NIWA
Taihoro Nukurangi

Climate Change Projections and Implications for Northland

Prepared for Northland Regional Council

September 2016

Prepared by:
Petra Pearce
Vijay Paul
Brett Mullan
Christian Zammit
Abha Sood
Daniel Collins
Rob Bell
Cliff Law

For any information regarding this report please contact:

Petra Pearce
Climate Scientist
Climate Applications
+64-9-375 2052
petra.pearce@niwa.co.nz

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

Phone +64 9 375 2050

NIWA CLIENT REPORT No: 2016072AK
Report date: September 2016
NIWA Project: ELF16102

Quality Assurance Statement		
	Reviewed by:	Dr Andrew Lorrey Group Manager – Weather and Climate Applications Auckland
	Formatting checked by:	Andrew Lorrey
	Approved for release by:	Dr Sam Dean, Chief Scientist Climate

Contents

Tables

Figures

Executive summary

This report describes changes which may occur over the coming century in the climate of the region administered by the Northland Regional Council, and outlines some possible impacts of these changes.

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

- Warming of the climate system is 'unequivocal', and most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the increase in greenhouse gas concentrations caused by human activities.

- The IPCC updates projections for global and regional changes in temperature, sea level, and precipitation for the coming century, and points to an expected increase in the frequency of heavy rainfall events.

- Recent global warming is already having physical and biological effects in many parts of the world.

- Work assessed by the IPCC indicates that limiting future global warming to targets which are currently being discussed internationally would require substantial reductions in global greenhouse gas emissions from human activities.

- Continued emissions of greenhouse gases will cause further warming and changes in all parts of the climate system. There are four scenarios named RCPs (Representative Concentration Pathways) by the IPCC. These RCPs represent different climate change mitigation scenarios – one (RCP 2.6) leading to very low anthropogenic greenhouse gas concentrations (requiring removal of CO_2 from the atmosphere), two stabilisation scenarios (RCPs 4.5 and 6.0), and one (RCP 8.5) with very high greenhouse gas concentrations. Therefore, the RCPs represent a range of 21st century climate policies.

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

- New Zealand has warmed by 0.09 ± 0.03°C per decade since 1909, with more heat waves, fewer frosts, more rain in the south and west of New Zealand, less rain in the north and east of the North and South Islands, and a rise in sea level since 1900 of 1.7 ± 0.1 mm/yr.

- Ongoing vulnerability in New Zealand to extreme events is demonstrated by substantial economic losses caused by droughts, floods, fire, tropical cyclones, and hail. During the 21st century, New Zealand's climate is virtually certain to warm further, with noticeable changes in extreme events.

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

- Precipitation changes are projected to lead to increased runoff in the west and south of the South Island and reduced runoff in the northeast of the South Island, and the east and north of the North Island.

- The potential impacts of climate change on industry are likely to be substantial. New Zealand's predominantly hydroelectric power generation is vulnerable to precipitation variability, changes in snow cover are likely to have a significant impact on the ski industry, and pasture production may be impacted by warming and elevated CO_2.

Northland Region's present climate is then described.

- A short thirty four year temperature record at Dargaville shows a small upward trend in annual mean temperature, somewhat less than the overall New Zealand warming through the full 20th century. There are substantial year to year fluctuations in temperature superimposed on this long-term trend, with some years being over 1.5°C different from others.

- There is also substantial year to year variation in rainfall. Dargaville exhibits annual rainfall totals ranging from around 800 mm up to more than 1600 mm, with a long term trend showing reduction in rainfall.

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

Projections for changes in Northland's climate are compared with projections for changes in other parts of New Zealand, in terms of temperature, precipitation, hot days and cold nights, and dry days.

- Future temperature scenarios for 2040 (2031-2050 relative to 1986-2005) show that annual average temperatures across the region are projected to increase by between 0.7°C (RCP 2.6) and 1.1°C (RCP 8.5). By 2090 (2081-2100 relative to 1986-2005) annual average temperatures are projected to increase by between 0.7°C (RCP 2.6) and 3.1°C (RCP 8.5). The greatest warming is projected for summer or autumn (depending on the RCP) and the least warming is projected for spring. A slight acceleration in warming is projected for the second 50 years of the 21st century compared to the first 50 years under the higher emission scenarios, and inland areas tend to warm more. There are only modest spatial gradients in the warming relative to the mean increase. By 2090 for RCP 4.5, the greatest warming is expected to occur in the northern half of Northland Region in autumn and summer, and warming is uniform across the region in winter and spring. For RCP 8.5 by 2090, warming is uniform across the region in all seasons, except for winter where more warming is expected for the south-western portion of the region than elsewhere.

- Over the region on average, the number of hot days (days >25°C) is projected to increase from 25 days per year during the historical period to 55 days per year under RCP 4.5 at 2090 and 99 days per year under RCP 8.5 at 2090. The number of cold nights (nights <0°C, i.e. frosts) is projected to decrease from 1 day per two years (0.5 days per year) during the historical period to 1 day per 10 years (0.1 days per year) under both RCP 4.5 and RCP 8.5 at 2090.

- Future precipitation projections indicate slightly less rainfall for eastern parts of the region in spring to 2040 and a less than 5% change in other seasons. The same pattern occurs for RCP 4.5 at 2090, but by 2090 for RCP 8.5 significant decreases in precipitation are projected for eastern areas in spring (up to 20% decrease) and increases are projected for eastern areas in summer and autumn (up to 10% increase).
- For many locations in Northland Region, there is no clear precipitation signal, even at 2090 under RCP 8.5. The average across all models used in the study (ensemble-average) is often less than ± 5% change, with the model range (the 5th and 95th percentile values) varying between quite large (>10%) increases and decreases. By 2040 (2031-2050, relative to 1986-2005), spring is the season with the most precipitation change, with a small decrease in the ensemble-average (up to 7% at Whangarei under RCP 8.5).
- By 2090, there is a slightly clearer precipitation signal. For both Kaitaia and Whangarei, spring is still the season with the most precipitation change, with Whangarei projecting decreases in the ensemble average at around 17% and Kaitaia around 12% under RCP 8.5.
- Projections for Northland Region for the coming century show a decrease in the frequency of very heavy rainfall. This decrease is in contrast to the common expectations of increasing extreme rainfall with climate change. As such, this Northland specific result requires further analysis before it can be applied with any confidence.
- For engineering purposes some scenarios for changes in rainfall depth/duration/frequency statistics are provided for Whangarei.
- Potential Evapotranspiration Deficit (PED) is calculated for the region, and analysis is broken down into sub-regions. PED, in units of mm, can be thought of as the amount of rainfall needed in order to keep pastures growing at optimum levels. A larger increase in PED over time equates to more drought risk in the future. In Northland Region, east coast, west coast and southern inland parts of the region experience the largest increases in PED by 2040 and 2090 under both RCP 4.5 and RCP 8.5.
- An increase in drought frequency is projected for Northland Region of about 7% for 2030-2050 and 10% for 2070-2090, compared to 1980-1999 levels. These projections were calculated from the IPCC Fourth Assessment Report emissions scenarios and will be updated in due course.
- The frequency of extreme winds (99th percentile) over the 21st century is likely to decrease in the North Island from Northland to the Bay of Plenty, probably because of increasing anticyclonic conditions.
- New guidance on planning for sea level is expected before the end of 2016 from the Ministry for the Environment (the last update was published in 2008). In the interim we suggest using

a minimum sea-level rise scenario of 0.5 m by the 2090s (2090 to 2099) relative to the 1980-1999 average for coastal planning, plus an assessment of sensitivity to possible higher mean sea levels. For longer-term considerations an allowance for further sea-level rise of 10 mm/year beyond 2100 is recommended.

- Currently, 10% of high tides at Opua exceed the MHWS-10 level (Mean High Water Spring level that 10% of high tides exceed, excluding weather and climate effects). With 0.4 m of sea-level rise, approximately 84% of high tides will exceed this level and with 0.8 m of sea-level rise 100% of high tides will exceed this level, again excluding weather and climate effects such as storm surge.

- The following hydrological projections for the Wairoa River are presented, derived from the national surface water hydrological model TopNet:

  - Mean annual flow is expected to decrease for most RCPs at 2040 and 2090, although the range of model results is quite large.

  - Mean annual flood (median model result) is expected to decrease under the two higher RCPs at 2040 and increase under the two lower RCPs. At 2090, a large increase in mean annual flood (22%) is projected under RCP 8.5, whereas the projections are smaller and the direction of change is mixed between the other RCPs.

  - Mean annual low flow is expected to decrease for all RCPs at both time periods except for RCP 2.6 at 2090 (median = 1). The largest median change is projected for 2090 under RCP 8.5, which is a reduction in mean annual low flow of 24%. However, the range of model results is quite large.

  - For average seasonal flow, the projections for summer, winter and spring at 2040 and 2090 are dominated by decreases, although some of the decreases are minimal (less than -5%). The summer months show the largest decreases. In contrast, the projections for autumn are mostly for increases in average seasonal flow, although a number of the changes are less than +5%.

  - FRE3 is the average number of high flow events (freshes or floods) per year that exceed three times the median flow. Most RCPs at both time periods show small increases in median FRE3, except for a small decrease under RCP 6.0 at 2090. However, the projected change is less than +5% in many cases.

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

Commentary on some potential climate change impacts on aspects of industry that are important for Northland:

- For agriculture, Horticulture and Forestry
    - As mean temperatures and drought occurrence increase, farmers and growers in Northland are likely to increase their usage and dependence on existing subtropical plant species and introduce new commercial species that are heat and drought-tolerant.
    - Kikuyu is likely to become the most prevalent forage grass in Northland due to its ability to spread readily and the fact that it is heat and drought-tolerant.
    - There will be a longer growing season for crops in Northland due to higher mean temperatures, but higher temperatures and lower availability of water may lead to decreasing yields, and lack of cold winter temperatures may be an issue for crops such as kiwifruit.
    - Fires are likely to become a larger issue for northern New Zealand with projected increasing temperatures and decreasing rainfall.
    - Potential increases in the intensity of tropical cyclones and severe storms could affect Northland's forest plantations in terms of wind damage.
- For terrestrial biosecurity
    - Climate change will create new biosecurity challenges by allowing establishment of new exotic pests, weeds and diseases which are currently prevented by New Zealand's climate.
    - The increased usage of subtropical plants will make Northland more susceptible to invasion by subtropical pests and diseases and new host/pest associations.
    - While much of the biosecurity risk with climate change will come from beyond New Zealand's borders, many of the future's pests and disease problems are currently 'sleeping' in New Zealand, awaiting some perturbation, such as climate change, to allow them to spread and flourish.
- For aquaculture
    - Warmer sea and fresh water temperatures modify host-pathogen interactions by increasing host susceptibility to disease.
    - Ocean acidification may have impacts on the early developmental stages of shellfish.
    - For Pacific oysters (*Crassostrea gigas*) in New Zealand, oyster herpesvirus (OsHV-1) outbreaks are exacerbated in warmer waters, as is the transmission of the parasite *Martelia refringens,* which affects flat oysters (*Ostrea chilensis*) and blue mussels (*Mytilus spp.*).

- There are concerns about the future of paua (*Haliotis spp*.) farming in Northland due to warmer waters creating a higher stress environment and potential spread of pathogens for these animals.

- For aquatic biosecurity
    - The primary source of entry for aquatic biosecurity risk organisms into New Zealand is and will remain to be through international shipping. However, changes in water temperature and ocean currents into the future, as a result of climate change, may result in species, including pests and pathogens, not usually seen in New Zealand waters to arrive and establish.
    - The strengthening East Auckland Current off the east coast of Northland is expected to promote establishment of tropical or subtropical species that currently occur as vagrants in warm La Niña years. The establishment of these species may have negative impacts on wild fisheries and also on aquaculture operations.

- For groundwater
    - With projected increases in potential evapotranspiration deficit (PED), the soil moisture conditions necessary to allow drainage of water below the root zone to the underlying aquifer will become less frequent, leading to less recharge.
    - The projected declines in mean annual low flow from the Wairoa River simulations also reflect potential future declines in aquifer recharge, although the rate of recharge is modulated by aquifer geology.
    - Groundwater levels near the coast are set by sea level. As sea level rises, coastal groundwater levels would increase to match, resulting in a reduction in groundwater flow velocities. This change would also be associated with an increase in salinisation of the coastal aquifers.

