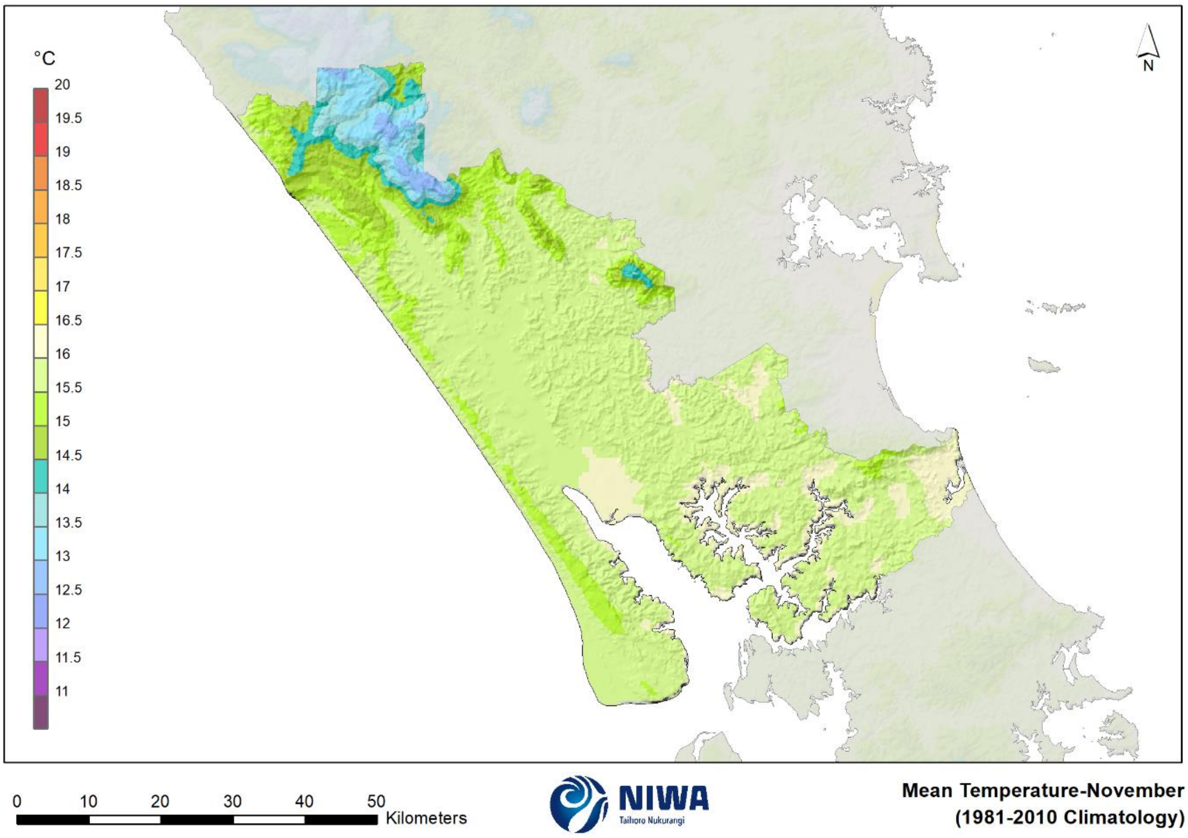
Taihoro Nukurangi
Mean Temperature-October
(1981-2010 Climatology)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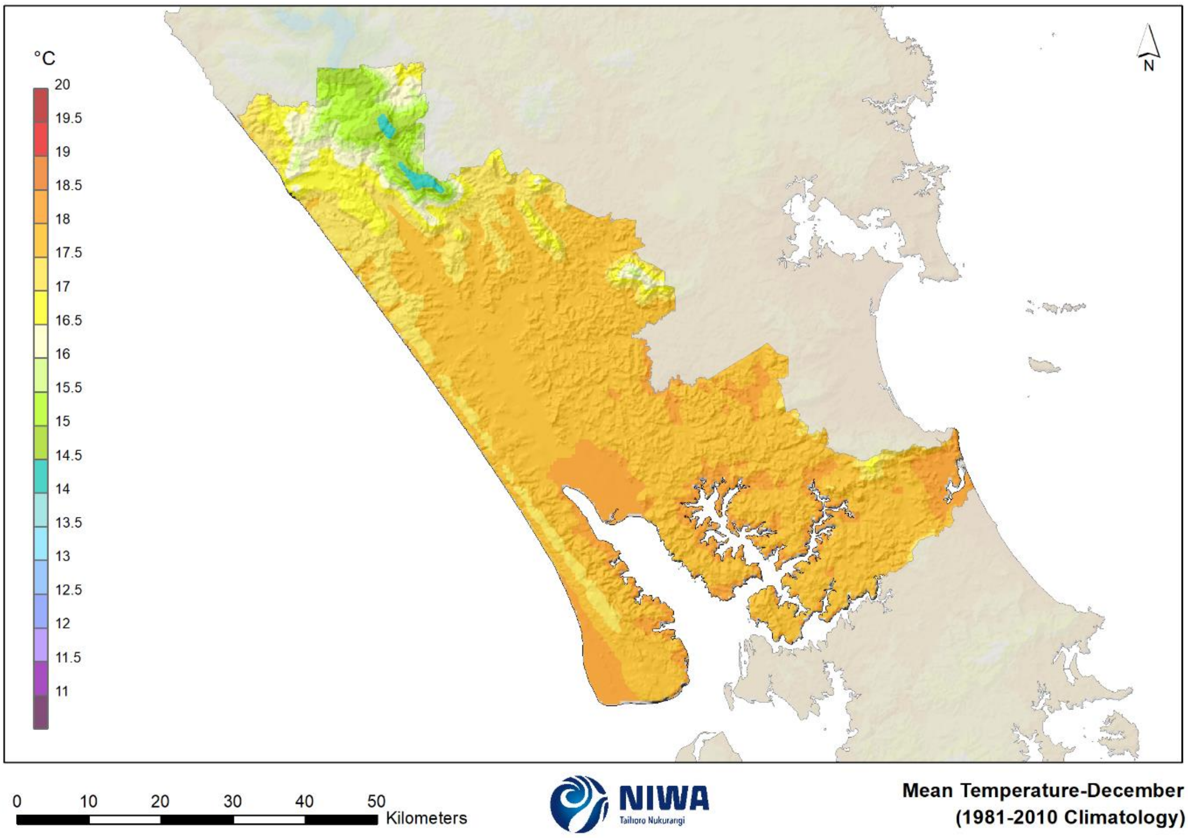
NIWA
Taihoro Nukurangi
Mean Temperature-November
(1981-2010 Climatology)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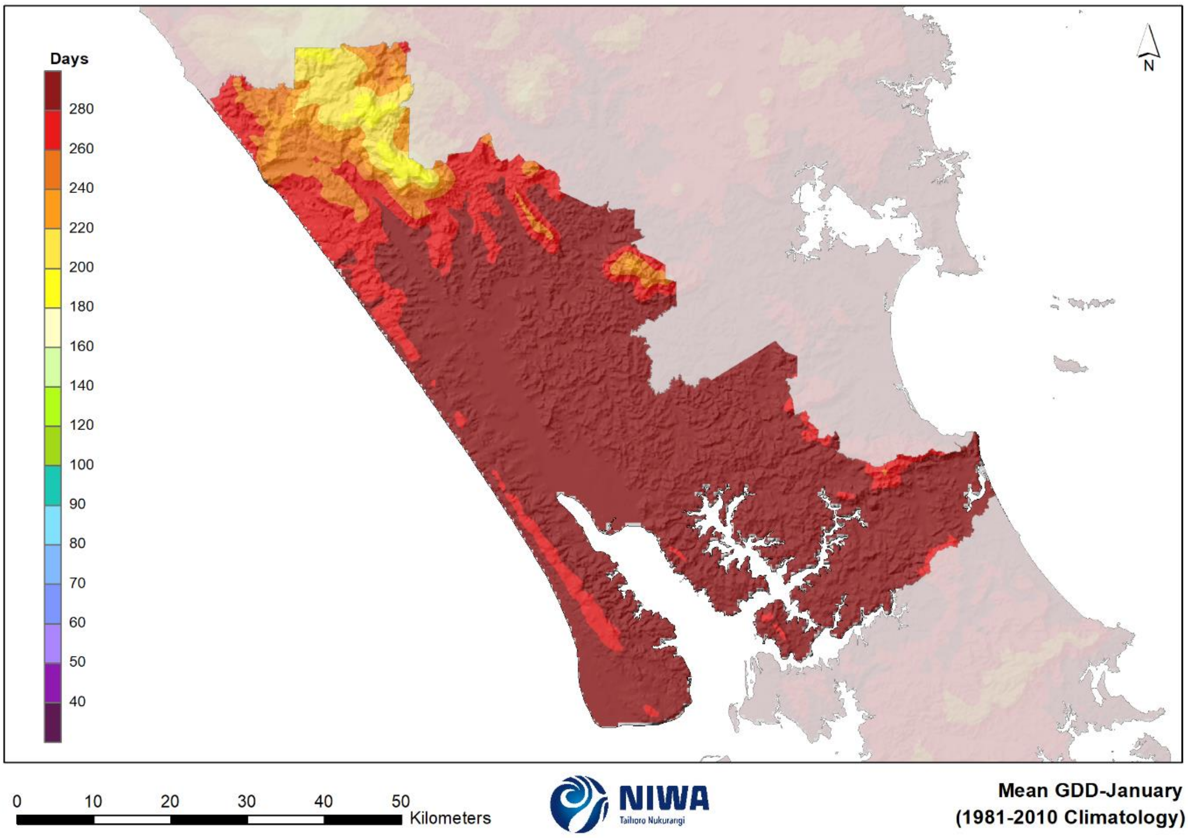
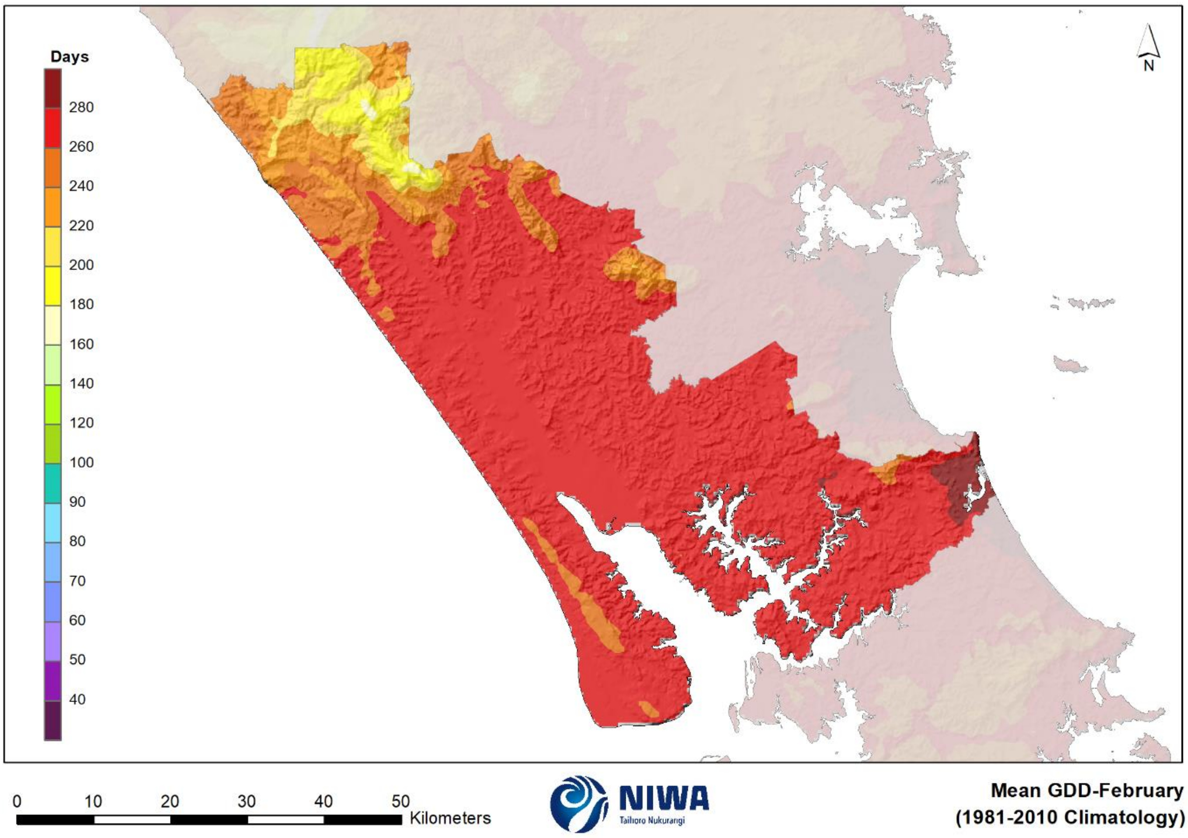
NIWA
Taihoro Nukurangi
Mean Temperature-December
(1981-2010 Climatology)

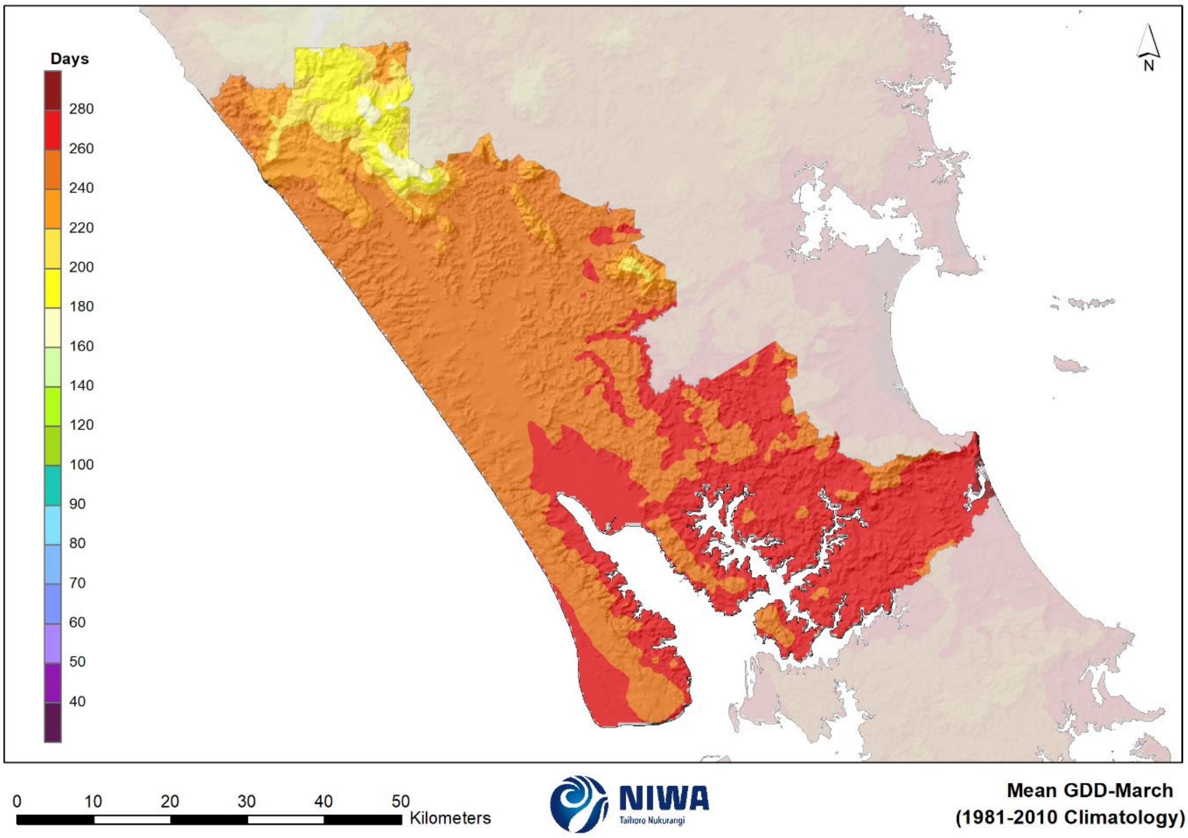
Appendix B Monthly growing degree day maps

Monthly mean growing degree maps for Kaipara District are included sequentially (i.e. January to December) below.