The Council is referred to material published by the Ministry for the Environment for guidance on assessing likely vulnerability and impacts for Northland Region of these projected climate changes, and for considering adaptation options. Relevant issues could include:

- Implications of sea-level rise and coastal change for planning and development in coastal areas.
- Implications of river flow and sedimentation changes, as well as changing flood regimes for river engineering planning.
- Implications of potential changes in rainfall and of drought frequency for water demand, availability and allocation (including planning for irrigation schemes and storage).

- Implications of projected changes in extreme rainfall, erosion risk and coastal hazards for council roading and stormwater drainage infrastructure, lifelines planning, and civil defence and emergency management.
- Opportunities which climate change may bring for new horticultural crops – and infrastructure and land-use issues that might arise.
- Implications of climate change (including potential changes in flood frequency, extreme rainfall (influencing hillslope and riverbank erosion) and in coastal hazards) for land-use planning (e.g. erosion control measures).
- Implications for natural ecosystems and their management, both terrestrial and marine. This is especially relevant given the multiple forest parks and marine protected areas in the region.
- Building consideration of climate change impacts and adaptation into council planning as outlined in MfE guidance. Also important is consultation and discussion with stakeholders (e.g. groups of farmers, iwi) to help them identify climate-related risks and ways of building resilience.

1 Introduction

Northland Regional Council applied for and received funding (Advice No. 1669-NLRC191) from the Envirolink Fund (Ministry of Business, Innovation, and Employment) for NIWA to undertake a review of climate change projections and potential impacts for the Northland Region, since the publication of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report in 2013 and 2014.

This report describes climate changes which may occur over the coming century for the region administered by the Northland Regional Council, and outlines some possible impacts of these changes. The report does not address the issue of mitigation (reducing greenhouse gas emissions, or increasing "sinks" such as areas of growing forest), apart from a brief summary of recent findings of the IPCC.

Consideration is given to both natural variations in the climate and to changes which may result from increasing global concentrations of greenhouse gases caused by human activities. Climatic factors discussed include temperature, rainfall, wind, evaporation, and soil moisture. River flow variables are also considered.

Possible changes along the coast in sea level are also considered. Figure 1-1 shows the Northland Regional Council area of administration.

Preparation of the report has been supported through an Envirolink medium advice grant. This did not fund any new data analysis, but enabled us to draw on information which is already available from various sources. Much of this information is very new, resulting from the latest assessments of the Intergovernmental Panel on Climate Change (IPCC, 2013, IPCC, 2014a, IPCC, 2014b), and scenarios for New Zealand generated by NIWA scientists based on downscaling from global climate model runs undertaken for these IPCC assessments (undertaken through NIWA's core-funded Regional Modelling Programme). The climate change information presented in this report is entirely consistent with recently-updated climate change guidance produced for the Ministry of the Environment (Mullan et al., 2016).

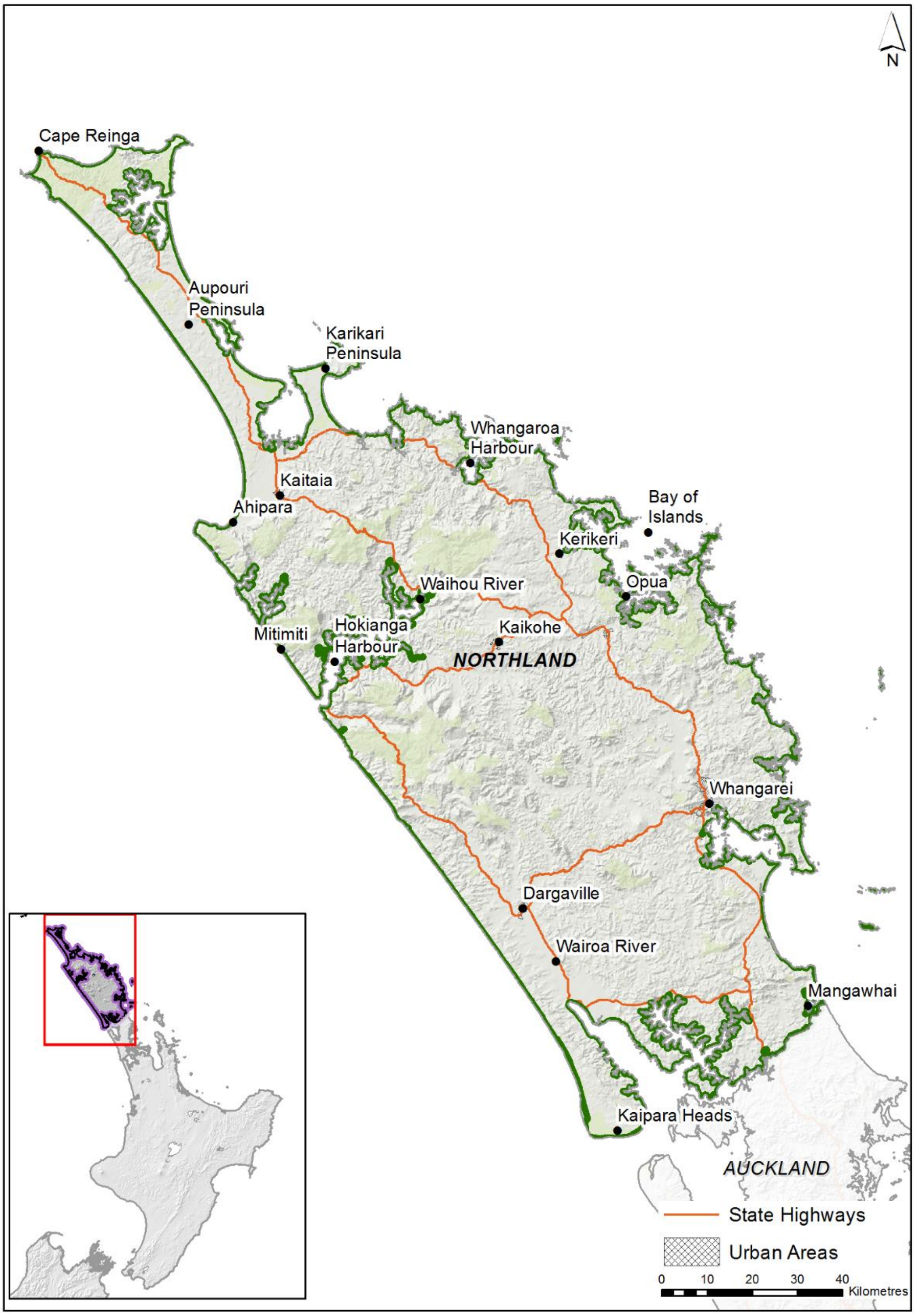


Figure 1-1: The Northland Regional Council area. The region administered by the Council is outlined.

2 Background: Global Climate Change – Science and Impacts

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

2.1 The Physical Science Basis (IPCC Working Group I)

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

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

Continued emissions of greenhouse gases will cause further warming and changes in all parts of the climate system. There are four scenarios named RCPs (Representative Concentration Pathways) by the IPCC. These RCPs represent different climate change mitigation scenarios – one (RCP2.6) leading to very low anthropogenic greenhouse gas concentrations (requiring removal of CO_2 from the atmosphere), two stabilisation scenarios (RCPs 4.5 and 6.0), and one (RCP8.5) with very high greenhouse gas concentrations. Therefore, the RCPs represent a range of 21st century climate policies.

By the middle of the 21st century, the magnitudes of the projected climate changes are substantially affected by the choice of scenario. **Global surface temperature change for the end of the 21st century is likely to exceed 1.5°C relative to 1850-1900** for all scenarios except for the lowest emissions scenario (RCP 2.6).

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

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

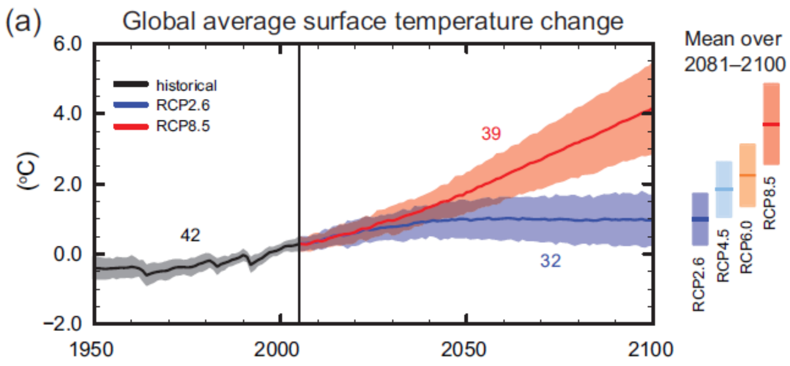


Figure 2-1: CMIP5 multi-model simulated time series from 1950-2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled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

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

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

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

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

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

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

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

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

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

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

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

2.3 Mitigation of Climate Change (IPCC Working Group III)

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

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

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

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

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

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

Delaying mitigation efforts beyond those in place today through 2030 is estimated to substantially increase the difficulty in obtaining a longer term low level of greenhouse gas emissions, as well as narrowing the range of options available to maintain temperature change below 2°C relative to pre-industrial levels.

3 Background: New Zealand Climate Change – Science and Impacts

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 recent report published by the Royal Society of New Zealand (Royal Society of New Zealand, 2016). Key findings from these publications include:

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

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

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

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

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

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

3.1 Sectoral Impacts

Some New Zealand sectors have the potential to benefit from projected changes in climate and increasing CO_2, including reduced winter mortality, reduced energy demand for winter heating, and forest and pasture growth in currently cooler regions. Impacts specific to Northland are discussed in Section 6.

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

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

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

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

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

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

Tourism: Changes in snow cover are likely to have a significant impact on the ski industry, but tourist numbers from Australia to New Zealand may increase due to the rapid reduction in snow cover in Australia, and the greater perceived scenic attractiveness of New Zealand. Warmer and drier conditions mostly benefit tourism but wetter conditions and extreme climate events undermine tourism.

4 Present Climate of Northland Region

Northland, with its northern location, low elevation and close proximity to the sea is characterised by a mild, humid, and rather windy climate (Chappell, 2013). Summers are warm and tend to be humid, while winters are mild, with many parts of the region having only a few light frosts per year. Rainfall is typically plentiful all year round with sporadic very heavy falls. However, dry spells do occur, especially during summer and autumn. Most parts of Northland receive about 2000 hours of sunshine per year. It can be very windy in exposed areas and occasionally Northland experiences gales, sometimes in association with the passage of depressions of tropical origin.

More detailed information about Northland's present climate can be found in Chappell (2013).

4.1 Spatial Patterns in Northland Region's Climate

The spatial variation in annual average temperature over the Northland Region is shown in Figure 4-1. Figure 4-2 shows the spatial pattern of annual total rainfall, and also the median seasonal total rainfalls. Temperature varies with elevation, with the coolest mean annual temperatures of the Northland Region experienced in the hill country near the west coast in the middle of the region. Mean annual temperatures are highest north of Kaitaia on the Aupouri Peninsula. Annual rainfall varies significantly throughout the Northland Region. The hilly areas north of Kaikohe, north of Dargaville and north of Whangarei receive the most rain in the region. These areas receive more than 2000 mm per year, on average. The driest part of the region is around the northern portion of the region, near Cape Reinga. These parts receive around 950 mm per year, on average.

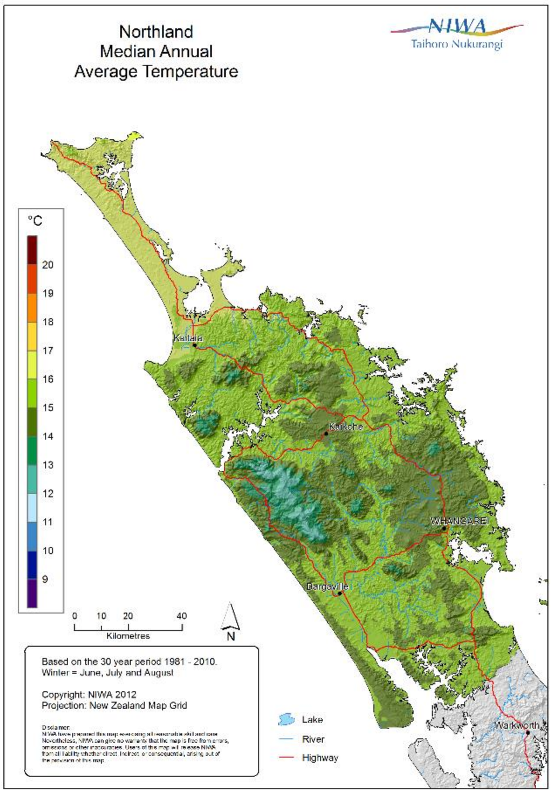


Figure 4-1: Annual average temperature for the Northland region (median for 1981-2010). ©NIWA.

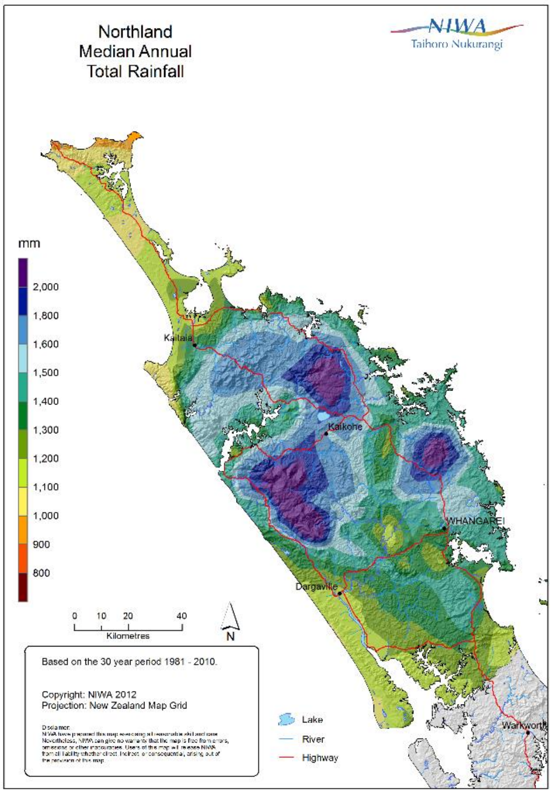


Figure 4-2: Annual rainfall for the Northland region (median for 1981-2010). ©NIWA.

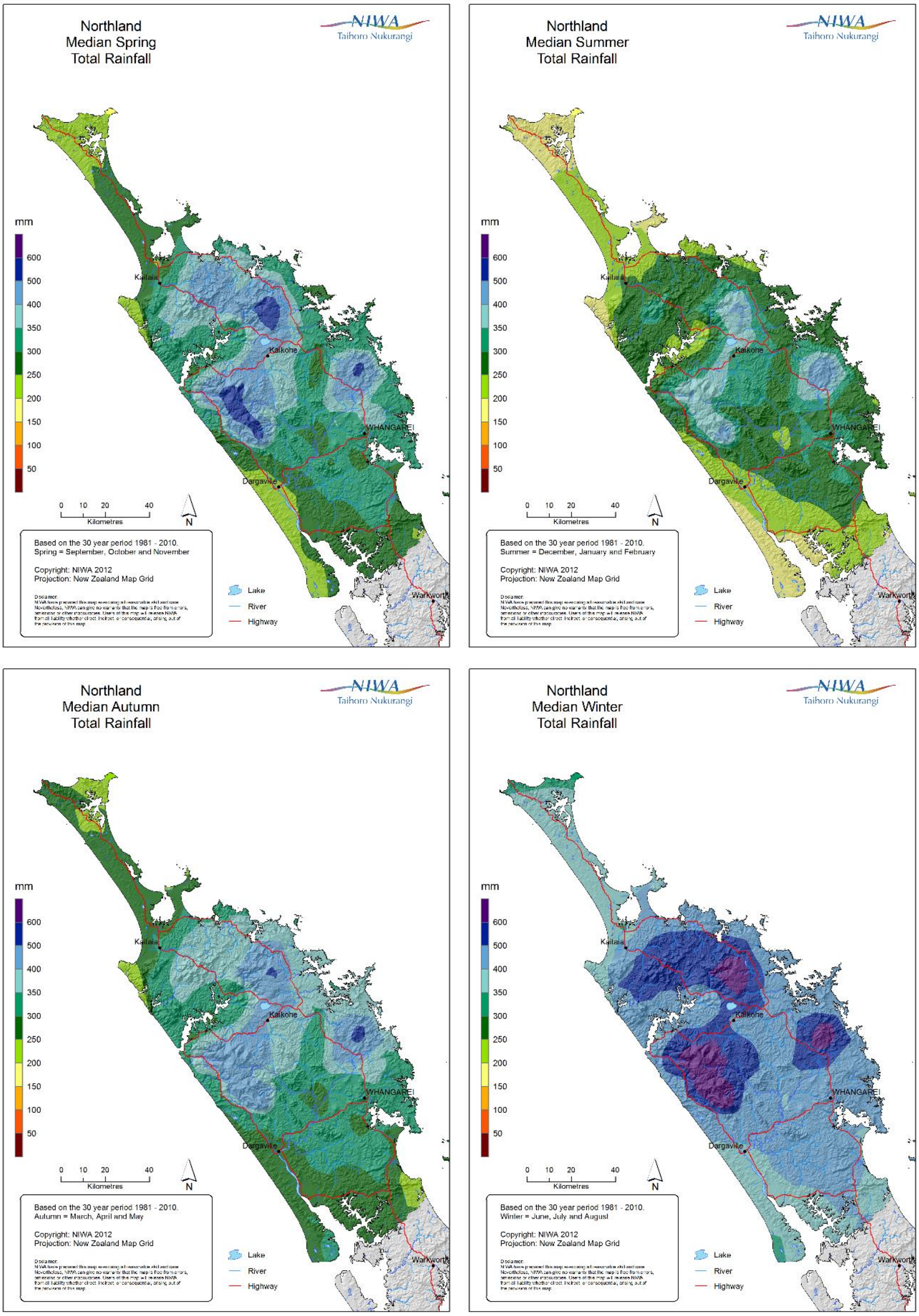


Figure 4-2 continued: **Seasonal rainfall totals (medians for spring, summer, autumn, and winter). ©NIWA.**

4.2 Temporal Variability in Northland Region's Climate

4.2.1 Temperature

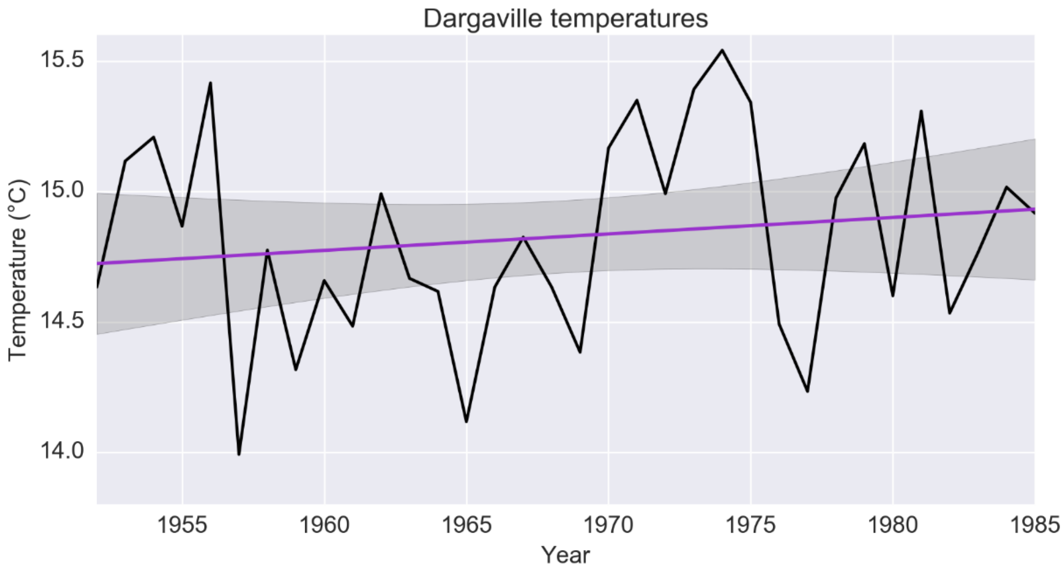


Figure 4-3: Annual mean temperature time series for Dargaville (agent number 1192) from 1951 to 1985. The purple line removes the year-to-year variability and shows a small upward trend. © NIWA.

There is significant year-to-year variability in Northland Region's climate. For example, Figure 4-3 shows the average annual temperature for Dargaville from 1951 to 1985. There are substantial differences between years, with some years having temperatures over 1.5°C different to others.

The temperature trend at Dargaville from 1951 to 1985 (shown on Figure 4-3), is 0.21 ± 0.54 °C. This trend is not statistically significant so cannot be formally attributed to increasing concentrations of anthropogenic greenhouse gases. The annual variability in the record is due to natural causes, such as the El Niño-Southern Oscillation, together with random year-to-year fluctuations ("climate noise").

For Northland, the availability of continuous long-term temperature series is very limited due to the sporadic nature of observations. The Dargaville series shown in Figure 4-3 is the longest continuous mean temperature record for Northland that is held in NIWA's National Climate Database. In order to assess trends in Northland's temperature, longer records are needed. Temperature data from nearby sites could be combined into one longer series, but in order to do this homogenisation of the data would need to be undertaken. This would be the subject of future work.

4.2.2 Rainfall

As shown in Figure 4-4, there is also substantial variability in annual rainfall totals. At Waimatenui, south of Kaikohe, rainfall varies from around 1300 mm per year to over 3000 mm. The long term trend from 1914-2000 is almost flat, showing a small reduction of 70 mm ± 292 mm (the error is shown by the grey shading either side of the purple trend line).

Figure 4-4: Annual rainfall total (mm) at Waimatenui (south of Kaikohe) from 1914 to 2000. The purple line removes the year-to-year variability and shows a long term flat trend. © NIWA.

4.2.3 Drought

Northland Region has experienced numerous droughts, and due to the importance of primary production to the region, the occurrence of drought is of major concern. In this report, the measure of climatic drought that is used is 'potential evapotranspiration deficit' (PED). Evapotranspiration is the combined loss of soil water by transpiration through plants and evaporative loss from the soil and other surfaces. Days when water demand is not met, and pasture growth is reduced, are often referred to as days of potential evapotranspiration deficit. PED, in units of mm, can be thought of as the amount of rainfall needed in order to keep pastures growing at optimum levels.

The following plots (Figures 4-5 to 4-8) show PED accumulations over growing years (July-June) through the historical record for the sites chosen. The higher the PED accumulation, the drier the soils were during that year. Note the change in scale between sites.

The highest PED accumulation for Whangarei (Figure 4-5) occurred in 2009-2010, with a secondary maximum in 2012-2013. Accumulated PED was over 500 mm during these two years. These were two of the most severe droughts in Northland's history. However, rainfall patterns in Whangarei are quite variable, so the temporal variability in PED changes from year to year – a drought year might follow a wet year and vice versa.

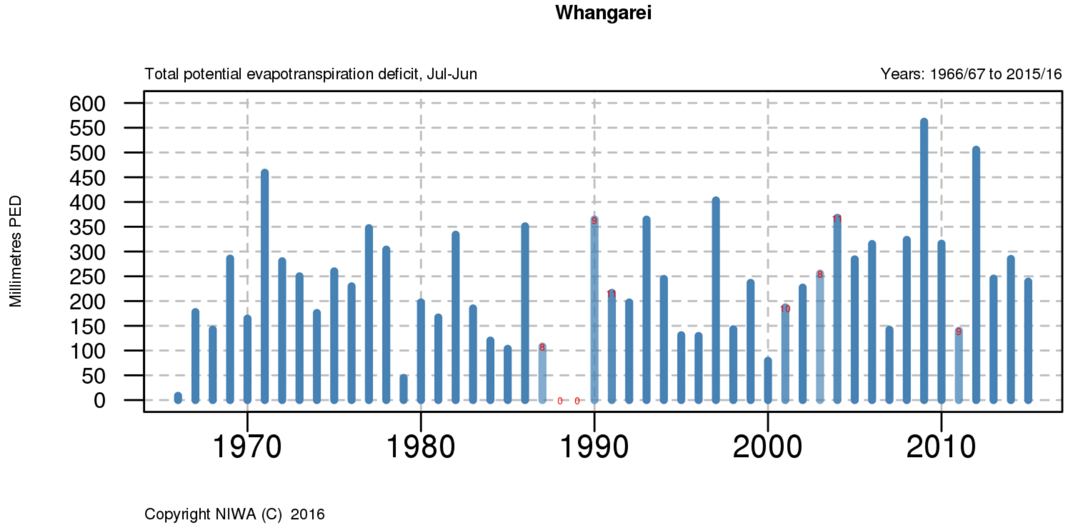


Figure 4-5: PED accumulation from 1966-2015 (July-June years) for Whangarei (combined record from agent numbers 1283 and 1287). Light blue bars indicate years where there are missing data, and small red numbers indicate the amount of months in that year with full data. © NIWA.