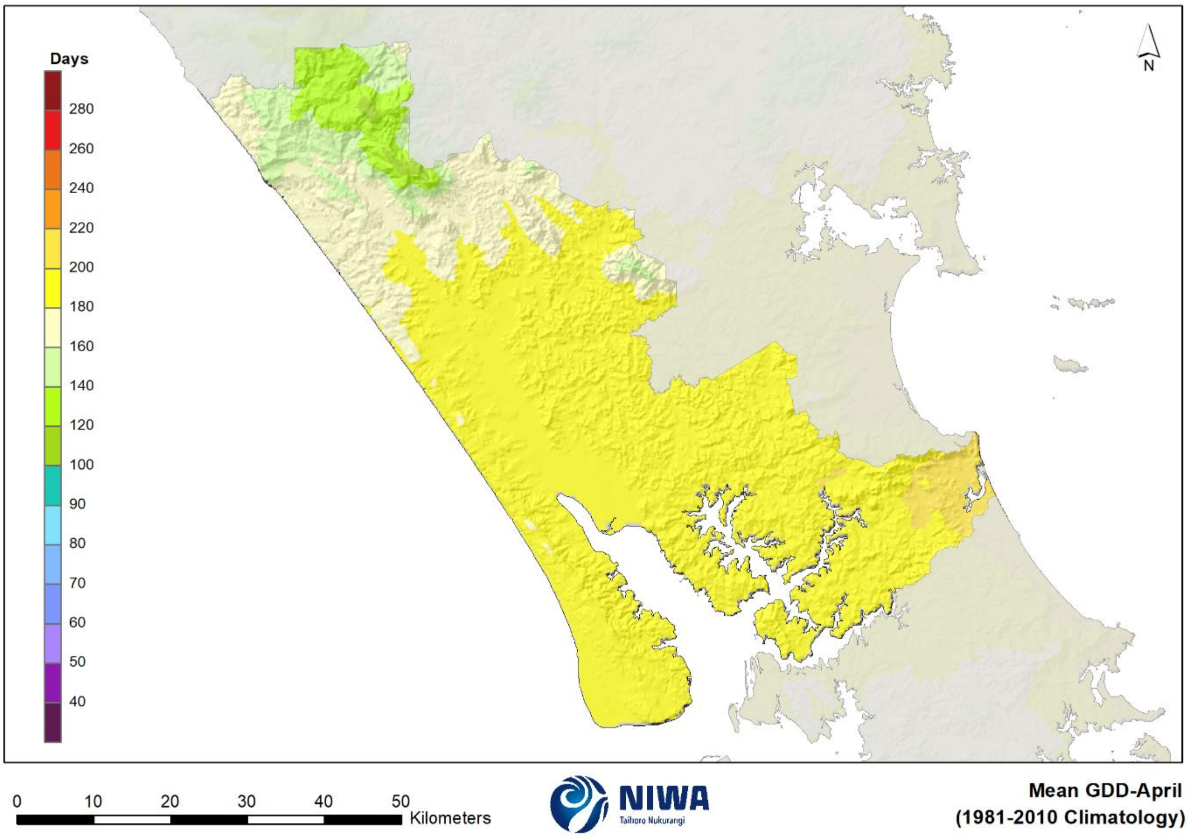




Mean GDD-February
(1981-2010 Climatology)



Mean GDD-March
(1981-2010 Climatology)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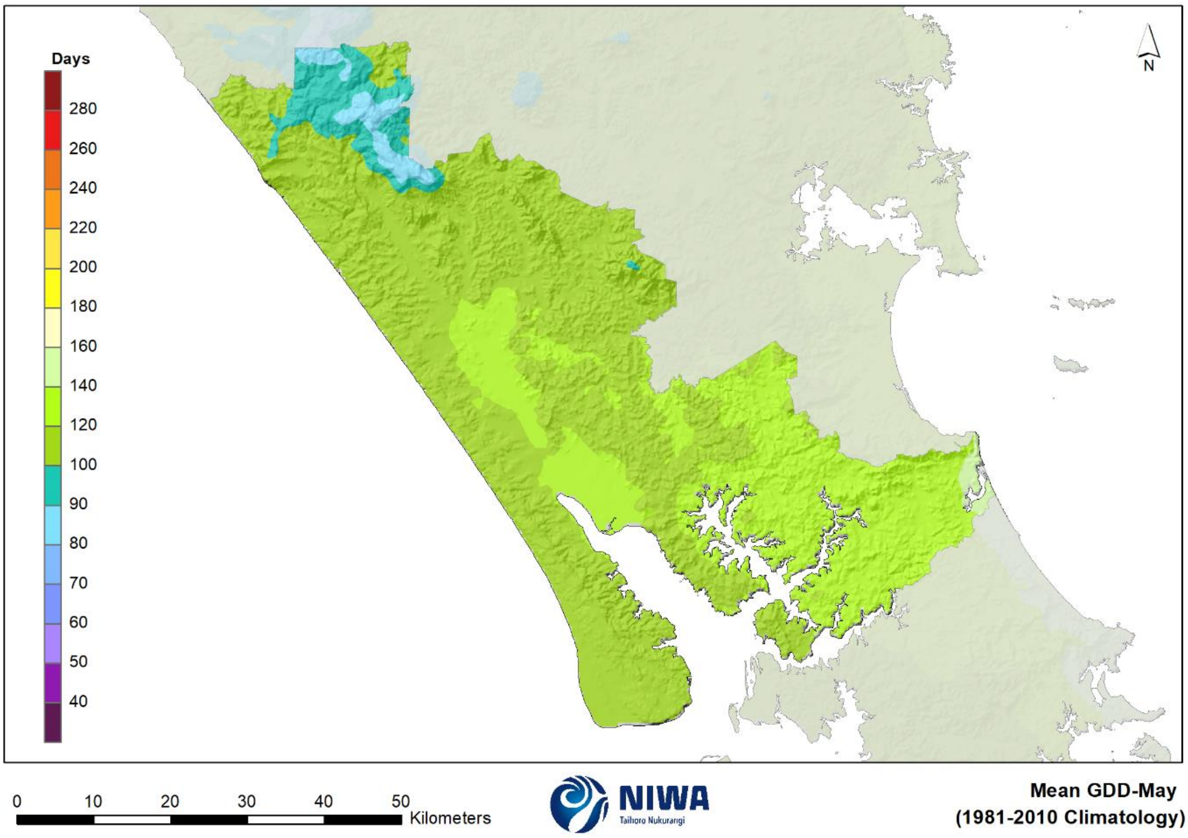
Taihoro Nukurangi
Mean GDD-April
(1981-2010 Climatology)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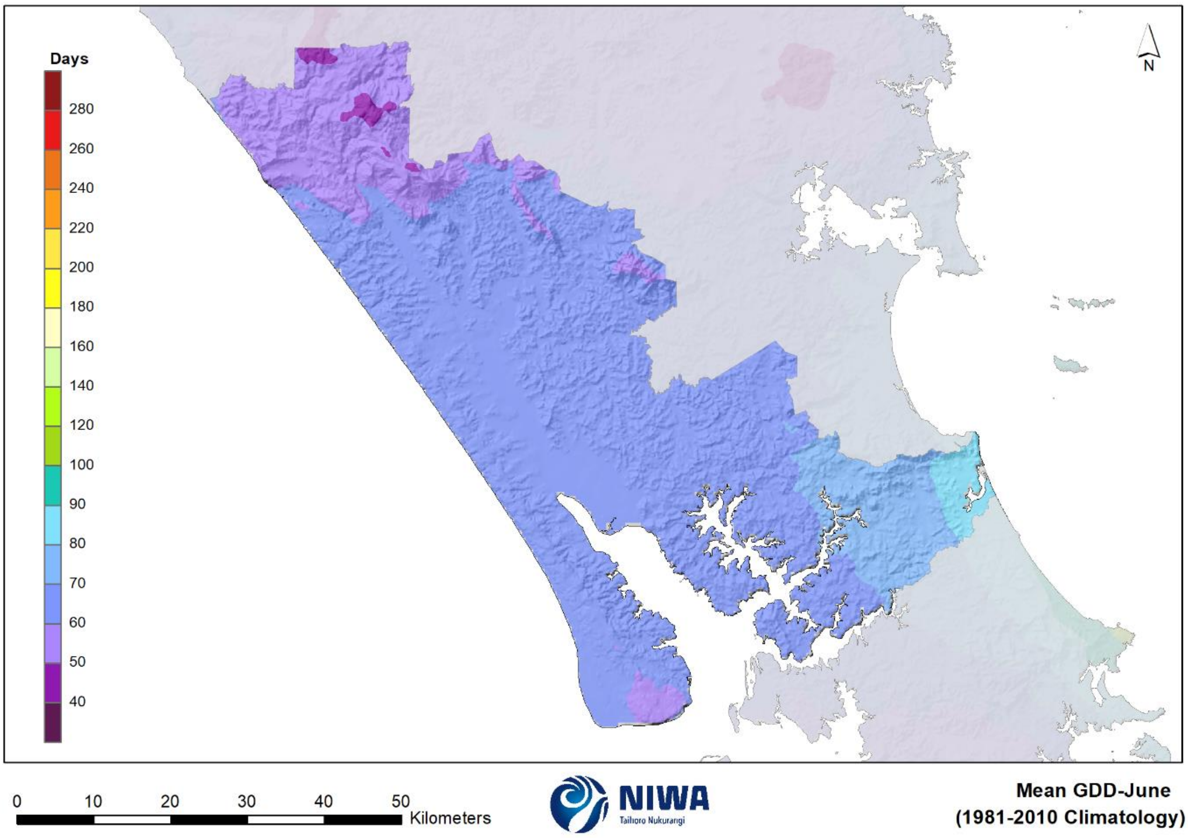
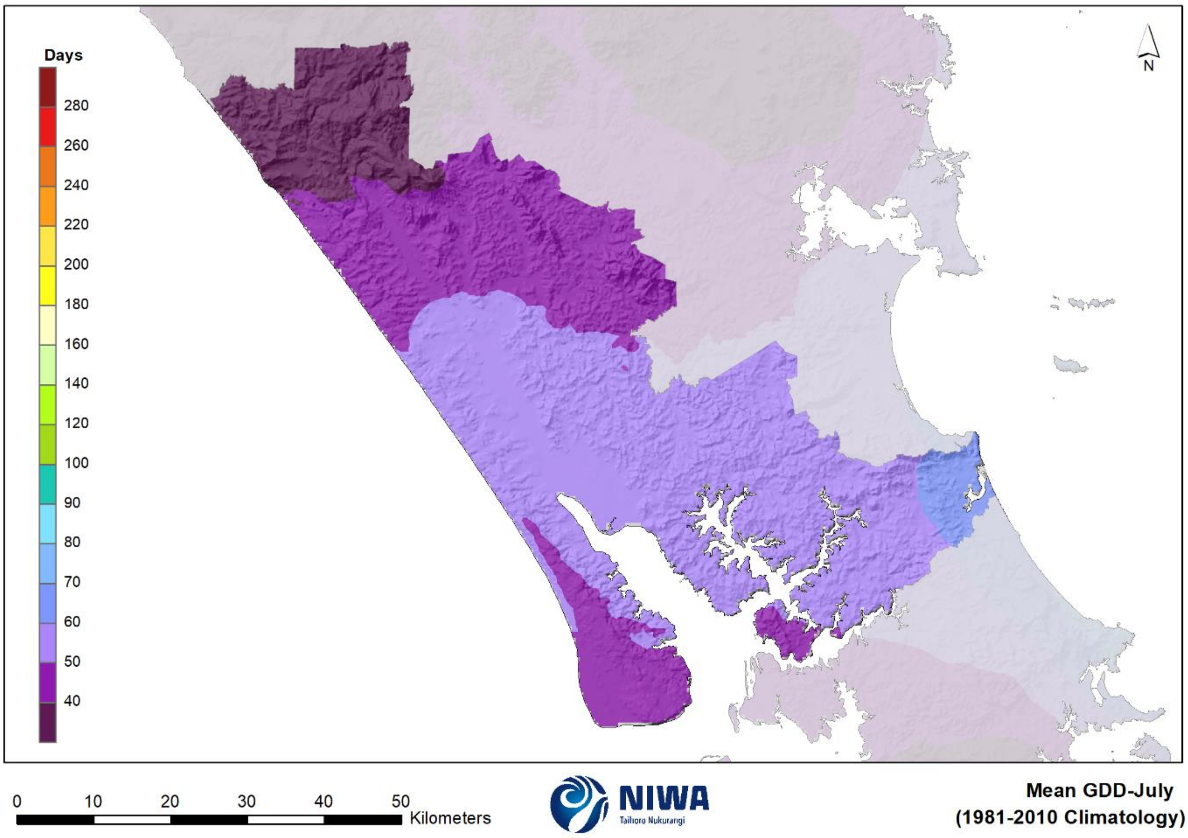
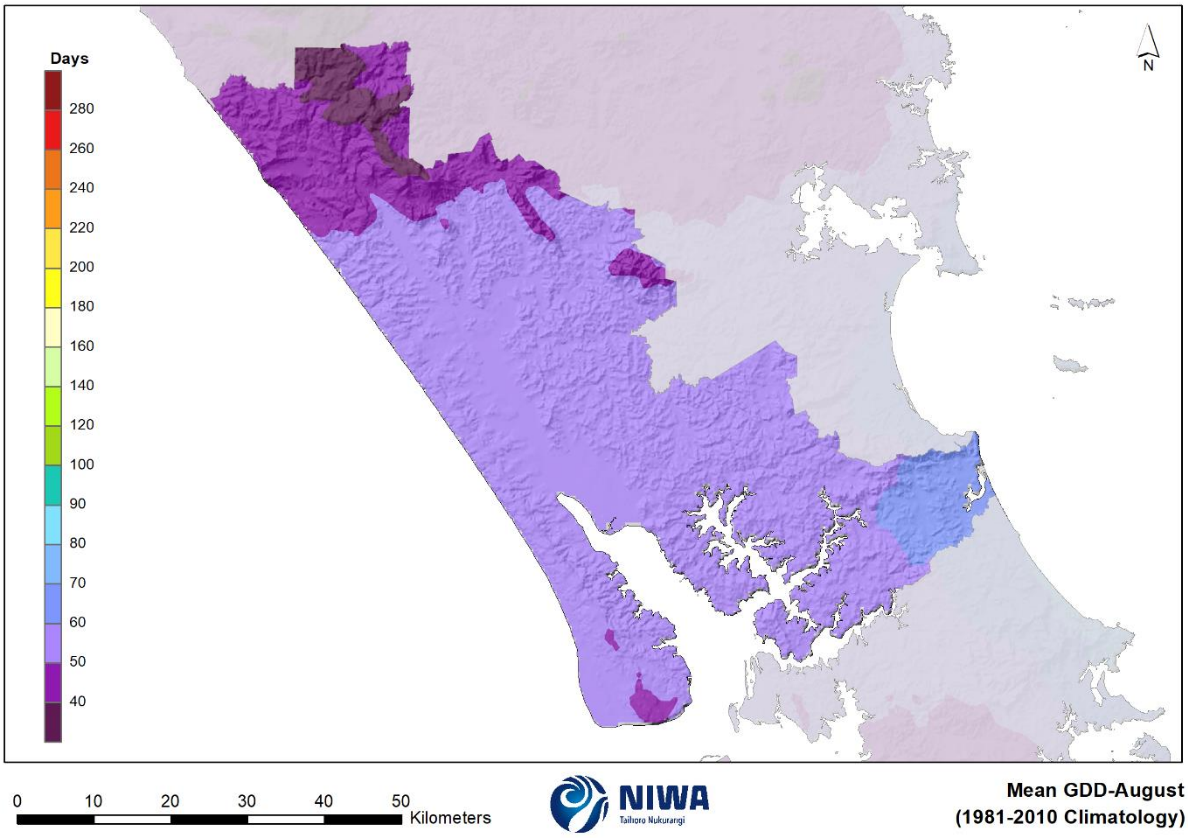
Mean GDD-May
(1981-2010 Climatology)