Dargaville has experienced numerous years when high PED accumulations have been recorded (Figure 4-6). The highest accumulation occurred during 2012-2013, when over 550 mm of PED accumulation was recorded, and 1971-1972 recorded just under 550 mm of accumulated PED. Since 2000, PED has accumulated to a higher level more often than during previous decades, suggesting an increase in drought incidence.

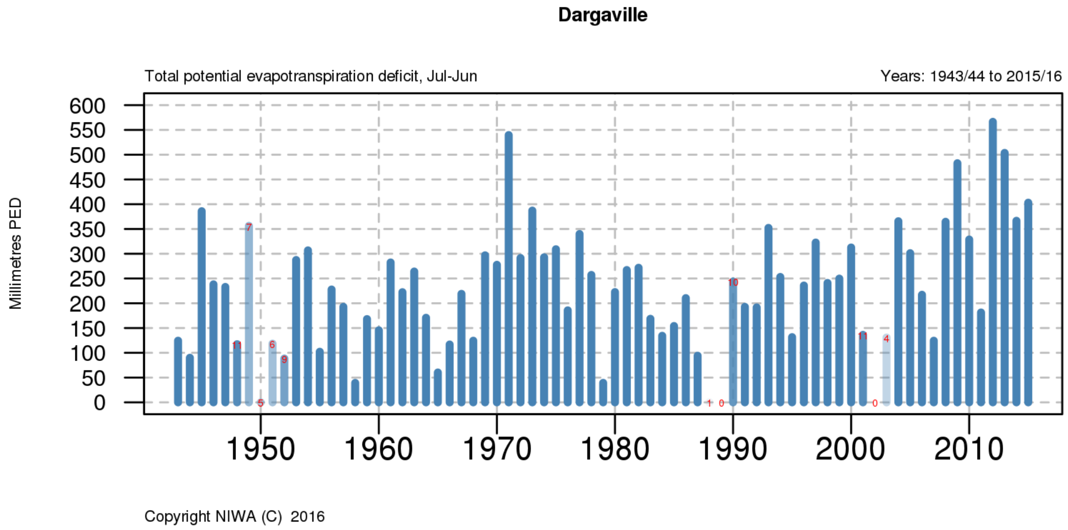


Figure 4-6: PED accumulation from 1943-2015 (July-June years) for Dargaville (combined record from agent numbers 1192, 16137, 25119). Light blue bars indicate years where there are missing data, and small red numbers indicate the amount of months in that year with full data. © NIWA.

Kaitaia's most severe drought, in terms of PED accumulation, was in 2009-2010, when over 500 mm of PED accumulated (Figure 4-7). The next highest accumulation was in 1963-1964, with about 425 mm of accumulated PED. Most years record less than 250 mm of accumulated PED.

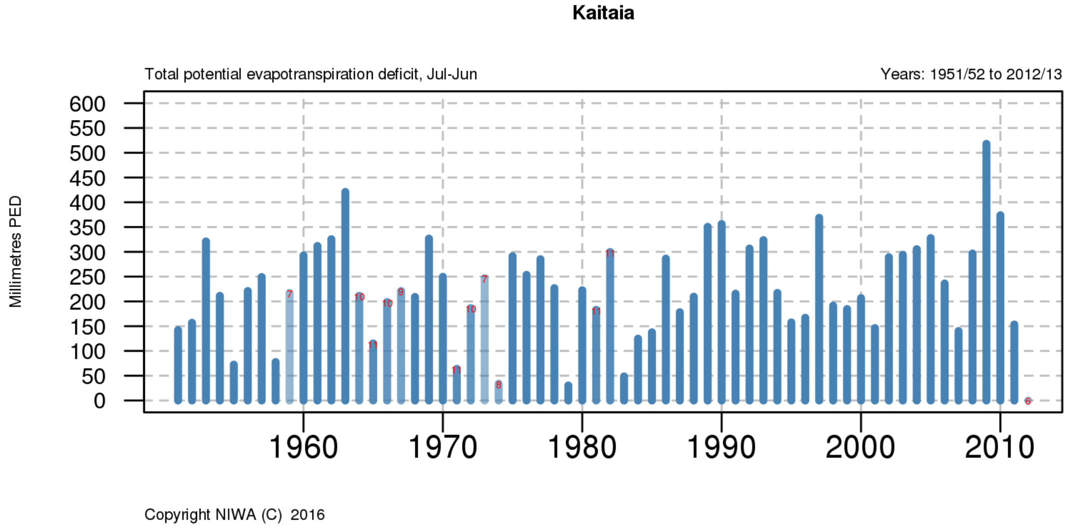


Figure 4-7: PED accumulation from 1951-2015 (July-June years) for Kaitaia (agent number 1037). Light blue bars indicate years where there are missing data, and small red numbers indicate the amount of months in that year with full data. © NIWA.

Kaikohe (Figure 4-8) has not recorded PED accumulations as high as the other sites – the maximum there was just over 350 mm of PED accumulated in 1945-1946 (note the change in vertical scale). Kaikohe recorded just over 300 mm of PED accumulation in 2009-2010, whereas the other sites recorded over 500 mm (550 mm in some cases). There is one month of data missing during this year but the accumulated PED is still quite low across the remainder of years that have no missing data, compared to other sites.

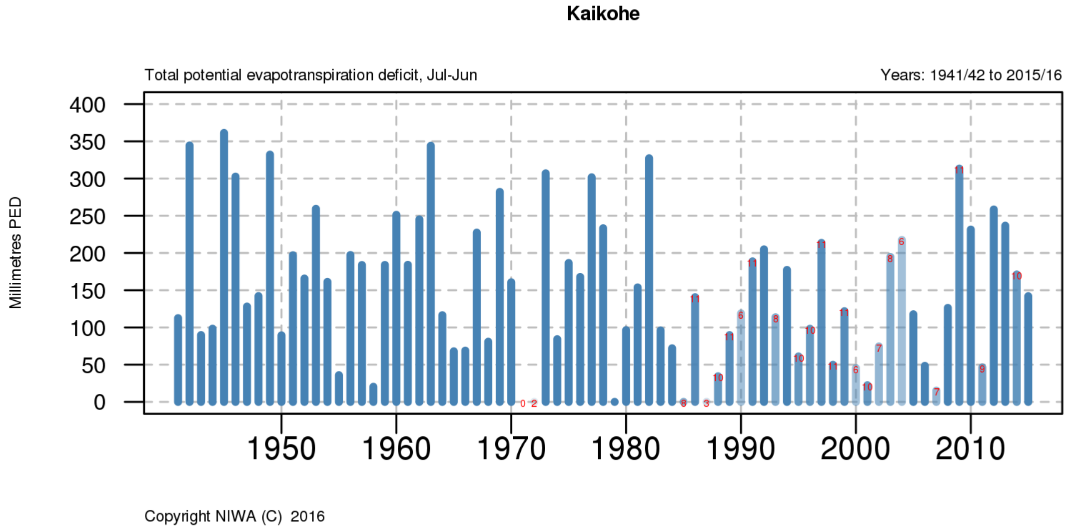


Figure 4-8: PED accumulation from 1941-2015 (July-June years) for Kaikohe (combined record from agent numbers 1126, 1129, 1134). Light blue bars indicate years where there are missing data, and small red numbers indicate the amount of months in that year with full data. © NIWA.

4.2.4 Extreme Rainfall Events

High intensity rainfall is a concern in Northland Region, due to flooding and soil erosion which impacts rivers, land-based primary industries, and urban settlements. Griffiths (2006) showed that during the periods 1930-2004 and 1950-2004, there were increases in the annual mean and annual extreme daily rainfall in the west of the North Island (west of a line from Wellington to Waiouru to Hamilton), and decreases to the east of that line (including Northland). As shown in Figure 4-9, there is a small downward trend in the number of days with >10 mm and >20 mm of rain at Whangarei from 1956 to 1986 (the longest period of continuous data at Whangarei Airport). The two rainfall thresholds show a similar pattern. However, as with Section 4.2.1, there are issues with assessing the trends of short records. Further work would be required to properly assess the statistical significance of these extreme rainfall trends.

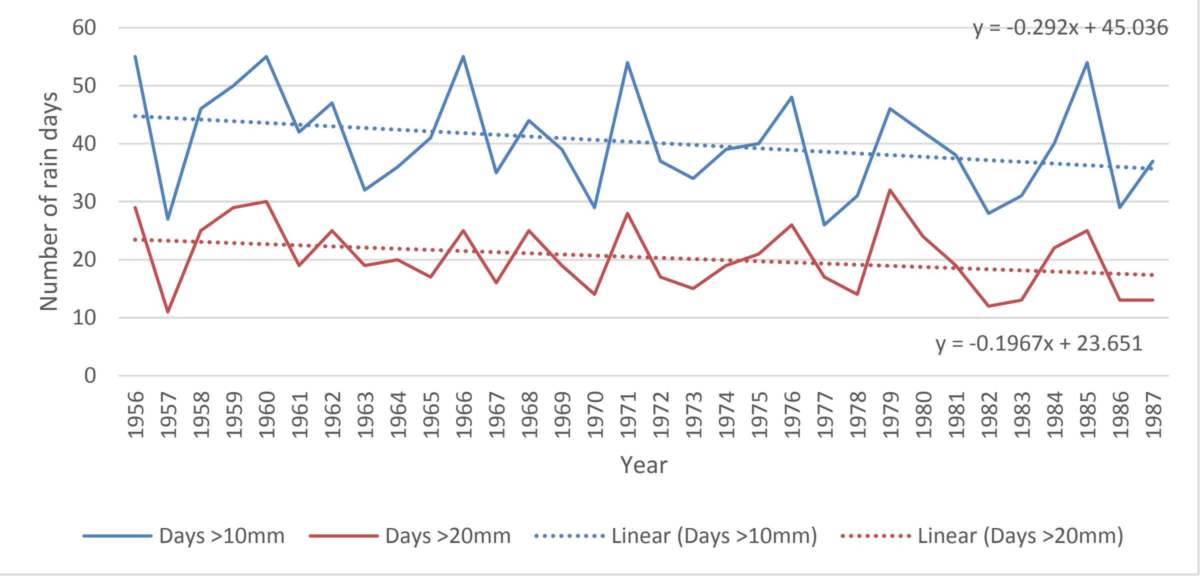


Figure 4-9: Number of days per year between 1956 and 1987 with >10mm rain and >20mm rain at Whangarei airport.

4.2.5 Growing Degree Days

The departure of mean daily temperature above a base temperature which has been found to be critical to the growth or development of a particular plant is a measure of the plant's development on that day. The sum of these departures then relates to the maturity or harvestable state of the crop. Thus, as the plant grows, updated estimates of harvest time can be made. These estimates have been found to be very valuable for a variety of crops with different base temperatures. Degree-day totals indicate the overall effects of temperature for a specified period, and can be applied to agricultural and horticultural production. Growing degree-days express the sum of daily temperatures above a selected base temperature that represent a threshold of plant growth. Figure 4-10 shows the median annual growing degree-day totals for base temperatures 5°C and 10°C for Northland Region.