Mean GDD-June
(1981-2010 Climatology)



Mean GDD-July
(1981-2010 Climatology)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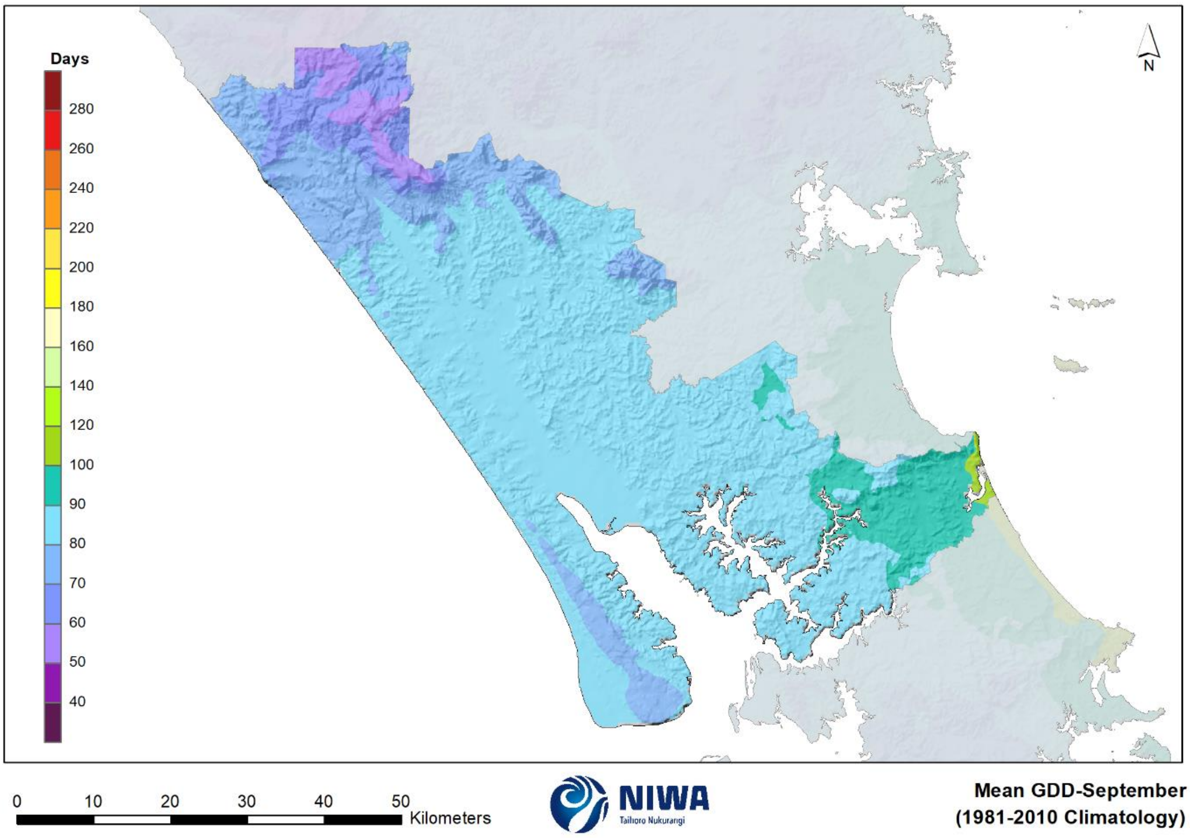
Kilometers
NIWA
Taihoro Nukurangi
Mean GDD-August
(1981-2010 Climatology)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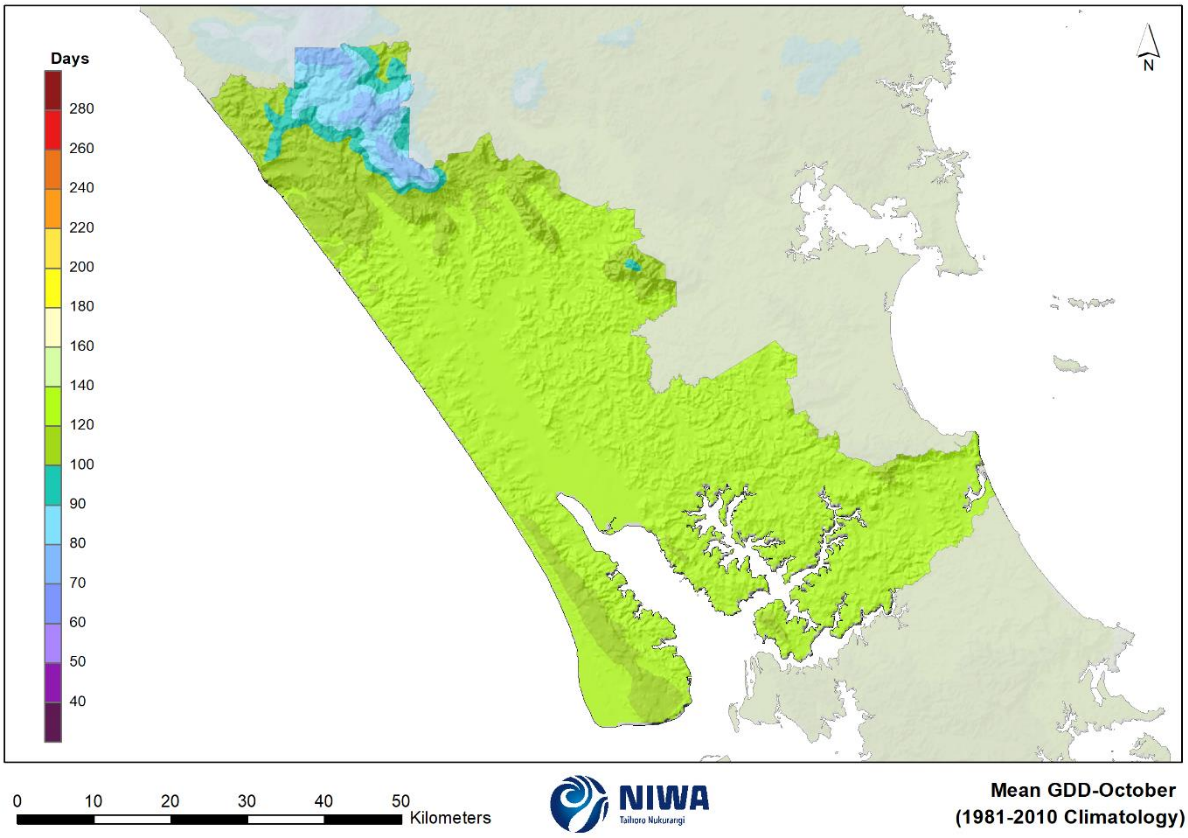
Kilometers
NIWA
Taihoro Nukurangi
Mean GDD-September
(1981-2010 Climatology)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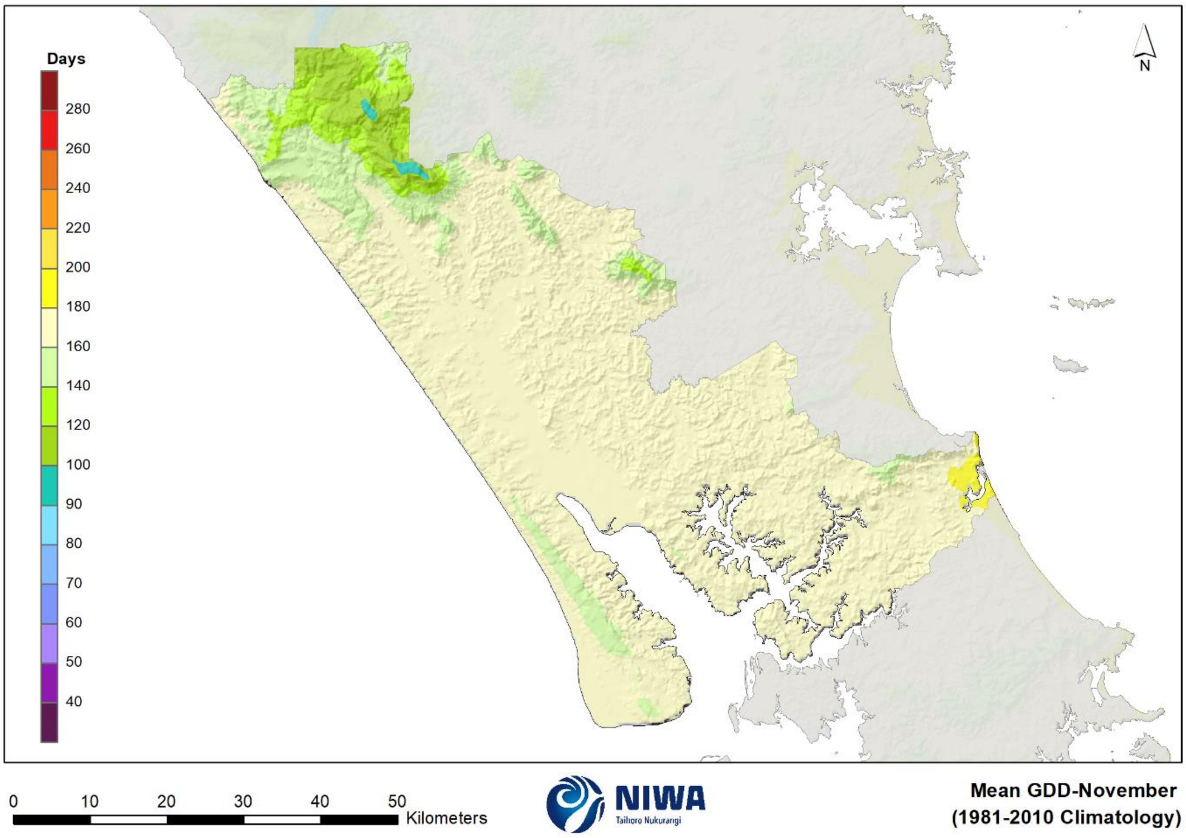
Taihoro Nukurangi
Mean GDD-October
(1981-2010 Climatology)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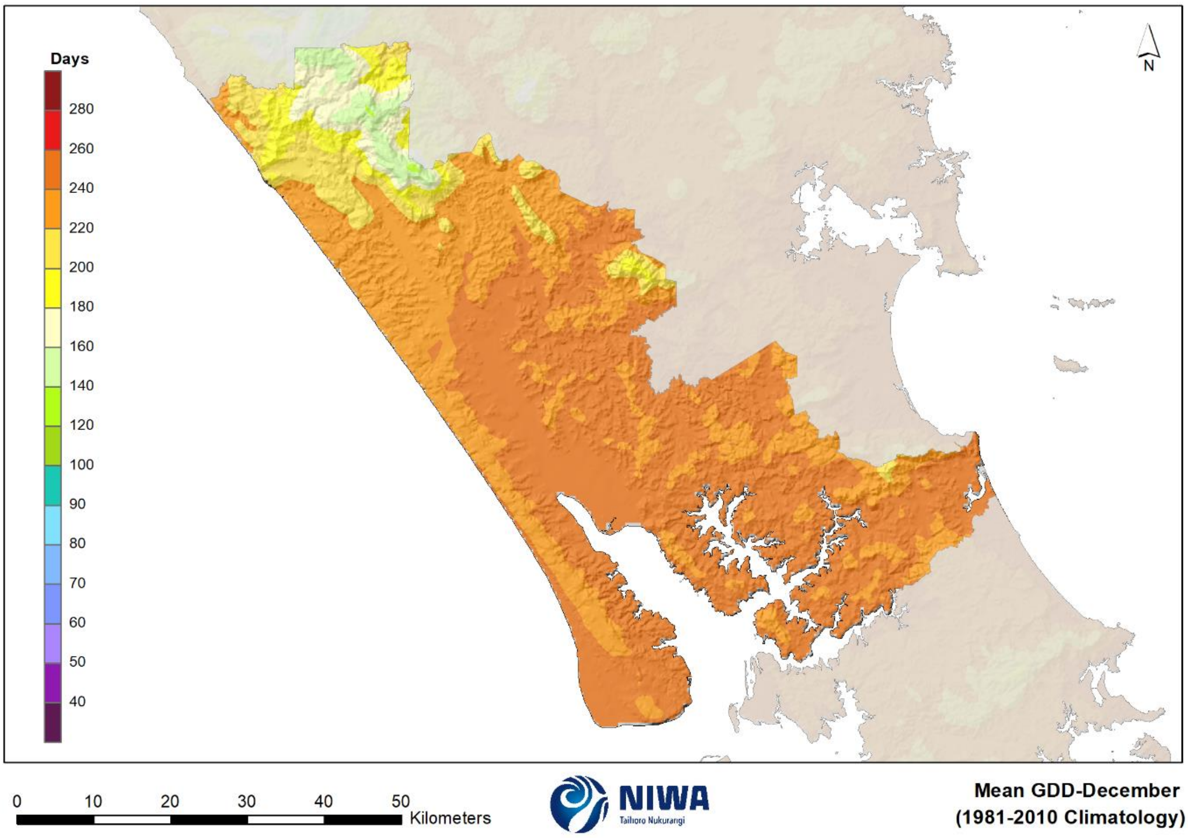
Kilometers
NIWA
Taihoro Nukurangi
Mean GDD-November
(1981-2010 Climatology)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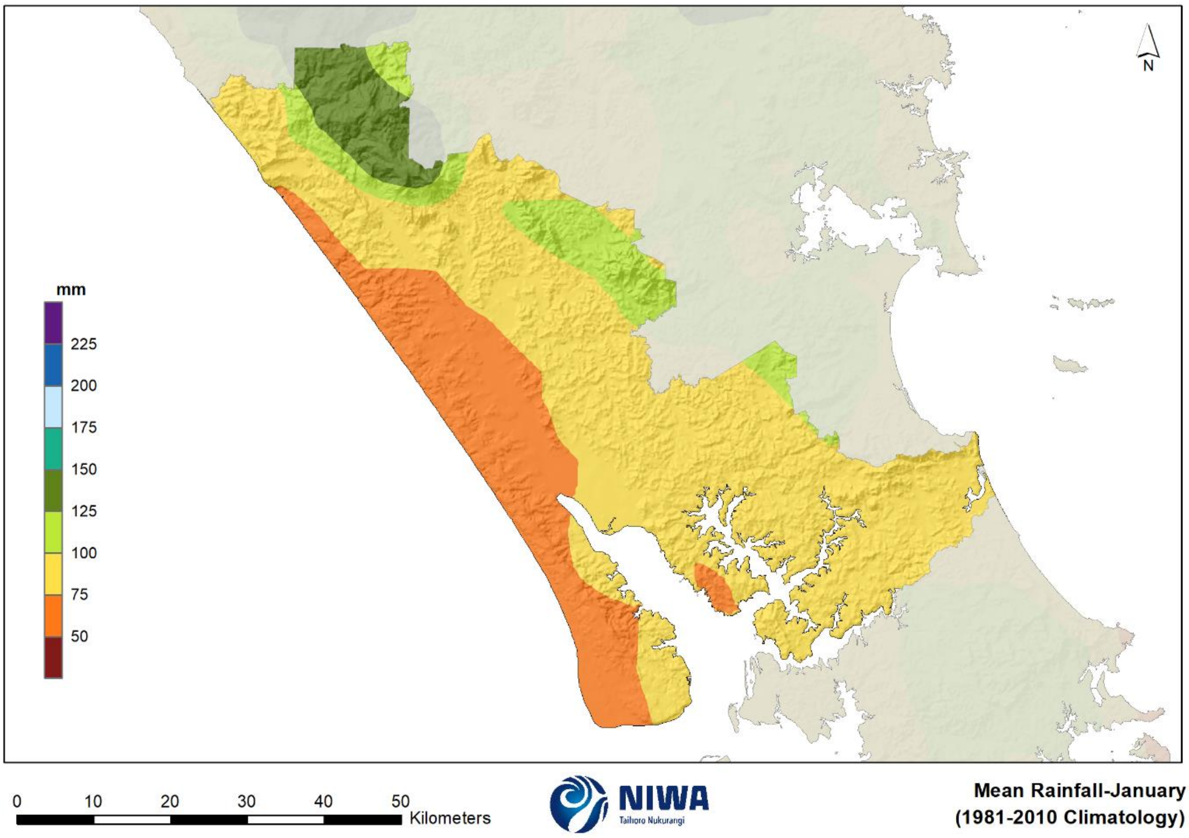
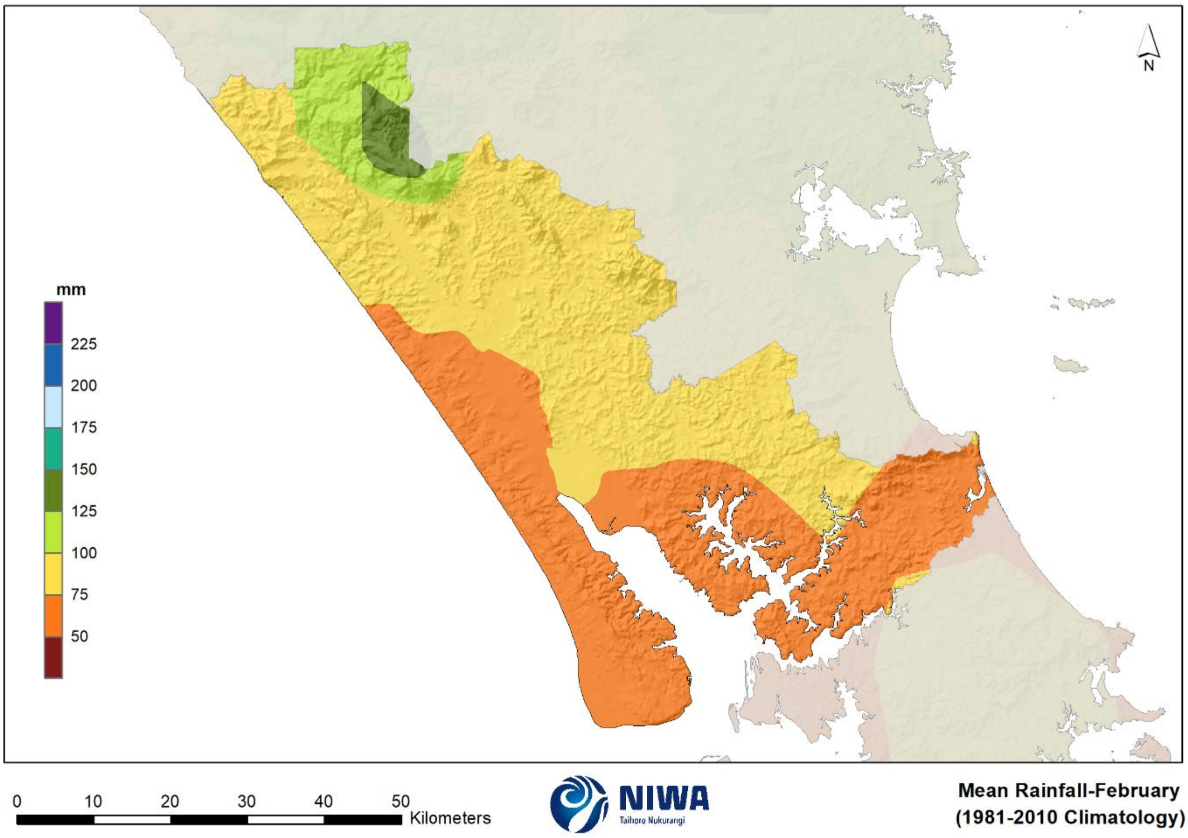
Kilometers
NIWA
Taihoro Nukurangi
Mean GDD-December
(1981-2010 Climatology)