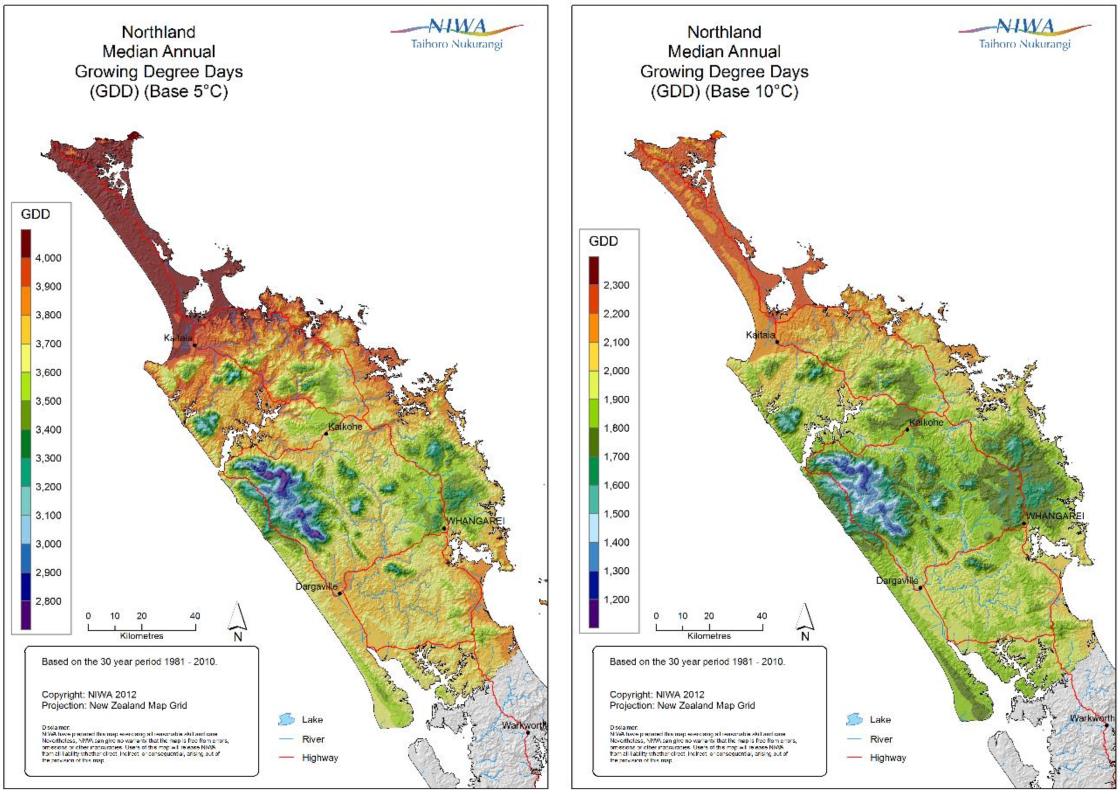


Figure 4-10: Median annual growing degree-days in Northland Region, 1981-2010. Left: Base 5°C, Right: Base 10°C. Note the change in scale between the figures. © NIWA.

Air temperatures in Northland Region have increased over the past century (Figure 4-3). As the calculation of growing degree-days is inherently dependent on temperature, one would expect to see an upward trend in the number of growing degree-days also.

4.3 Natural factors causing fluctuation in climate patterns over New Zealand

Much of the variation in New Zealand's climate is random and lasts for only a short period, but longer term, quasi-cyclic variations in climate can be attributed to different factors. Three large-scale oscillations that influence climate in New Zealand are the El Niño-Southern Oscillation, the Interdecadal Pacific Oscillation, and the Southern Annular Mode (Ministry for the Environment, 2008a).

4.3.1 The effect of El Niño and La Niña

The El Niño-Southern Oscillation (ENSO) is a natural mode of climate variability that has wide-ranging impacts around the Pacific basin (Ministry for the Environment, 2008a). The oscillation involves a movement of warm ocean water from one side of the Pacific to the other, and the movement of rainfall across the Pacific associated with this warm water.

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

El Niño events occur on average 3 to 7 years apart, typically becoming established in April or May and persisting for about a year thereafter. The Southern Oscillation Index, or SOI, uses the pressure difference between Tahiti and Darwin to determine the state and intensity of ENSO. Persistence of about -1 signifies El Niño events, whereas +1 signifies La Niña (Figure 4-11).

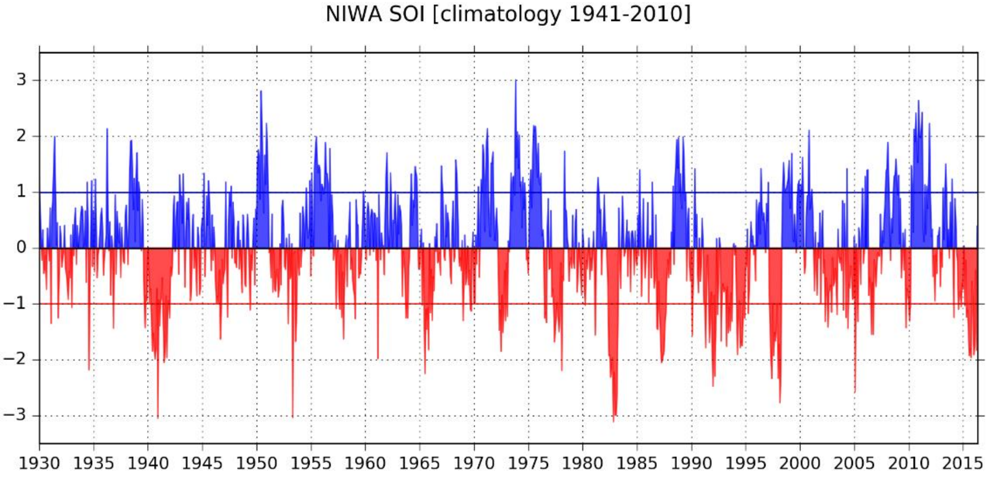


Figure 4-11: Time series of the Southern Oscillation Index from 1930 to 2016. Blue shades are indicative of La Niña periods and red shades are indicative of El Niño periods.

The effects of El Niño and La Niña are most clearly observed in the tropics, but impacts are well-recognised in New Zealand also. In 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.

In La Niña conditions, the strengthened trade winds cause New Zealand to experience more north-easterly airflow than normal, higher temperatures, and wetter conditions in the north and east of the North Island. In the South Island higher pressures are often dominant, which can cause drought conditions there. Therefore, drought conditions can persist in either El Niño or La Niña phases in the South Island. Figure 4-12 shows average summer rainfall anomalies in New Zealand associated with El Niño and La Niña conditions. However, individual ENSO events may have significantly different rainfall patterns to those pictured.

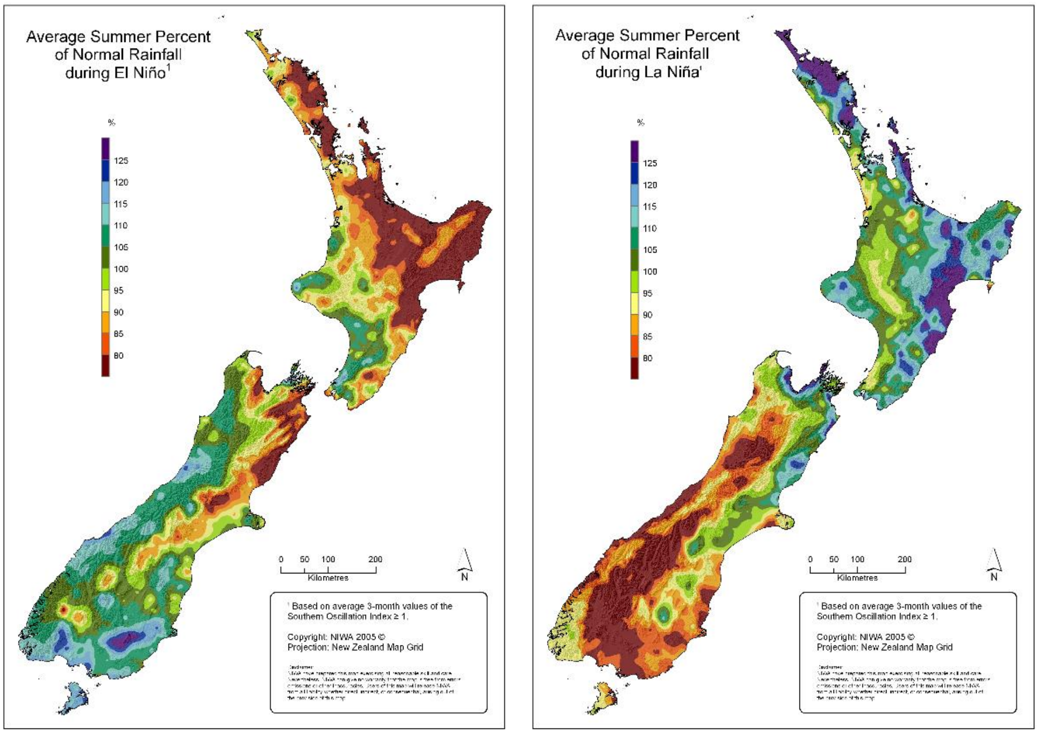


Figure 4-12: Average summer percentage of normal rainfall during El Niño (left) and La Niña (right). © NIWA.

From Figure 4-12 it is evident that on average summer rainfall for eastern Northland is below normal during El Niño periods and above normal during La Niña periods. Western Northland receives slightly below normal rainfall during El Niño periods and near normal rainfall during La Niña periods.

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

4.3.2 The effect of the Interdecadal Pacific Oscillation

The Interdecadal Pacific Oscillation, or IPO, is a large-scale, long period oscillation that influences climate variability over the Pacific Basin including New Zealand (Salinger et al., 2001). The IPO operates at a multi-decadal scale, with phases lasting around 20 to 30 years (Figure 4-13). During the positive phase of the IPO, sea surface temperatures around New Zealand tend to be lower, and westerly winds stronger, with the opposite occurring in the negative phase.

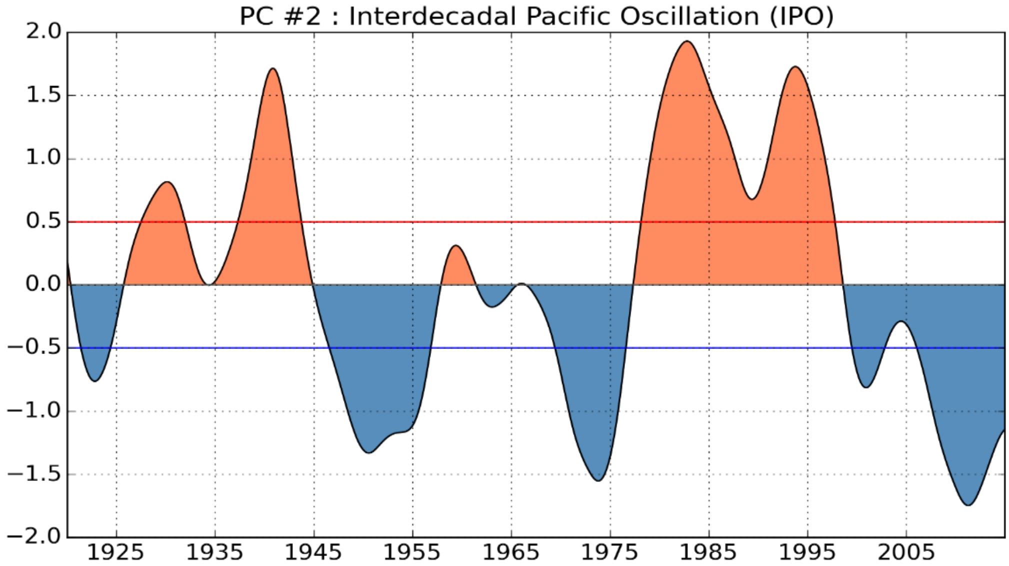


Figure 4-13: The Interdecadal Pacific Oscillation (IPO) index. Positive values indicate periods when stronger-than-normal westerlies occur over New Zealand, with more anticyclones than usual over northern New Zealand. Negative values indicate periods with more northeasterlies than normal over northern regions of the country. Vertical axis is the IPO index, and horizontal axis is the year.