Appendix C Monthly average rainfall maps

Monthly average rainfall maps for Kaipara District are included sequentially (i.e. January to December) below.

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Kilometers
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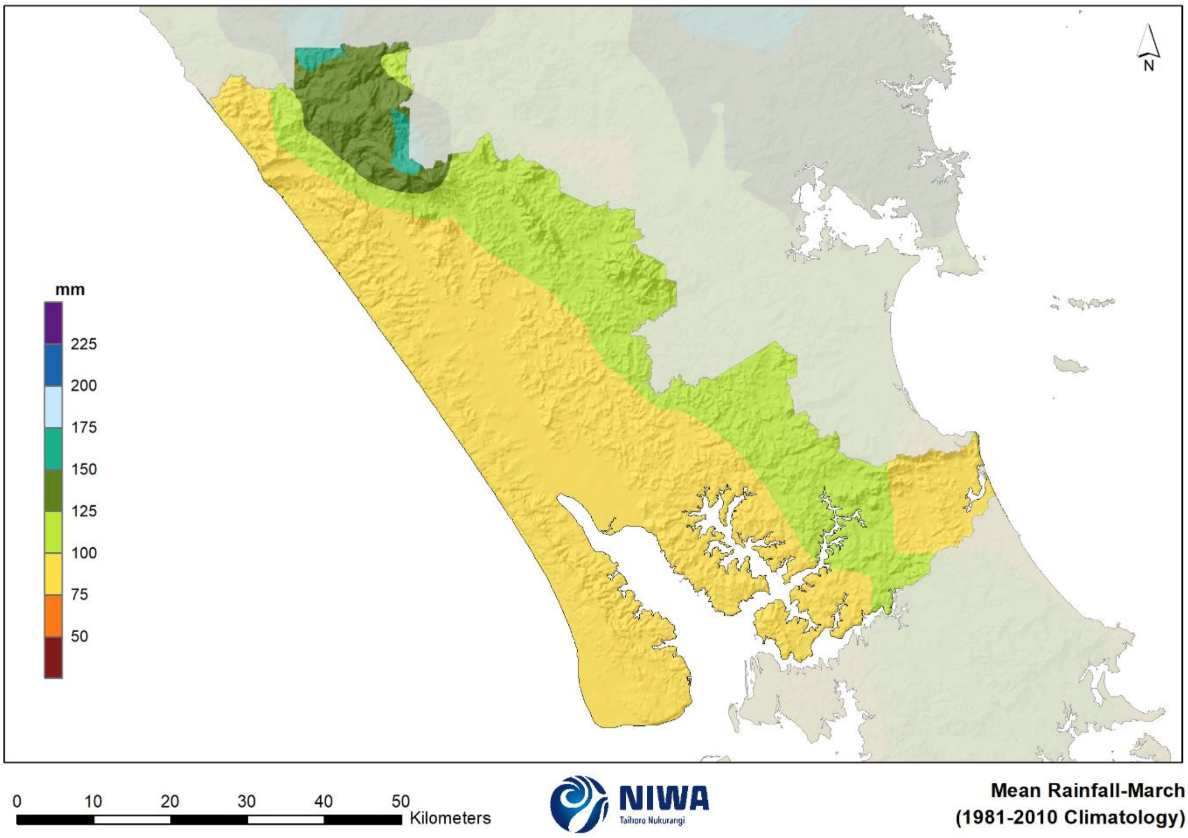
Taihoro Nukurangi
Mean Rainfall-February
(1981-2010 Climatology)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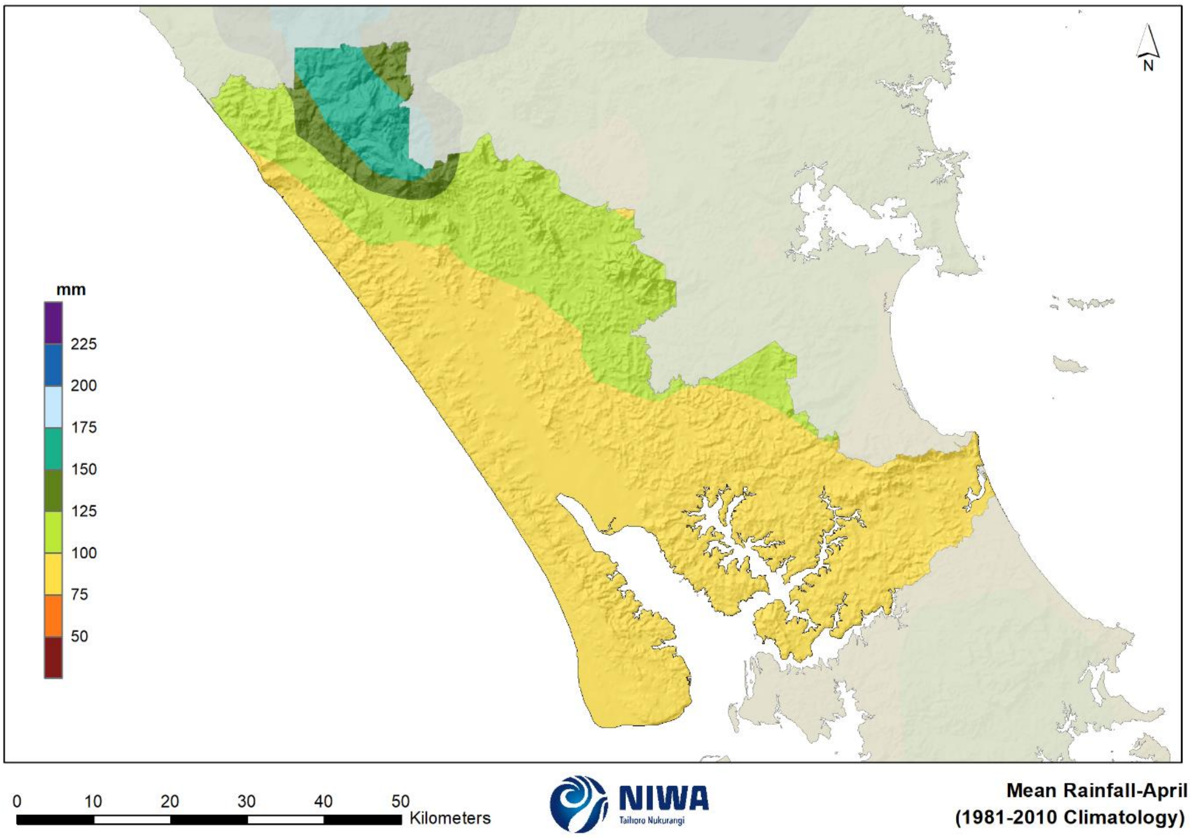
Kilometers
NIWA
Taihoro Nukurangi
Mean Rainfall-March
(1981-2010 Climatology)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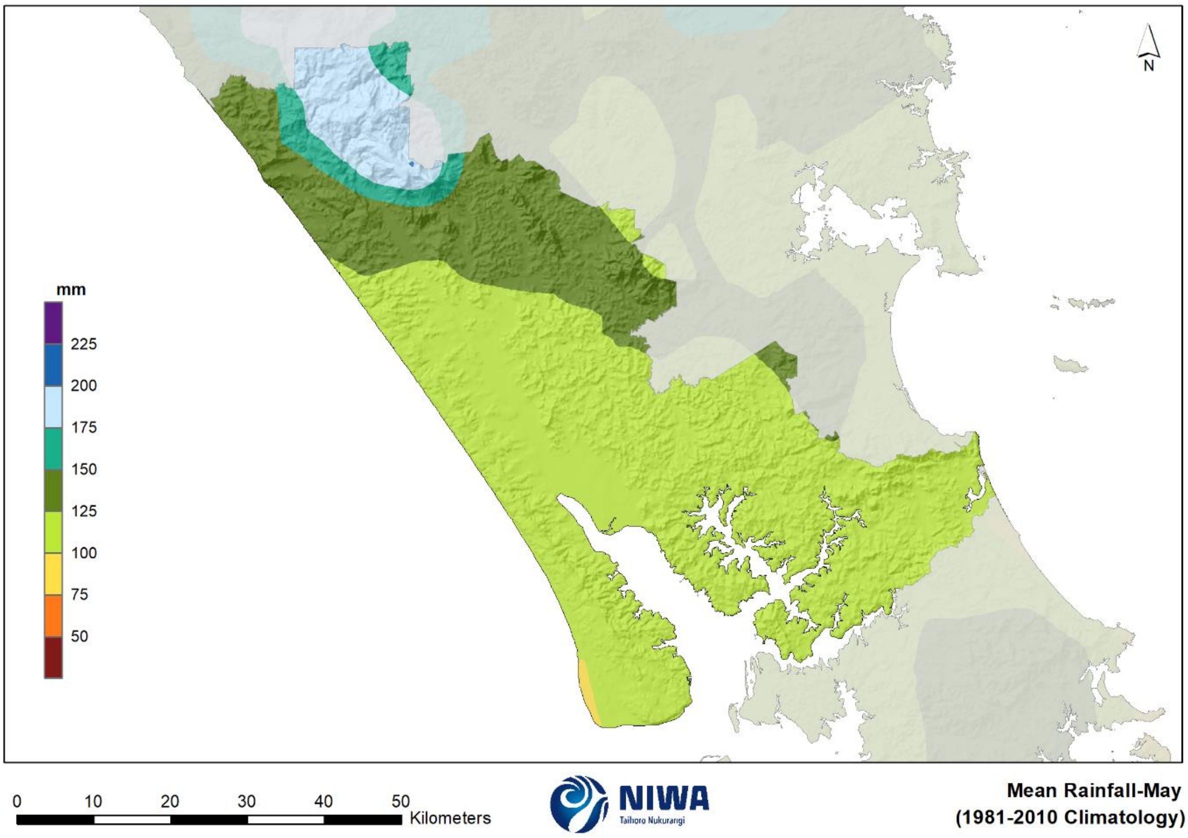
NIWA
Taihoro Nukurangi