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

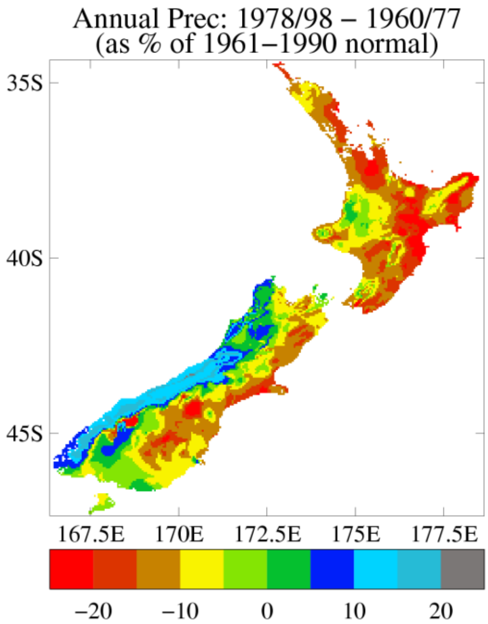


Figure 4-14: Percentage change in average annual rainfall, for the 1978-1998 period compared to the 1960-1977 period. (Note: From 1978-98 the IPO was in its positive phase, compared to the previous 18 years when the IPO was negative. Any local rainfall response due to global warming would also be contained within this pattern of rainfall trends). ©NIWA.

As suggested by Figure 4-14, periods of positive IPO (which generally coincide with increased El Niño activity) tend to be drier, on average, for most of Northland Region, particularly in the north and southeast of the region. The IPO has been in a more negative phase since 1999.

During the periods 1930-2004 and 1950-2004, a trend to increases in mean and extreme 1-day rainfall was generally observed in the west of both the North Island and South Island[1] (Griffiths, 2006). Griffiths suggests this results from a trend to increased westerly circulation across New Zealand between 1950 and 2004. This trend is consistent with enhanced warming since 1950 (as predicted by climate change modelling); the stronger IPO westerly phase since 1977; the increased frequency of El Niño events since 1977; or a mixture of all these considerations.

4.3.3 The effect of the Southern Annular Mode

The Southern Annular Mode (SAM) is a ring of climatic variability that encircles the South Pole and extends out to the latitudes of New Zealand, which affects New Zealand's climate in terms of westerly wind strength and storm occurrence (Renwick and Thompson, 2006). In its positive phase, the SAM is associated with relatively light winds and more settled weather over New Zealand, with stronger westerly winds further south towards the pole. In contrast, the negative phase of the SAM is associated with unsettled weather over New Zealand and stronger westerly winds, whereas wind and storms decrease towards Antarctica.

In contrast to the longer-lived oscillations of ENSO and the IPO, each phase of the SAM may only last for a number of weeks before switching to the opposite phase. The phase and strength of the SAM is influenced by the size of the ozone hole, with the past increase in ozone depleting substances giving rise to a positive trend in the phase of the SAM (Thompson et al., 2011). However, with the recovery of the ozone hole and reduction of ozone-depleting substances projected into the future, the trend of summertime SAM phases is expected to become more negative and stabilise slightly above zero (i.e., it is expected that there will be slightly more positive SAM phases than negative phases. Note that the phases of the SAM are defined relative to the historical climate). However, increasing concentration of greenhouse gases in the atmosphere will have the opposite effect, of an increasing positive trend in summer and winter SAM phases, i.e. there will be more positive phases than negative phases into the future (Figure 4-15). The net result for SAM behaviour, as a consequence of both ozone recovery and greenhouse gas increases, is therefore likely to be relatively little change from present by 2100. However, other drivers are likely to have an impact on SAM behaviour into the future, particularly changes to sea ice around Antarctica as well as changing temperature gradients between the equator and the high southern latitudes which could have an impact on zonal wind strength in the mid-high latitudes.

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

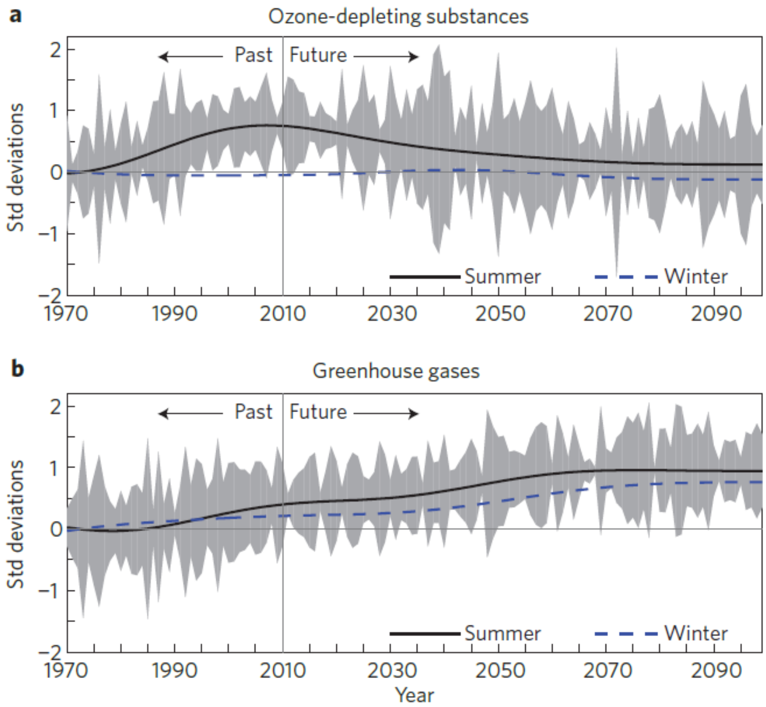


Figure 4-15: Time series of the Southern Annular Mode from transient experiments forced with time-varying ozone-depleting substances and greenhouse gases. a. Forcing with ozone-depleting substances; b. forcing with greenhouse gases. The SAM index is defined as the leading principal component time series of 850-hpa Z anomalies 20-90°S; positive values of the index correspond to anomalously low Z over the polar cap, and vice versa. Lines denote the 50-year low-pass ensemble mean response for summer (DJF, solid black) and winter (JJA, dashed blue). Grey shading denotes +/- one standard deviation of the three ensemble members about the ensemble mean. The long-term means of the time series are arbitrary and are set to zero for the period 1970-1975. Past forcings are based on observational estimates; future forcings are based on predictions. After Thompson et al. (2011).

4.4 New Zealand Sea Level Trends and Variability

According to the IPCC AR5 Working Group I, global mean sea level rose by 0.19 ± 0.02 m from 1901 to 2010 (IPCC, 2013). Sea level rise around New Zealand is comparable to the global average, being approximately 0.17 ± 0.1 m for the 20th century (Reisinger et al., 2014).

Along with the long-term positive trend in sea level, there are short-term variations as well (Figure 4-16 and Table 4-1). Seasonal (annual), El Niño-Southern Oscillation (ENSO, 3-7 year), and Interdecadal Pacific Oscillation (IPO, 20-30 year) variations can cause fluctuations in background sea levels for short periods. For example during El Niño phases, sea levels around New Zealand tend to be depressed, and during La Niña phases sea levels around the country tend to be higher. The IPO in its negative phase tends to increase sea levels around the North Island by around 0.06 m above the background sea level rise.

Storm surge can also temporarily increase sea level over 1-3 days. Storm surge occurs due to a reduction in atmospheric pressure (inverse barometer effect) and the influence of the wind on the sea surface. In a New Zealand context, maximum storm surge on the open coast is unlikely to be more than 1 m, but can be higher in estuarine and harbour settings. Wave conditions also affect localised water levels where inshore of the wave breaker zone, water levels are set-up. This is a localised phenomenon and can be highly variable along even a short stretch of coastline, being dependent on the wave conditions and configurations of offshore sandbars and beach slope.

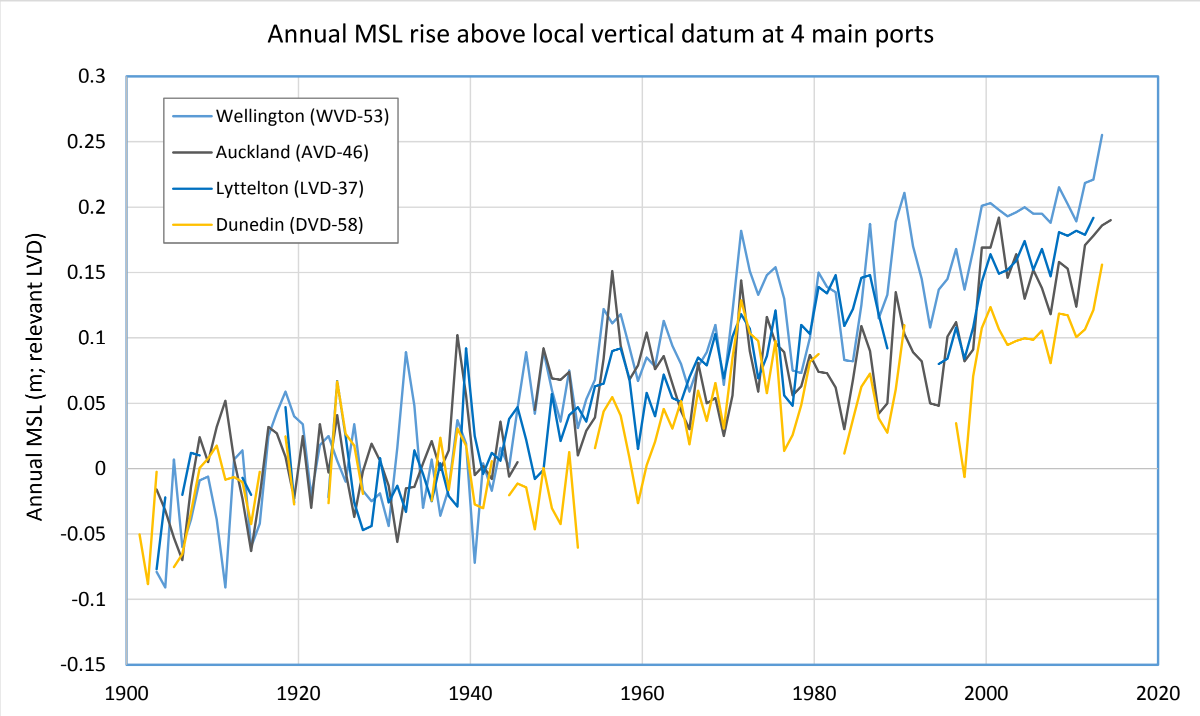


Figure 4-16: Relative sea-level rise at four main New Zealand ports, 1900-2007. Modified after Hannah and Bell (2012). Annual MSL quality assurance undertaken by Prof. John Hannah and NIWA – data sourced originally from the port companies and obtained from the Land Information NZ archives. Each local vertical datum (LVD) was established from tide-gauge measurements in the earlier part of last century for years listed in Table 1 of Hannah & Bell (2012). Note: the plot shows the increase in annual MSL since the zero MSL datums were established from measurements in the earlier part of the 1900s, where the average passes through the zero line.

Table 4-1: Historical relative sea-level rise rates. Source: Hannah and Bell (2012). The SLR rates are relative to the local landmass at the sea-level gauge locations (and implicitly include vertical landmass movement).

Location	Historical rate of sea-level rise (mm yr^{-1})
Auckland	1.5 ± 0.1
Wellington	2.0 ± 0.2
Lyttelton	1.9 ± 0.1
Dunedin	1.3 ± 0.1

5 Projections of Northland Region's Future Climate

Northland Region's future climate will be influenced by a combination of the effects of anthropogenic climate change (increasing global concentrations of greenhouse gases, Section 2) plus the natural year-to-year and decade-to-decade variability resulting from "climate noise" and features such as the El Niño-Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO), and the Southern Annular Mode (SAM), discussed in Section 4. This section first outlines the projected changes due to anthropogenic climate change in Northland Region, and then returns to the issue of natural variability. Note that the projected changes use 20-year averages, which will not entirely remove effects of natural variability.

Predicting future changes in climate due to anthropogenic activity is made difficult because (a) predictions depend on future greenhouse gas concentrations, which in turn depend on global greenhouse gas emissions driven by factors such as economic activity, population changes, technological advances and policies for sustainable resource use, and (b) even for a specific future trajectory of global greenhouse gas emissions, different climate models predict somewhat different amounts of climate change.