Mean Rainfall-April
(1981-2010 Climatology)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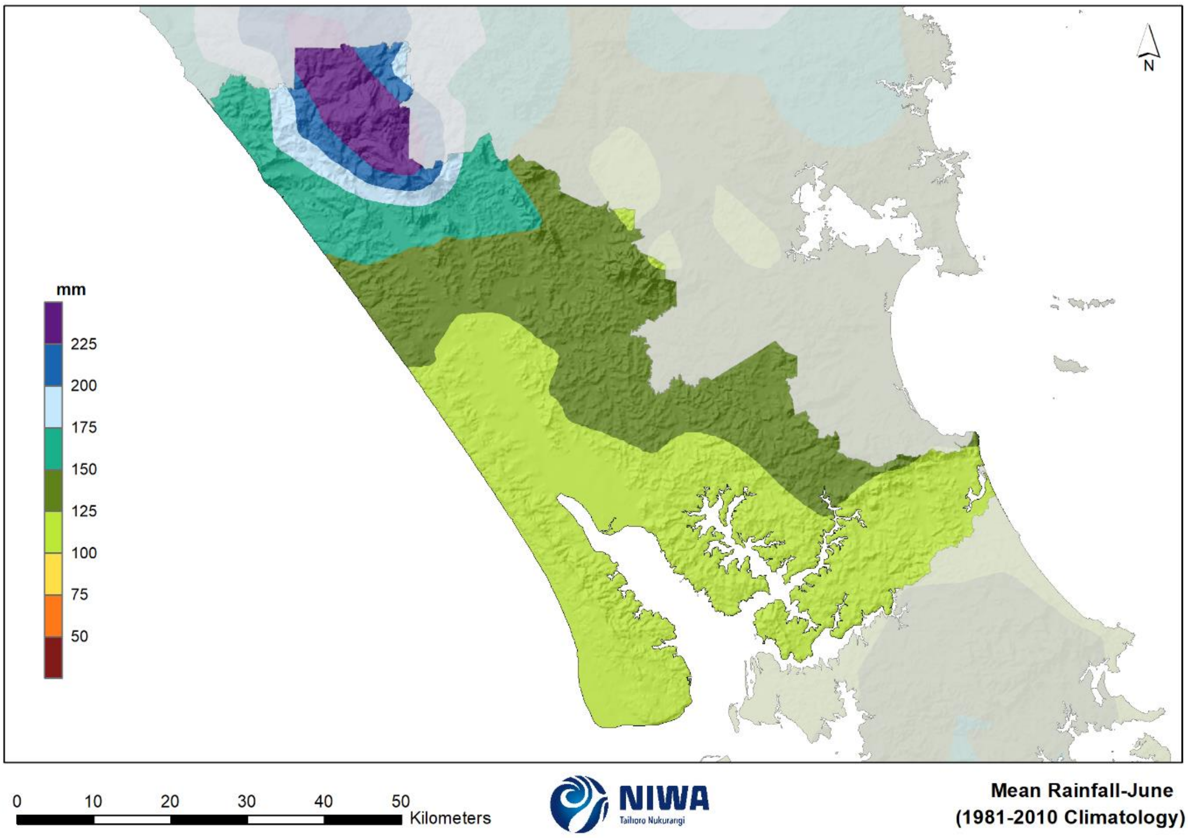
Mean Rainfall-May
(1981-2010 Climatology)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Kilometers
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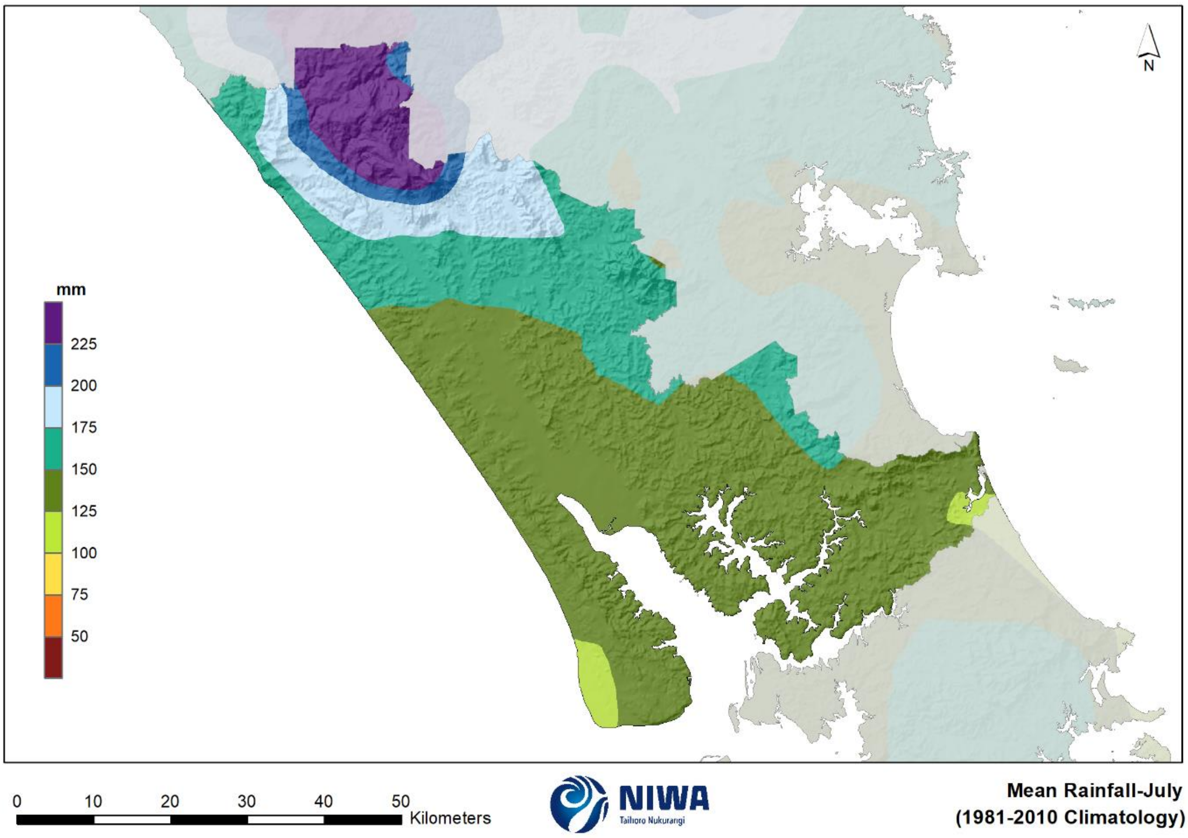
Taihoro Nukurangi
Mean Rainfall-June
(1981-2010 Climatology)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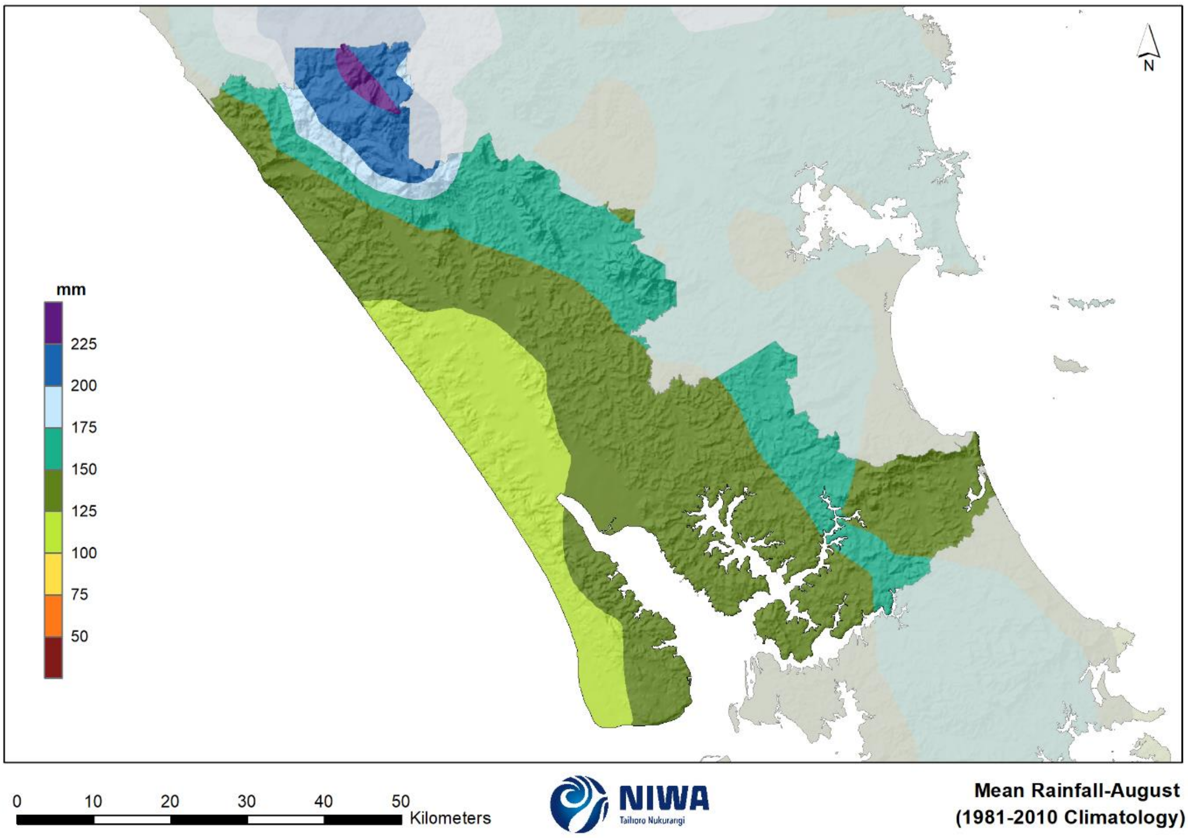
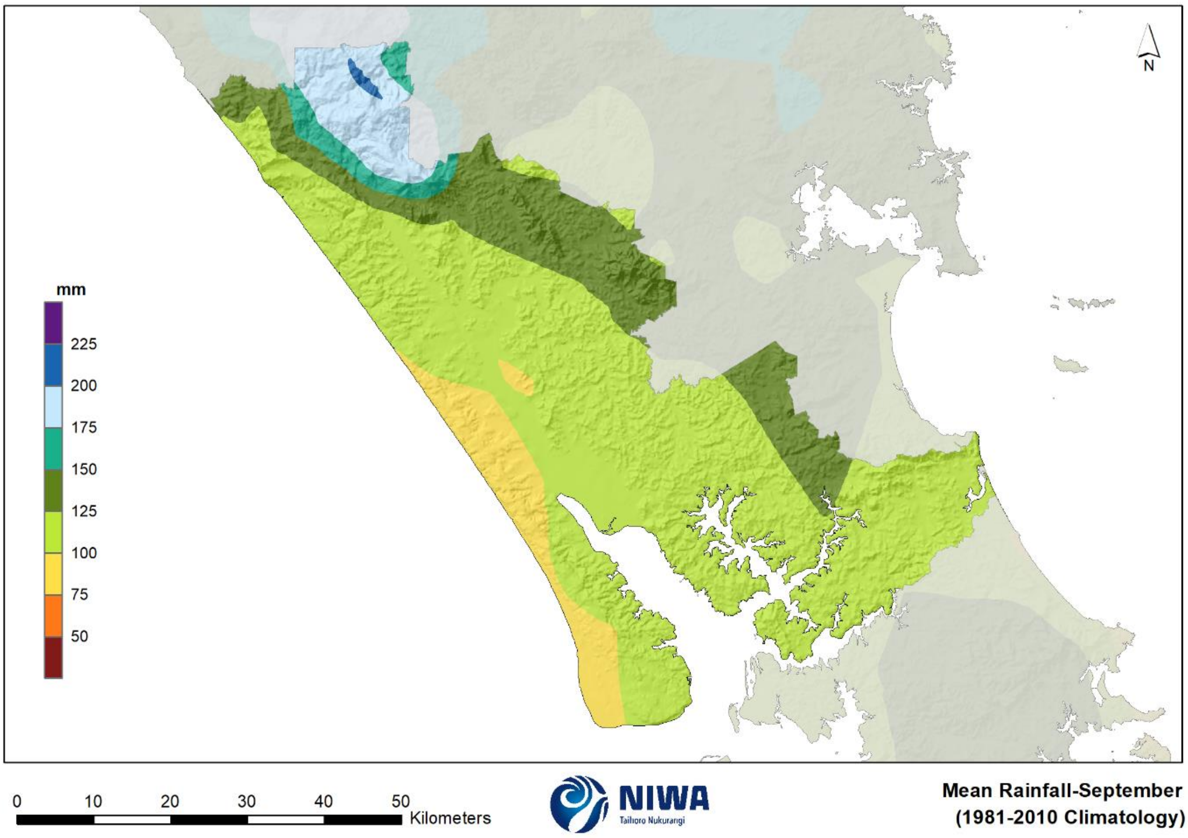
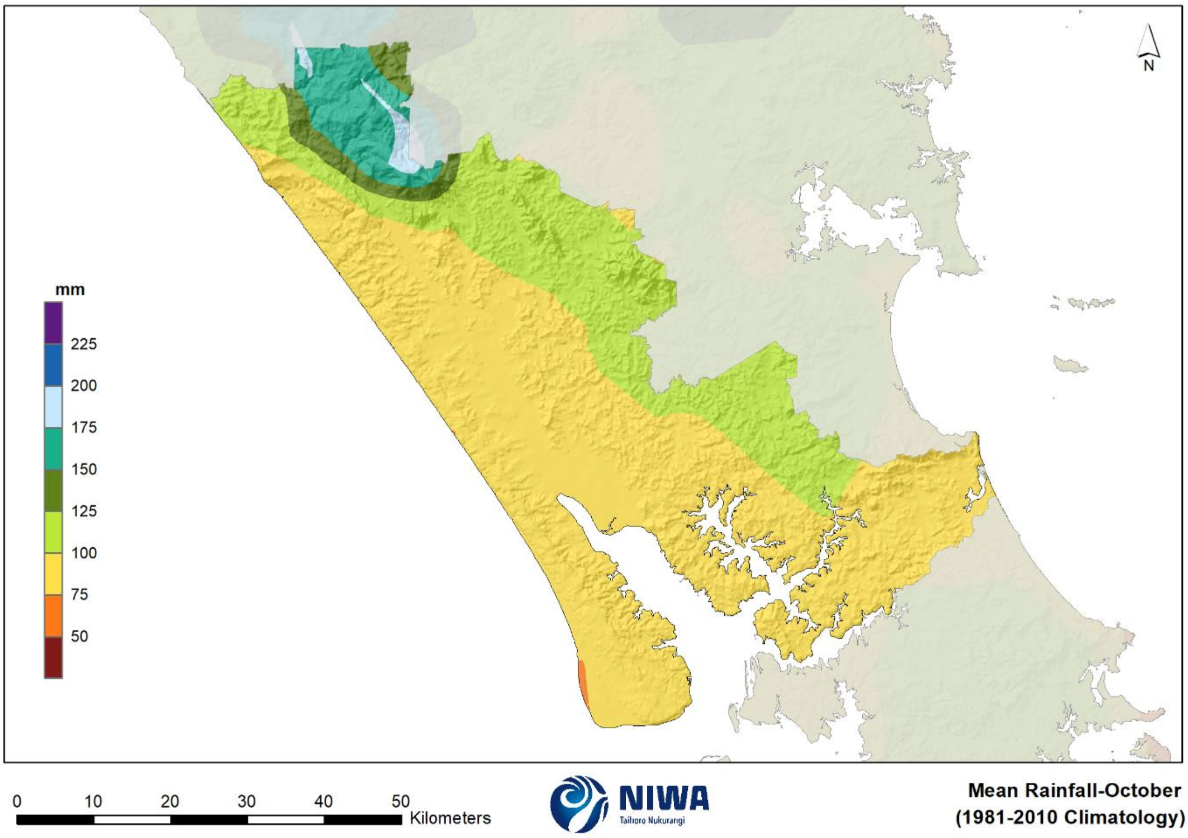
Taihoro Nukurangi
Mean Rainfall-July
(1981-2010 Climatology)



Mean Rainfall-August
(1981-2010 Climatology)