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

In Sections 5.1 and 5.2, global climate model output based on two RCPs has been downscaled to produce future projections for temperature and precipitation for Northland Region. The RCPs are based on 21st century climate policies, and thus differ from the previous IPCC SRES emissions scenarios and their 'no-climate policy' (IPCC, 2013). RCP 4.5 is a low-mid-range emissions scenario, which is also called a 'stabilisation' scenario where radiative forcing stabilises by 2100. RCP 8.5 is a scenario with very high greenhouse gas emissions, and radiative forcing continues to increase beyond 2100. Each RCP provides spatially-resolved data sets of land use change and sector-based emissions of air pollutants, and it specifies annual greenhouse gas concentrations and anthropogenic emissions up to 2500 (although this report only considers changes to 2100). RCPs are based on a combination of integrated assessment models, simple climate models, atmospheric chemistry and global carbon cycle models.

NIWA has used climate model data from the IPCC Fifth Assessment (IPCC, 2013) to update climate change scenarios for New Zealand, through both a regional climate model (dynamical) and statistical downscaling process. The dynamical and statistical downscaling processes are described in detail in an updated climate guidance manual prepared for the Ministry for the Environment (Mullan et al., 2016).

5.1 Northland Climate Change Temperature Projections

The magnitude of the temperature change projections varies with the RCP and also with the climate models used. In this report, statistical downscaling of two RCPs has been carried out to show the differences in temperature and precipitation projections for a stabilisation emissions scenario (RCP 4.5) and a high emissions scenario (RCP 8.5).

As shown by Figure 5-1, the seasonal patterns of projected temperature increase over the Northland Region for 2040 for the RCP 4.5 scenario, where the temperature changes of 37 climate models have been averaged together. Figure 5-2 shows corresponding patterns for 2090. Figure 5-3 shows the seasonal patterns of projected temperature increase for 2040 for the RCP 8.5 scenario, where the temperature changes of 41 climate models have been averaged together, and Figure 5-4 shows the corresponding patterns for 2090. These nominal years represent the mid-points of bi-decadal periods: 2040 is the average over 2031-2050, and 2090 the average over 2081-2100. All maps show changes relative to the baseline climate of 1986-2005.

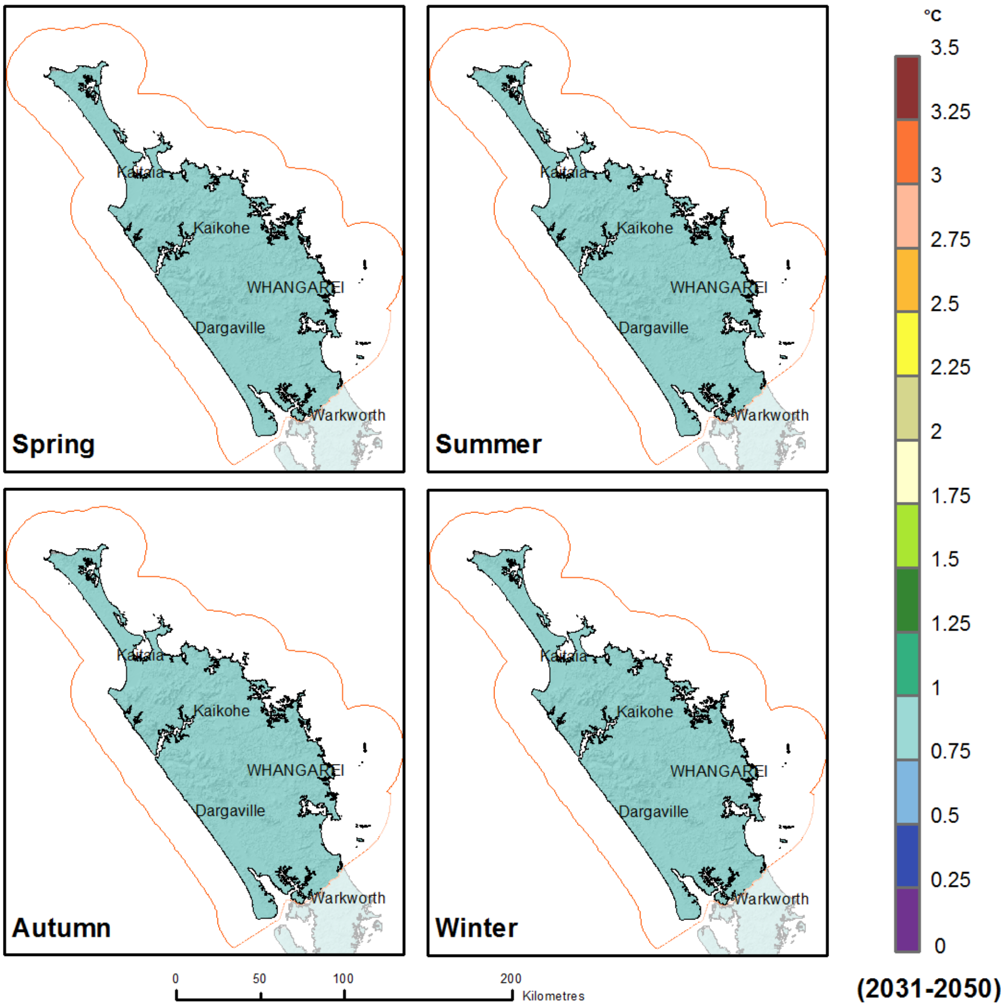


Figure 5-1: Projected seasonal temperature changes at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP 4.5 scenario, averaged over 37 climate models. ©NIWA.

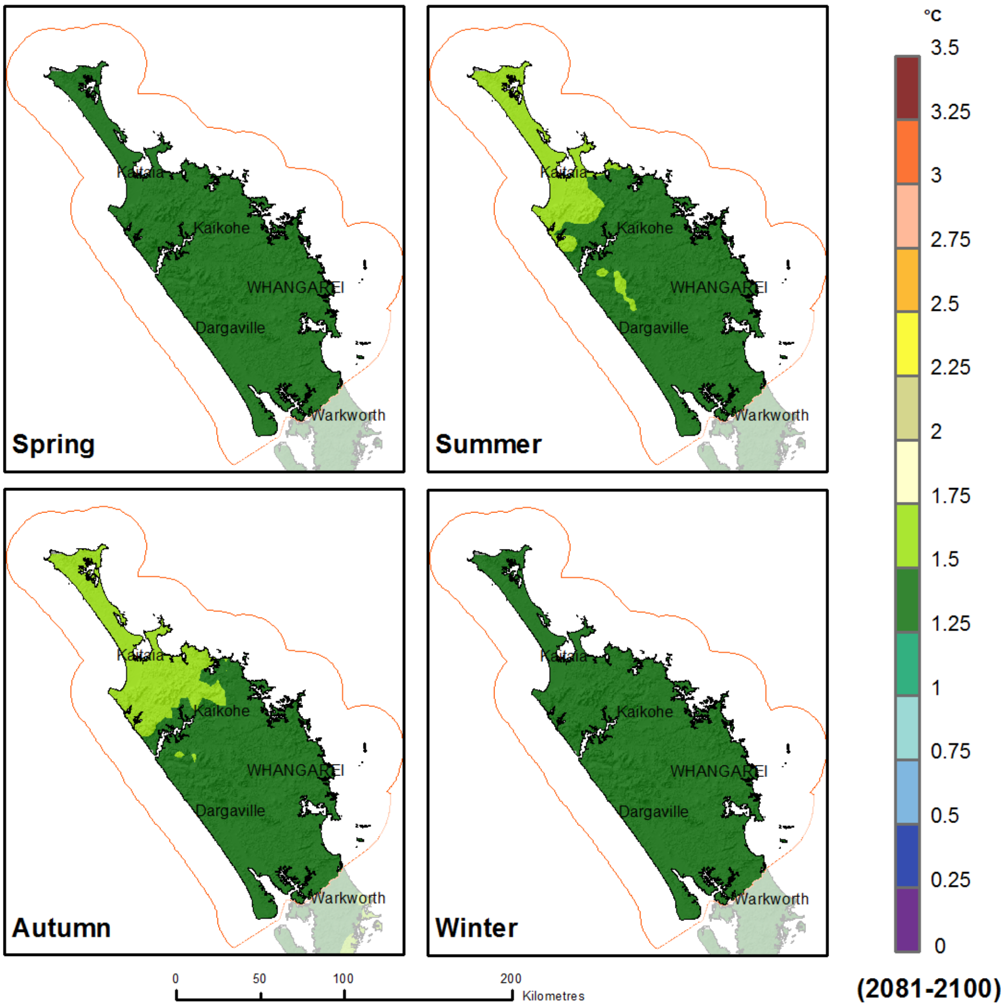


Figure 5-2: Projected seasonal temperature changes at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP 4.5 scenario, averaged over 37 climate models. ©NIWA.

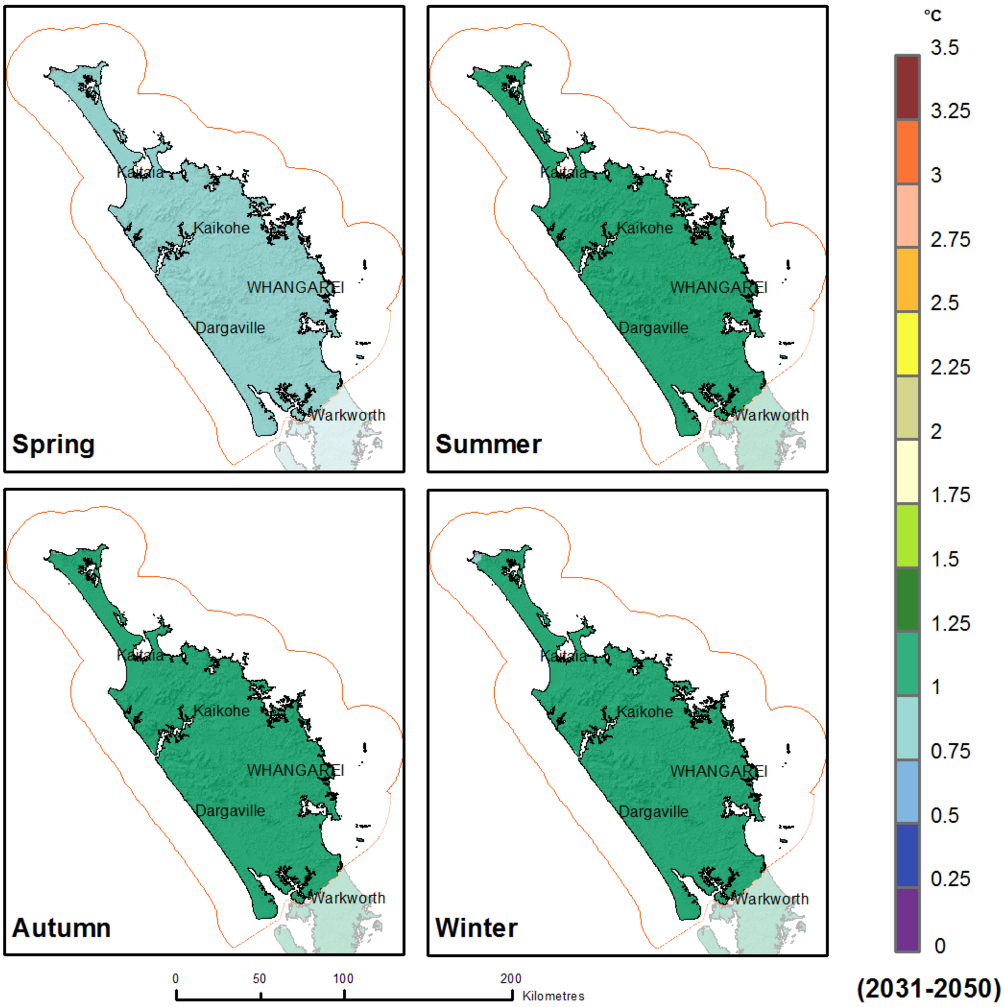


Figure 5-3: Projected seasonal temperature changes at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP 8.5 scenario, averaged over 41 climate models. ©NIWA.