Mean Rainfall-September
(1981-2010 Climatology)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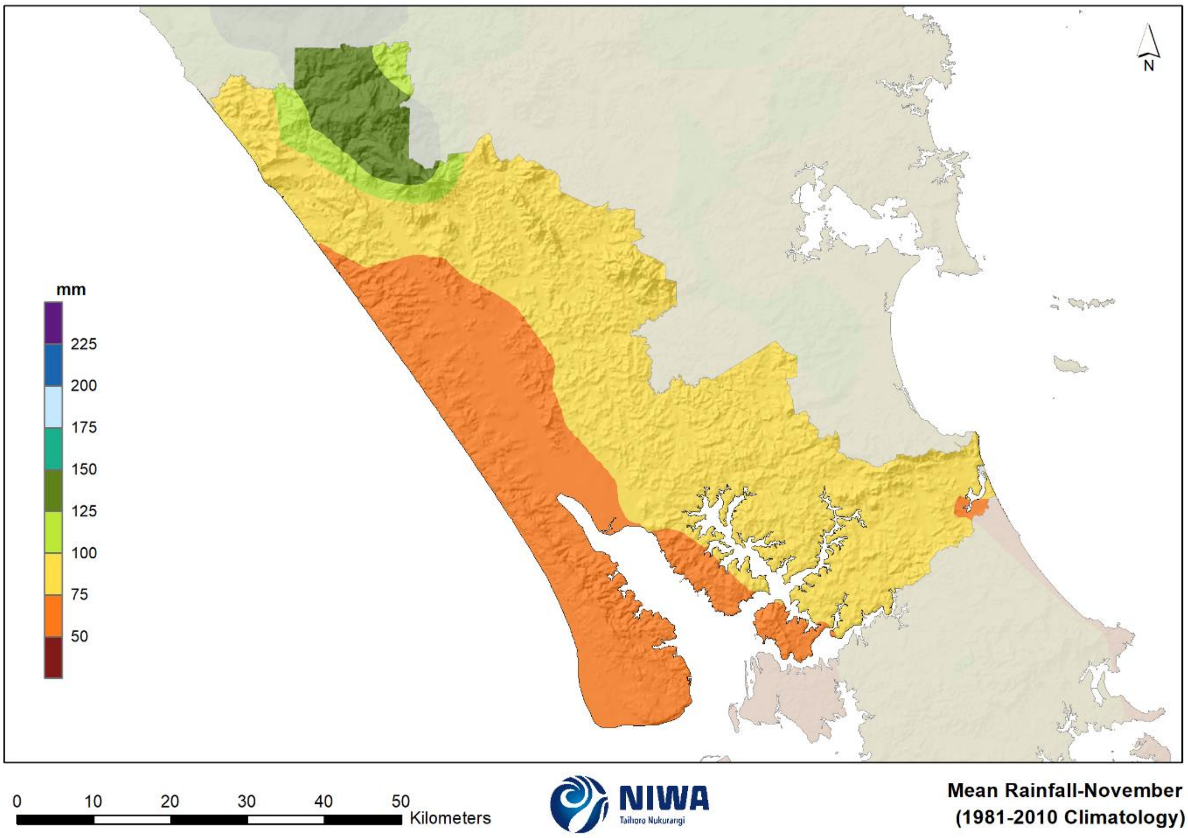
Taihoro Nukurangi
Mean Rainfall-October
(1981-2010 Climatology)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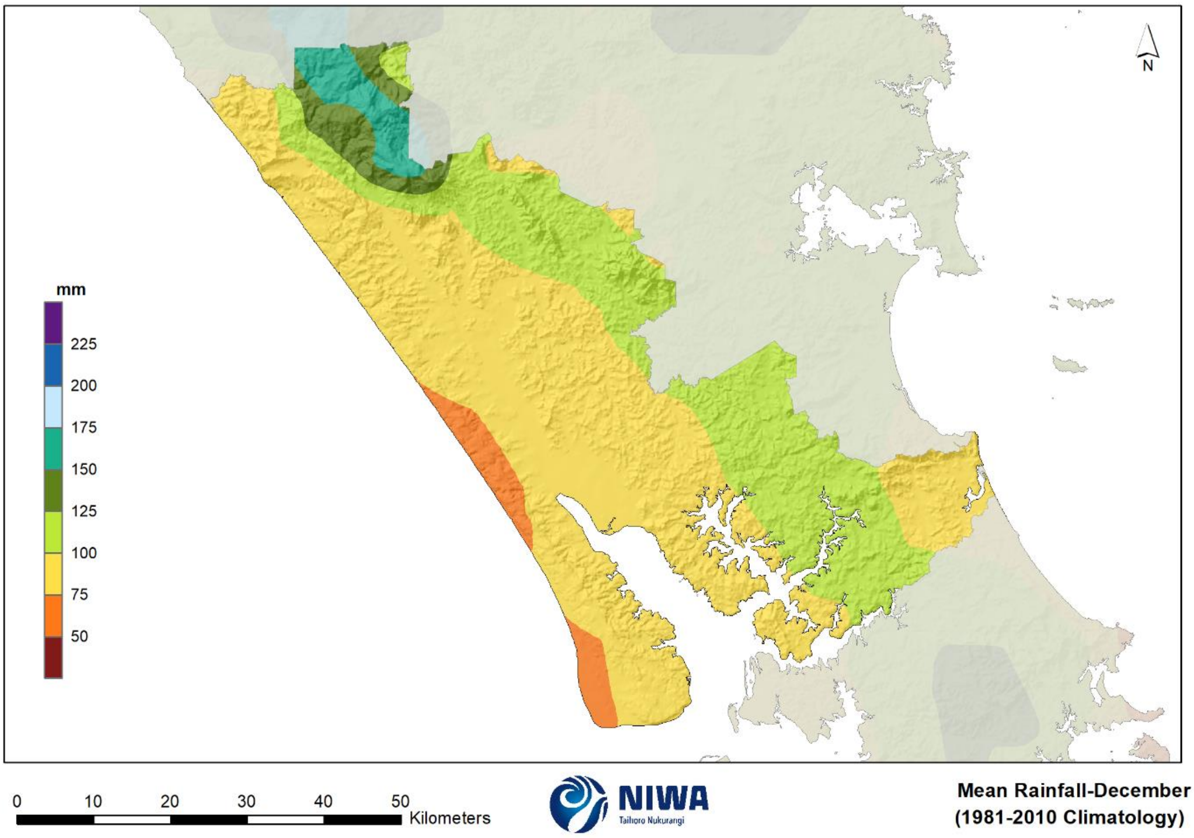
Taihoro Nukurangi
Mean Rainfall-November
(1981-2010 Climatology)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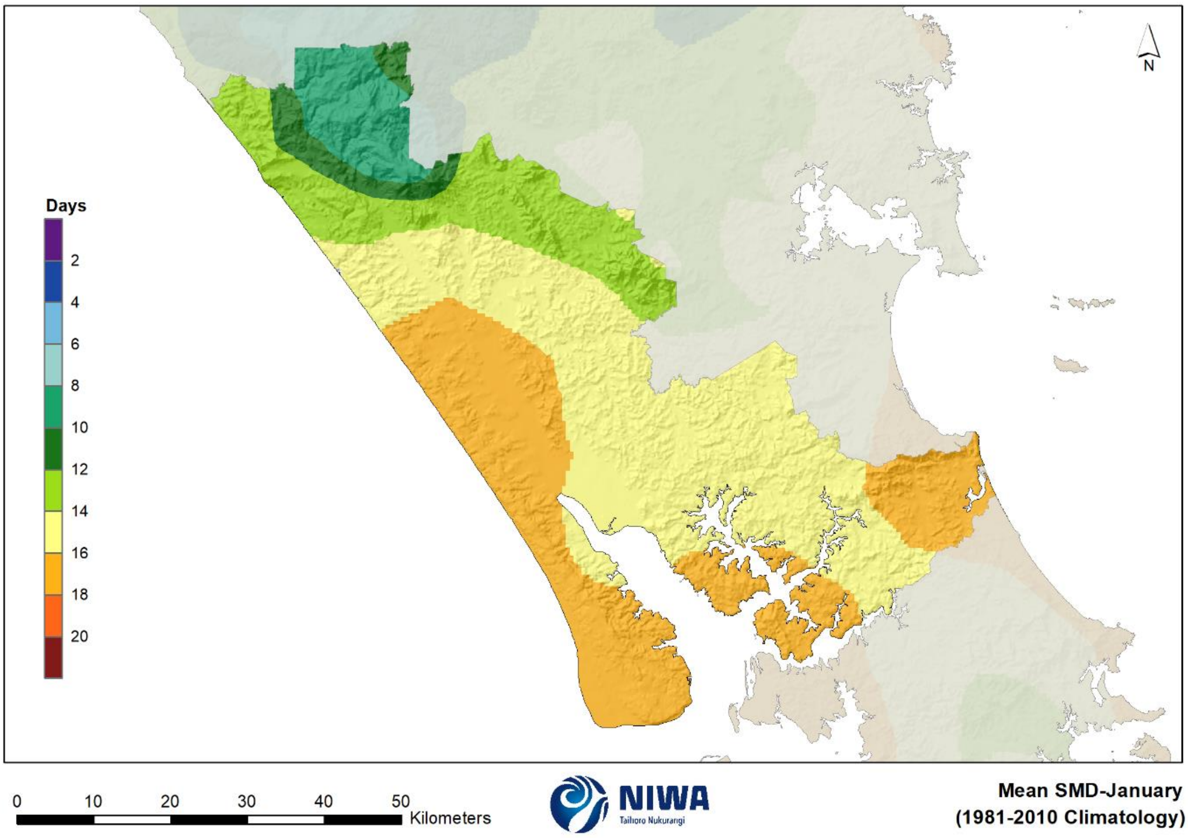
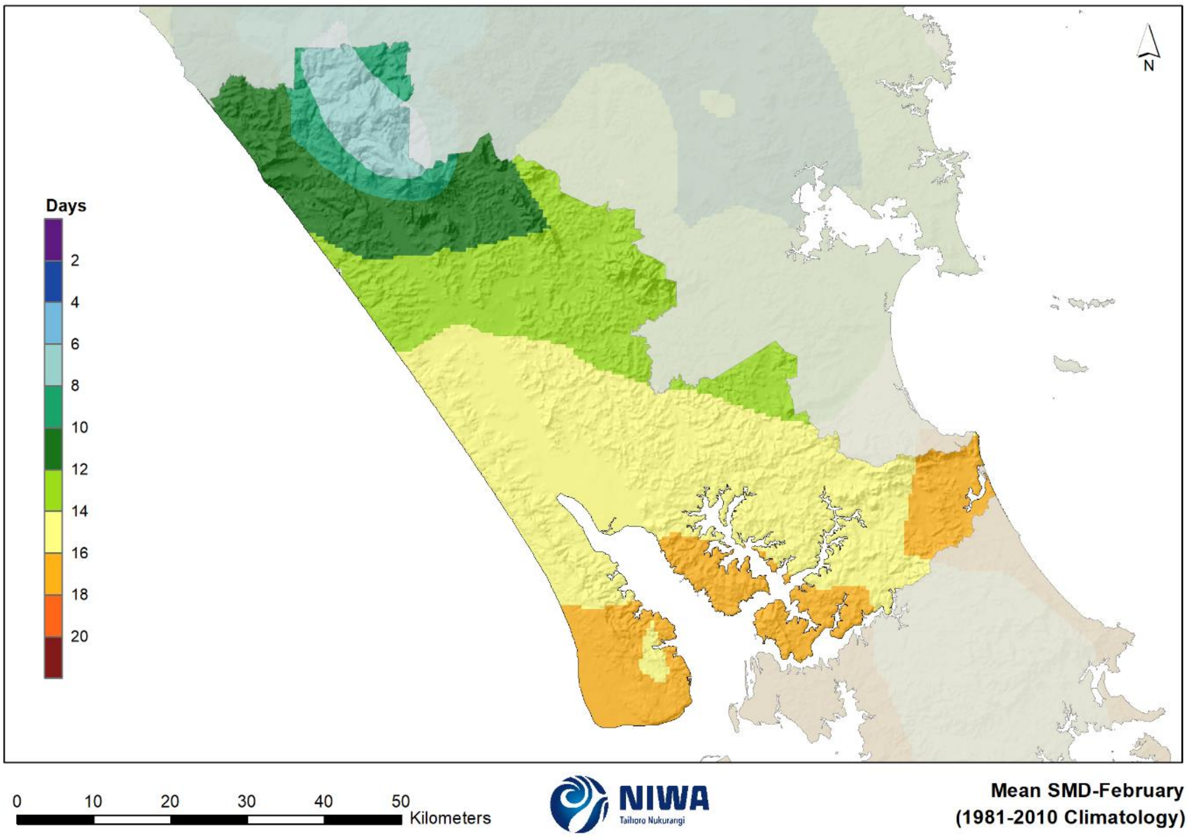
Kilometers
NIWA
Taihoro Nukurangi
Mean Rainfall-December
(1981-2010 Climatology)

Appendix D Monthly days of soil moisture deficit maps

Monthly mean days of soil moisture deficit maps for Kaipara District are included sequentially (i.e. January to December) below.

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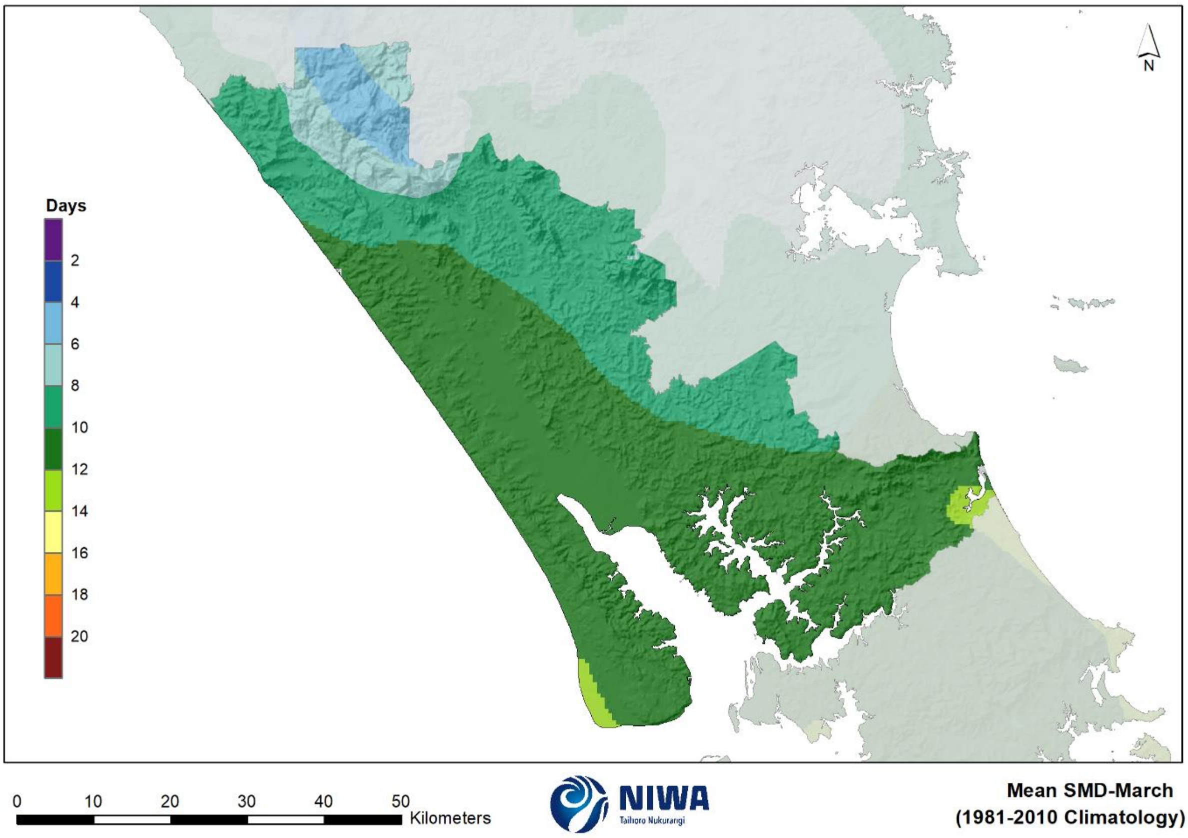
Kilometers
NIWA
Taihoro Nukurangi
Mean SMD-February
(1981-2010 Climatology)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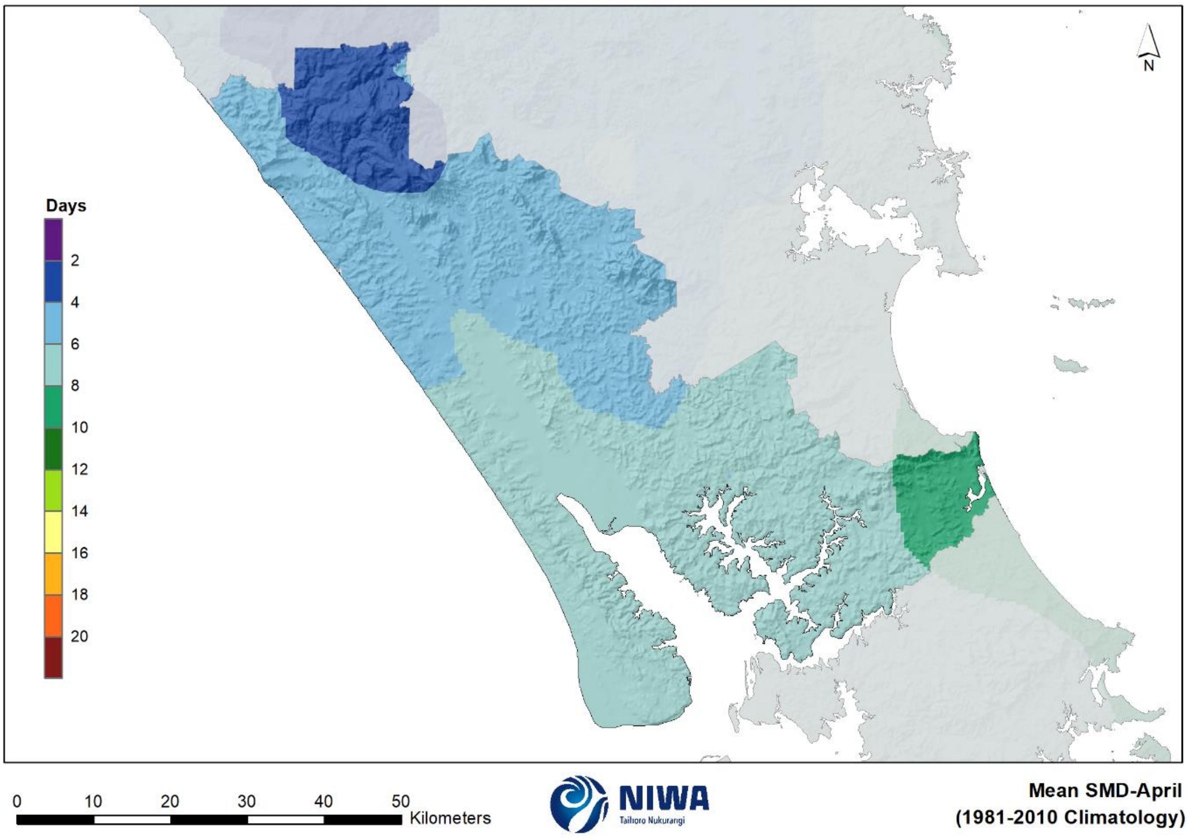
Kilometers
NIWA
Taihoro Nukurangi
Mean SMD-March
(1981-2010 Climatology)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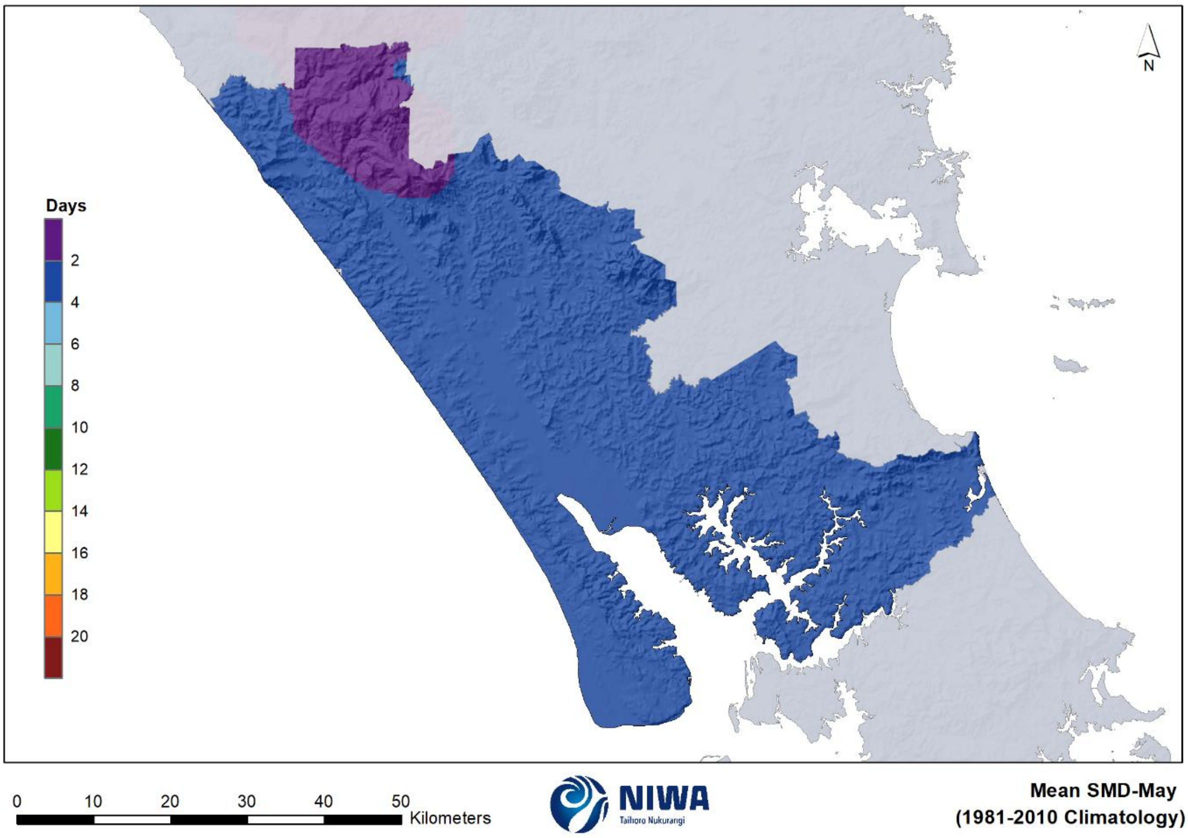
NIWA
Taihoro Nukurangi
Mean SMD-April
(1981-2010 Climatology)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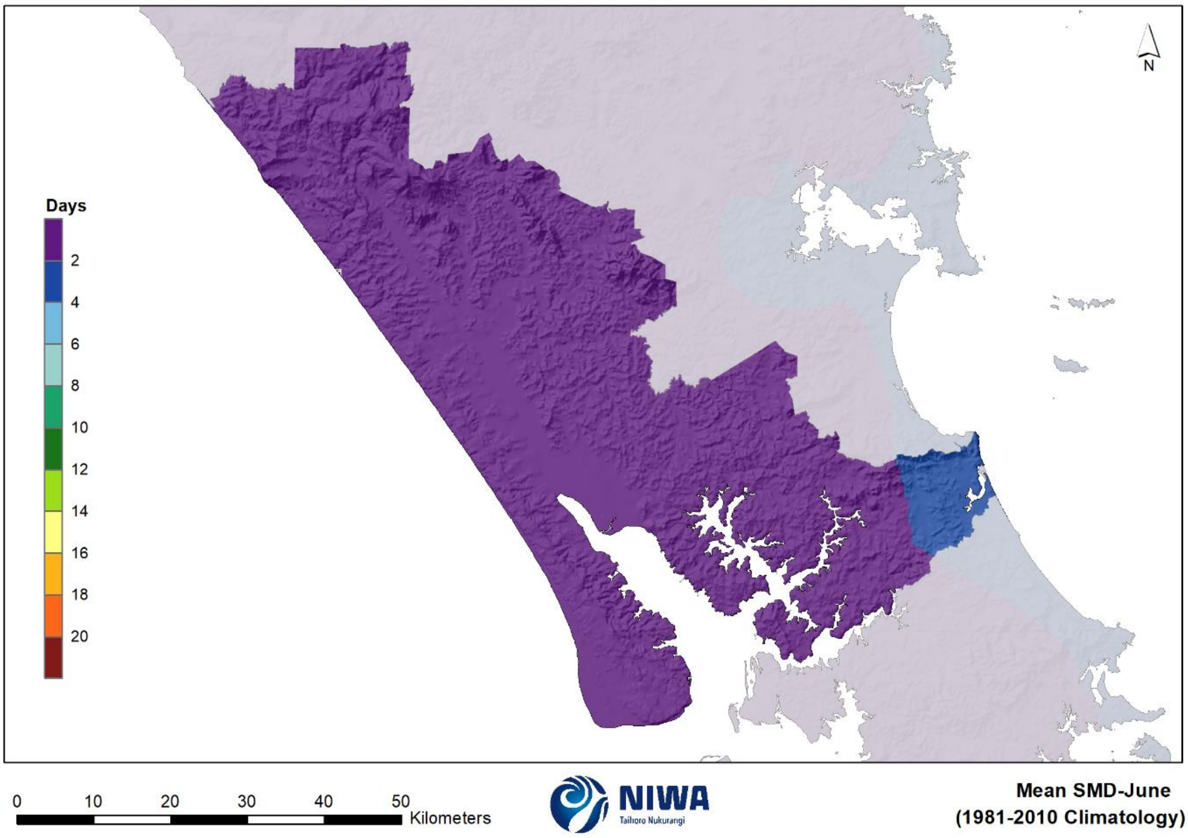
Taihoro Nukurangi
Mean SMD-May
(1981-2010 Climatology)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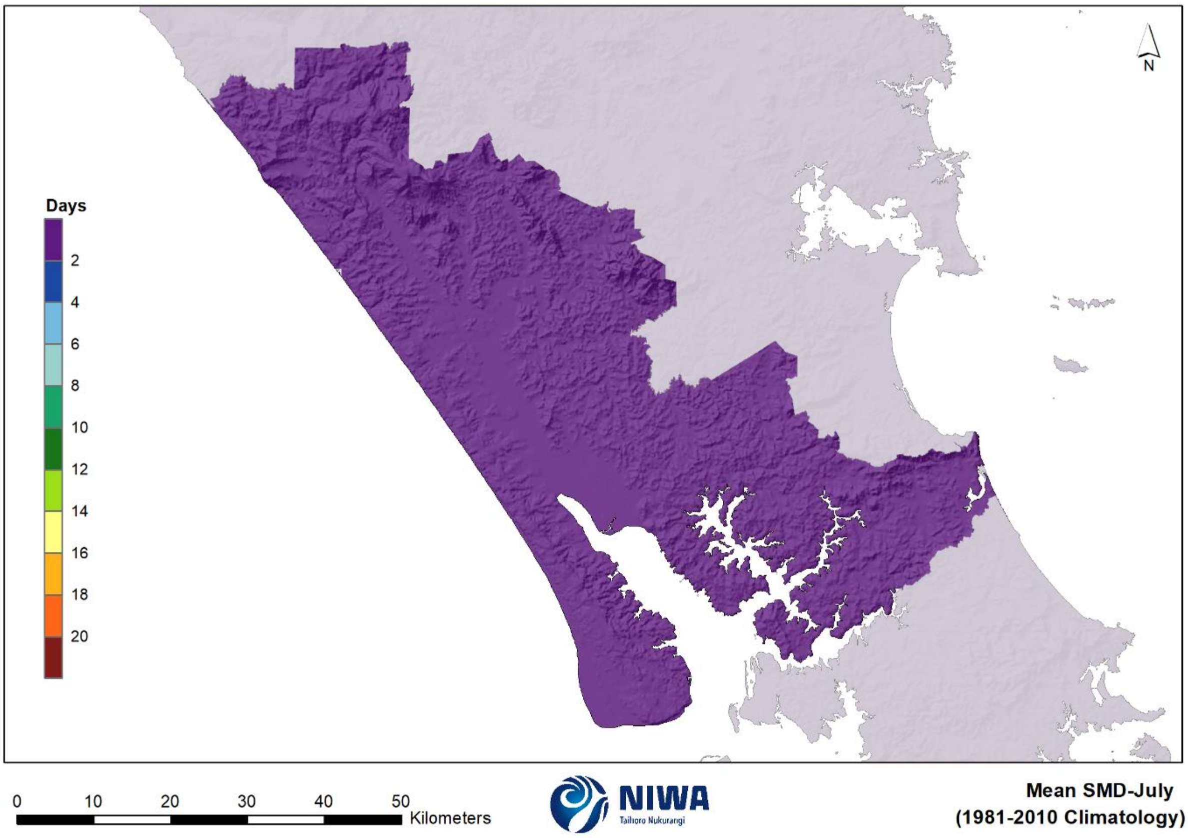
Kilometers
NIWA
Taihoro Nukurangi
Mean SMD-June
(1981-2010 Climatology)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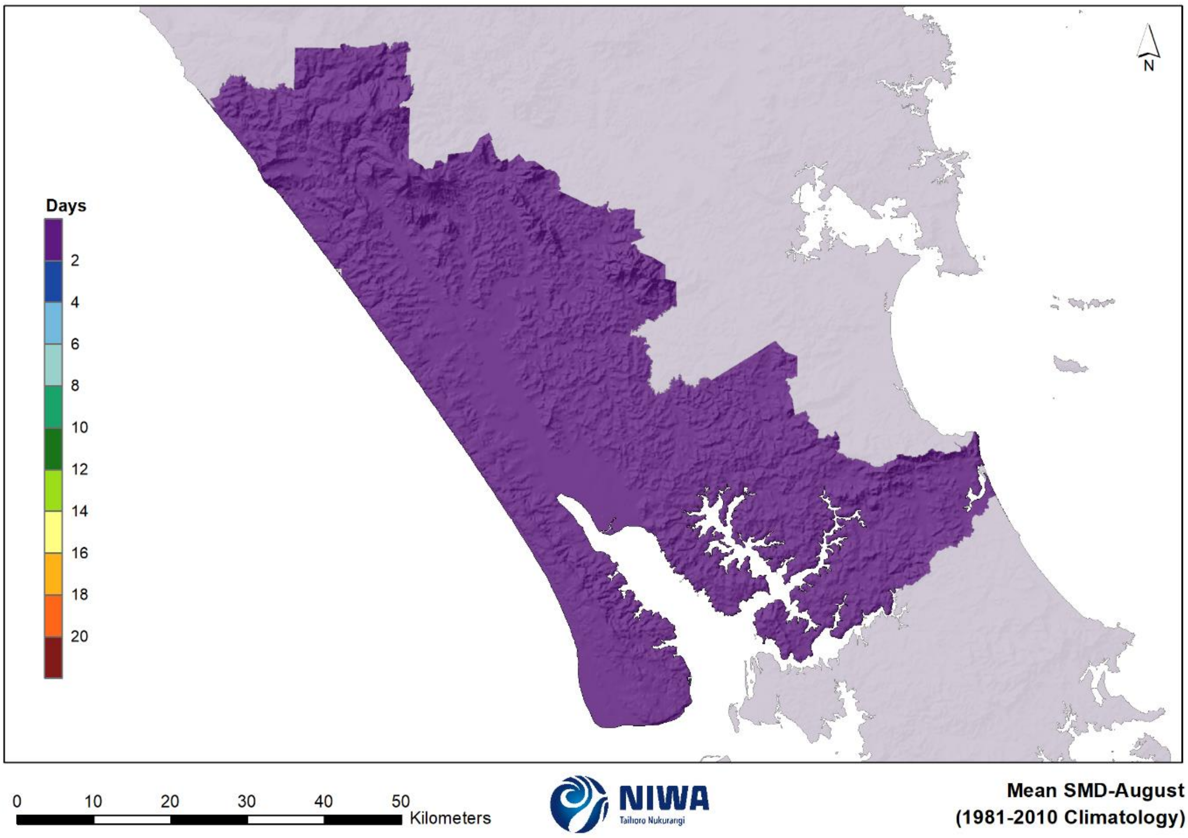
Kilometers
NIWA
Taihoro Nukurangi
Mean SMD-July
(1981-2010 Climatology)



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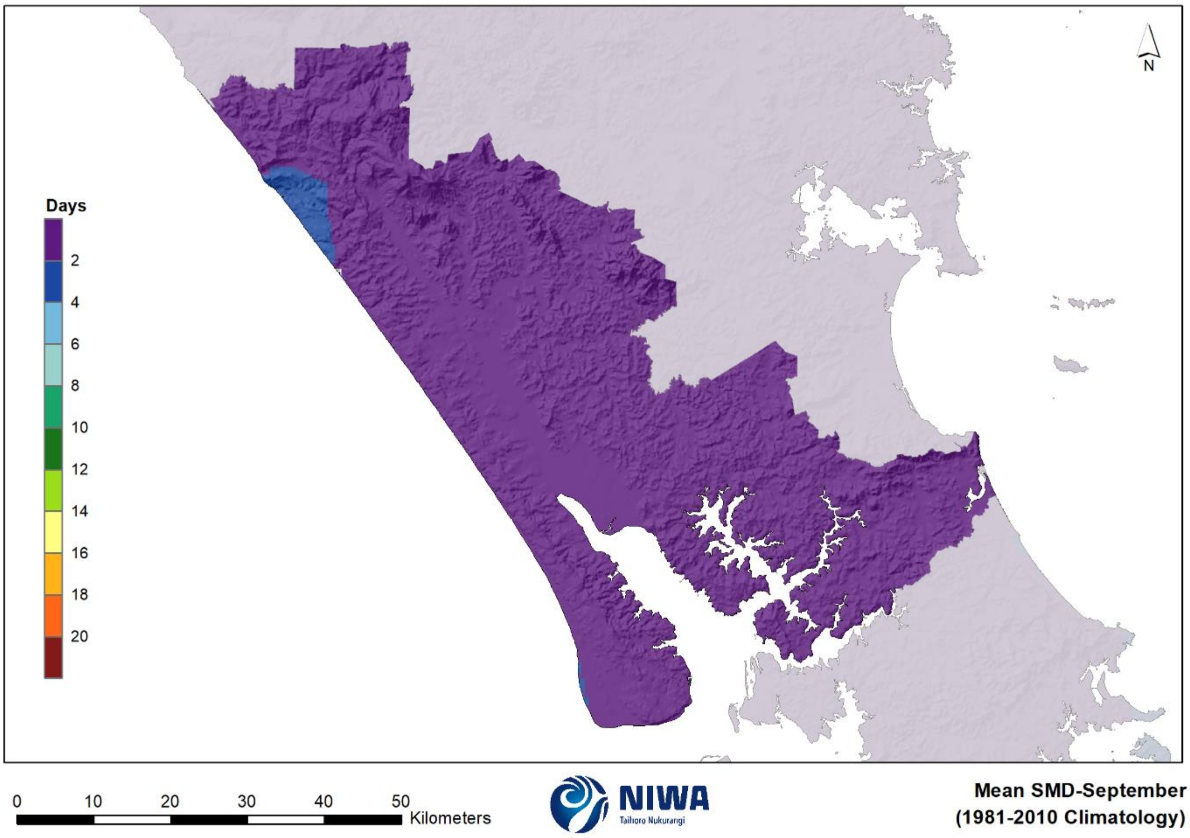
Kilometers
Mean SMD-August
(1981-2010 Climatology)



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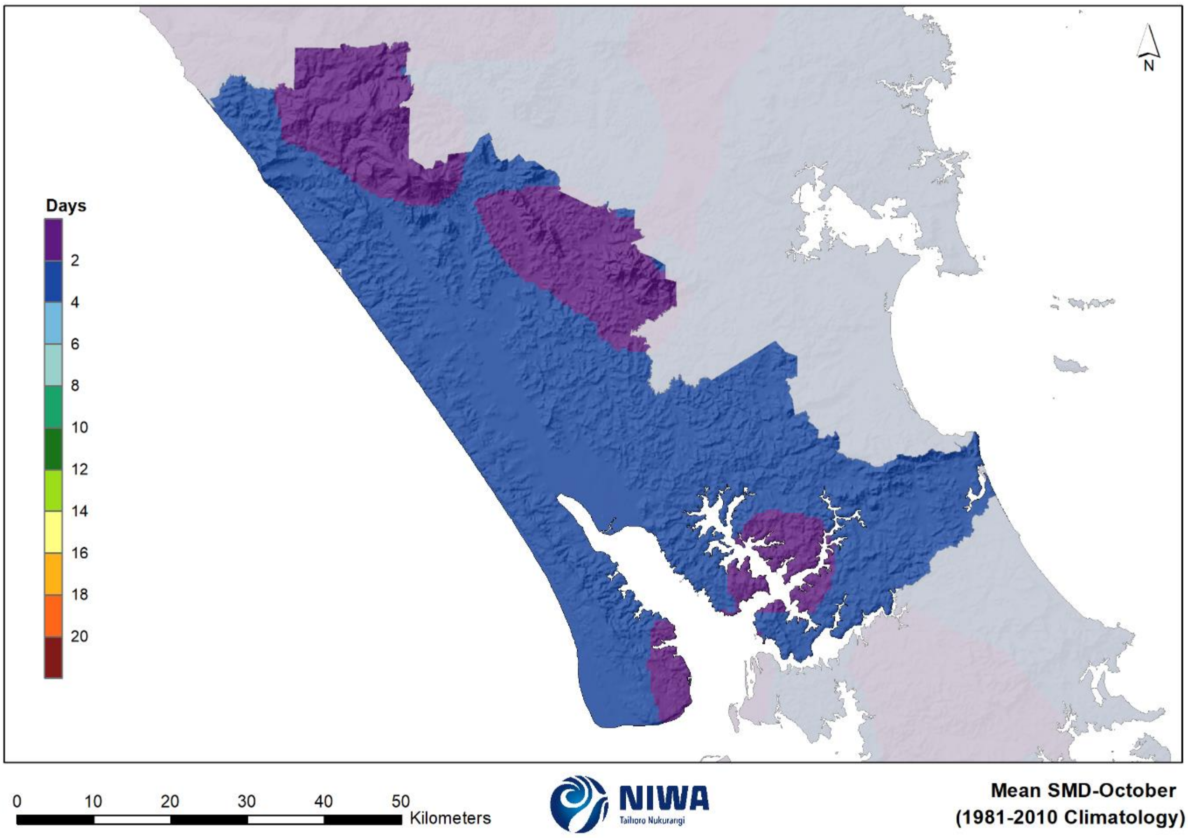
Kilometers
Mean SMD-September
(1981-2010 Climatology)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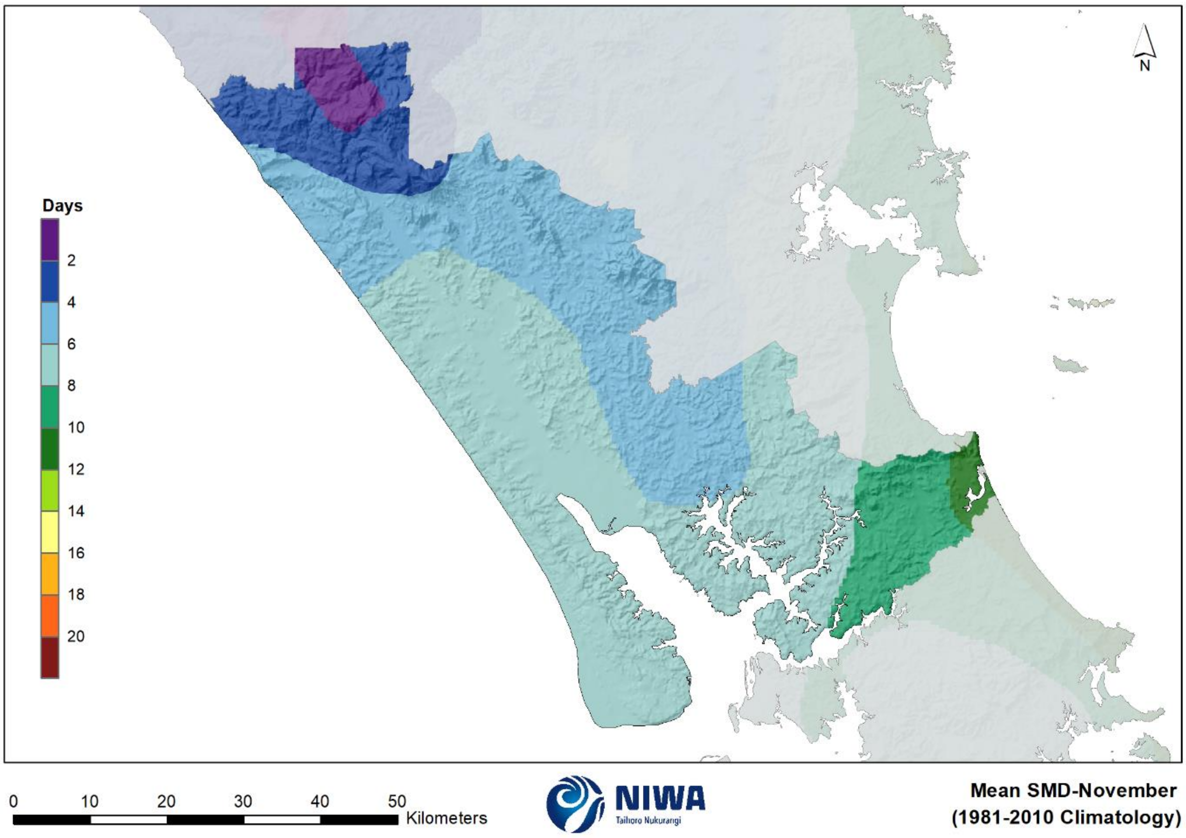
Kilometers
NIWA
Taihoro Nukurangi
Mean SMD-October
(1981-2010 Climatology)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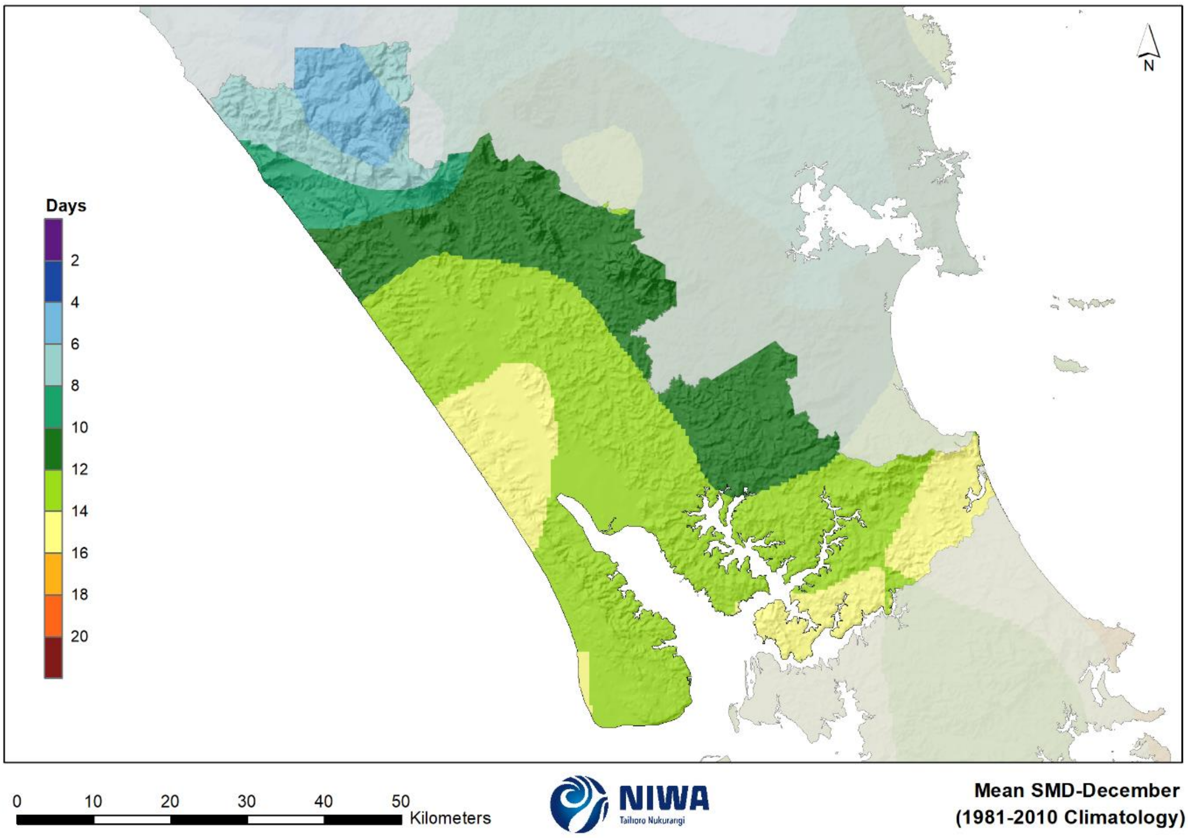
Kilometers
NIWA
Taihoro Nukurangi
Mean SMD-November
(1981-2010 Climatology)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Kilometers
NIWA
Taihoro Nukurangi
Mean SMD-December
(1981-2010 Climatology)

Appendix E Climate modelling methodology

Key messages

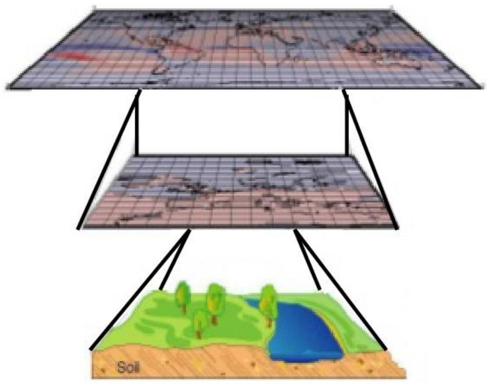
- Climate model simulation data from the IPCC Fifth Assessment has been used to produce climate projections for New Zealand.
- Six climate models were chosen by NIWA for dynamical downscaling. These models were chosen because they produced the most accurate results when compared to historical climate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

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 (2018), but a short explanation is provided below. Dynamical downscaling results are presented for all variables in this report.

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[9]. Figure 6-1 shows a schematic for the dynamical downscaling method used in this report.



Global Climate Model: ~140 km

Regional Climate Model 27 km

Bias corrected/downscaled RCM: 5 km

Figure 6-1: 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.

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

Appendix F Hydrological modelling methodology

Key messages

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

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

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

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

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

- Catchment topography based on a nationally available 30 m Digital Elevation Model (DEM).
- Physiographical data based on the Land Cover Database version two and Land Resource Inventory (Newsome et al., 2012).
- Soil data based on the Fundamental Soil Layer information (Newsome et al., 2012).
- Hydrological properties (based on the River Environment Classification version one (REC1) (Snelder and Biggs, 2002)[10].

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

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

Hydrological simulations are based on the REC 1 network aggregated up to Strahler[11] catchment order three (approximate average catchment area of 7 km^2) used within previous national and regional scale assessments (Pearce et al., 2017a; 2017b); residual coastal catchments of smaller stream orders remain included. The simulation results comprise hourly time-series of various hydrological variables for each computational sub-catchment, and for each of the six GCMs and two RCPs considered. To manage the volume of output data, only river flows information was preserved; all the other state variables and fluxes can be regenerated on demand.

Because of TopNet assumptions, soil and land use characteristics within each computational sub-catchment are homogenised. Essentially this means that the soil characteristics and physical properties of different land uses, such as pasture and forest, will be spatially averaged, and the hydrological model outputs will approximate conditions across land uses. The data used in the hydrology section of the reprt is consistent with Collins and Zammit (2016).

[10] Due to time constraints associated with this project, it is not possible to assess the potential impact of climate change on the Digital River Network 3 available for the Kaipara Dsitrict area.
[11] Strahler order describes river size based on tributary hierarchy. Headwater streams with no tributaries are order 1; 2nd order streams develop at the confluence of two 1st order tributaries; stream order increases by 1 where two tributaries of the same order converge.