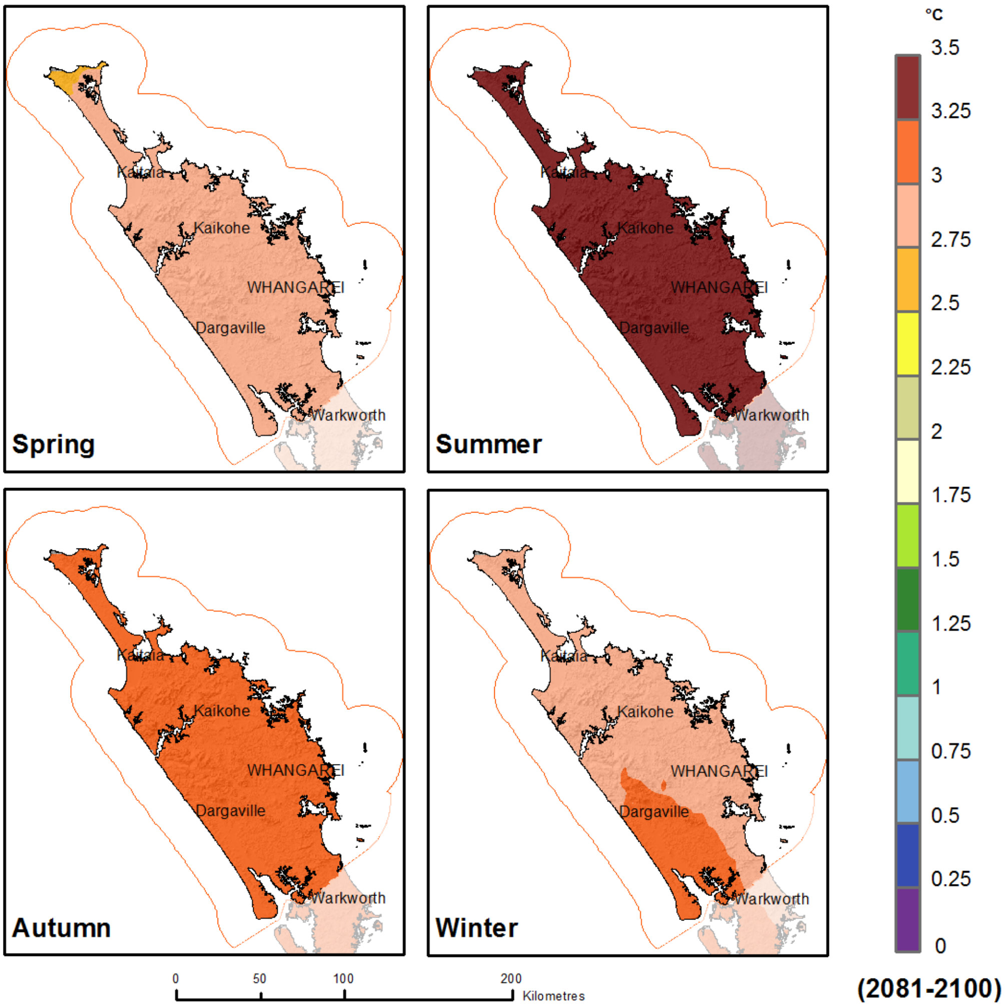


Figure 5-4: Projected seasonal temperature changes at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP 8.5 scenario, averaged over 41 climate models. ©NIWA.

As shown by Figure 5-1, projected future warming in the Northland Region is approximately 0.75°C by 2040 for the RCP 4.5 scenario, when averaged over the 37 climate models analysed by NIWA. Figure 5-2 shows projected future warming of 1.25°C to 1.75°C by 2090 under the RCP 4.5 scenario, with greater warming for the summer and autumn seasons for the northern part of the region. Figure 5-3 shows projected future warming of approximately 0.75°C to 1.25°C by 2040 for the RCP 8.5 scenario, when averaged over 41 climate models, with less warming in spring compared with other seasons. Figure 5-4 shows projected future warming of approximately 2.5°C to 3.5°C by 2090 under the RCP 8.5 scenario, with more warming in summer, then autumn, compared with other seasons. A slight acceleration in warming is projected for the second 50 years of the 21st century compared to the first 50 years.

Some models give less warming and others give a faster rate of warming (IPCC, 2013). The full range of model-projected warming is given in Table 5-1. The temperature ranges are relative to the baseline period 1986-2005 (as used by IPCC). Hence the projected changes at 2040 and 2090 should be thought of as 45-year and 95-year trends.

Table 5-1: Projected changes in seasonal and annual mean temperature (in °C) for the Northland Region for 2040 and 2090. Changes are relative to the baseline period, 1986-2005. The changes are given for all four RCPs (2.6, 4.5, 6.0, 8.5), where the ensemble-average is taken over (23, 37, 18, 41) models, respectively. The first number is the ensemble average, with the bracketed numbers giving the range (5th and 95th percentile). After Mullan et al. (2016).

Period	RCP	Summer	Autumn	Winter	Spring	Annual
2040	rcp 8.5	1.1 (0.5, 1.6)	1.1 (0.7, 1.5)	1.1 (0.6, 1.4)	1.0 (0.5, 1.3)	1.1 (0.7, 1.4)
	rcp 6.0	0.9 (0.5, 1.5)	0.9 (0.5, 1.3)	0.8 (0.4, 1.2)	0.8 (0.3, 1.1)	1.1 (0.7, 1.4)
	rcp 4.5	1.0 (0.4, 1.5)	0.9 (0.4, 1.4)	0.9 (0.5, 1.2)	0.8 (0.4, 1.1)	0.9 (0.5, 1.2)
	rcp 2.6	0.8 (0.3, 1.3)	0.8 (0.4, 1.1)	0.7 (0.4, 1.0)	0.7 (0.4, 1.0)	0.7 (0.4, 1.0)
2090	rcp 8.5	3.3 (2.4, 5.0)	3.2 (2.2, 4.3)	3.0 (2.3, 3.8)	2.8 (2.1, 3.6)	3.1 (2.4, 4.1)
	rcp 6.0	2.0 (1.4, 3.3)	1.9 (1.1, 2.8)	1.8 (1.1, 2.4)	1.7 (1.2, 2.3)	1.9 (1.2, 2.6)
	rcp 4.5	1.5 (0.9, 2.5)	1.5 (0.9, 2.1)	1.4 (0.8, 1.9)	1.3 (0.8, 1.8)	1.4 (0.9, 2.0)
	rcp 2.6	0.7 (0.4, 1.3)	0.7 (0.3, 1.3)	0.7 (0.4, 1.2)	0.7 (0.3, 1.2)	0.7 (0.4, 1.3)

The seasonal and annual ensemble average projection (the number outside the brackets) in Table 5-1 is the temperature increase averaged over all 23 models for RCP 2.6, 37 models for RCP 4.5, 18 models for RCP 6.0, and 41 models for RCP 8.5 analysed by NIWA. The bracketed numbers give the range (5th and 95th percentile) for each RCP for each season and the annual projection.

By 2040 (2031-2050, relative to 1986-2005), annual average temperatures are projected to increase by between 0.7°C (RCP 2.6) and 1.1°C (RCP 8.5). Summer, autumn and winter have similar projections for warming, and the least warming is projected for spring. By 2090 (2081-2100, relative to 1986-2005), annual average temperatures are projected to increase by between 0.7°C for RCP 2.6 and 3.1°C for RCP 8.5. As for 2040, summer, autumn and winter have similar projections for warming, and the least warming is projected for spring. Note that the mitigation scenario (RCP 2.6) temperature change for 2090 is less than the change for 2040 in autumn and no change is observed for summer, winter, and spring, whereas all other emissions scenarios show increased warming at 2090 relative to 2040.

5.1.1 Abrupt temperature changes

There is the potential for abrupt temperature changes in Northland over the 21st century. The projected mean annual temperatures for Whangarei are shown in Figure 5-5. This figure shows the individual model results as well as the ensemble-average results for each of the four RCPs. It is evident from Figure 5-5 that the temperature trend is not smooth, and increases and decreases occur from year to year within the different model projections and also with the ensemble-average of each RCP. For example, the ensemble-average of RCP 8.5 (solid red line) shows an increase in average annual temperature at Whangarei from 16.4°C at 2040 to 17.0°C at 2052.

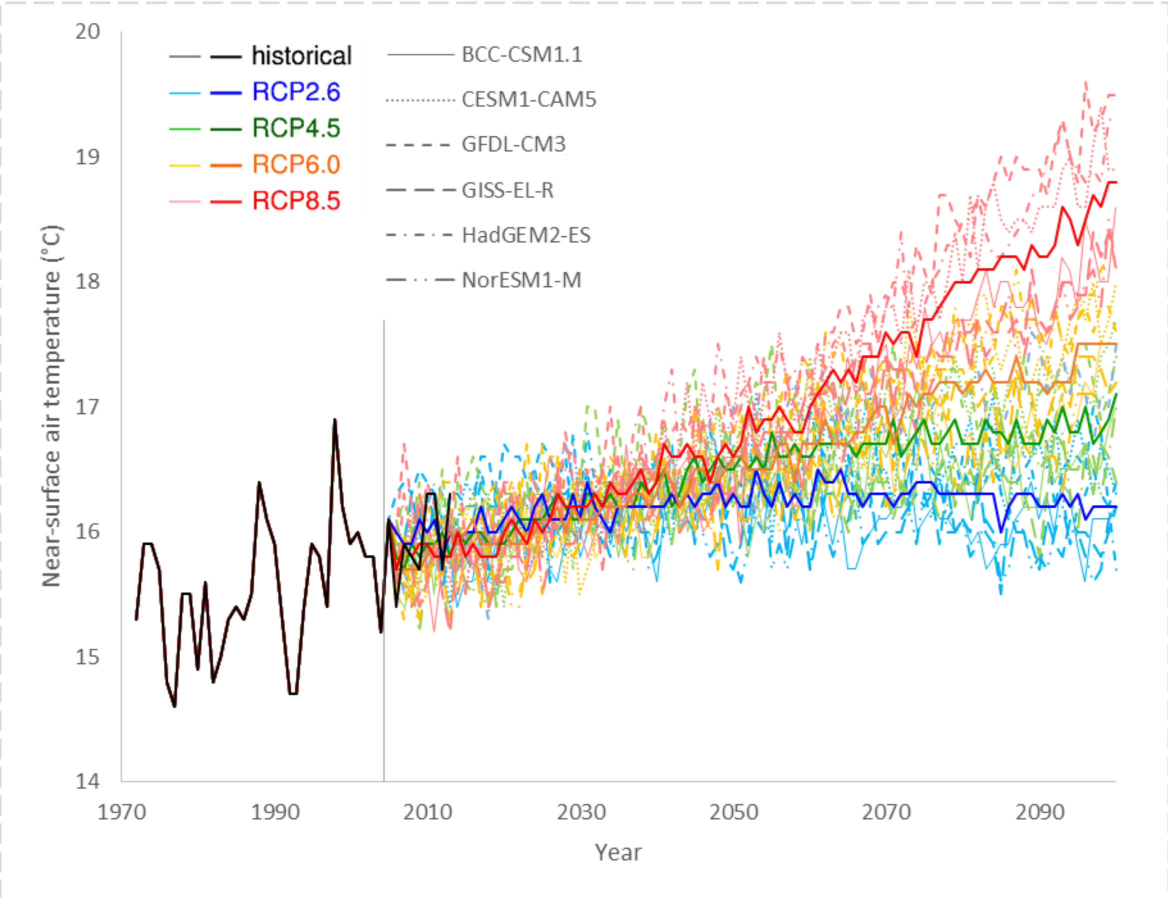


Figure 5-5: Projected Whangarei temperatures relative to 1986-2005, for 6 CMIP5 global climate models. Projections are shown for four future simulations (RCPs 2.6, 4.5, 6.0 and 8.5). Individual models are shown by thin dotted or dashed or solid lines (as described in the inset legend), and the 6-model ensemble-average by thicker solid lines, all of which are coloured according to the RCP. ©NIWA.

5.1.2 Projections of Growing Degree-Days

As discussed in Section 4.2.5, the calculation of growing degree-days is useful to primary industry in terms of monitoring plant growth and planning harvests. Due to projected mean temperature increases across the Northland Region, as discussed in Section 5.1, it is expected that the annual total of growing degree-days will increase, with larger increases expected in the seasons that are likely to experience greater warming (i.e. summer, autumn, and winter). At present, future projections of Growing Degree Days based on the IPCC AR5 model data have not been performed for New Zealand.

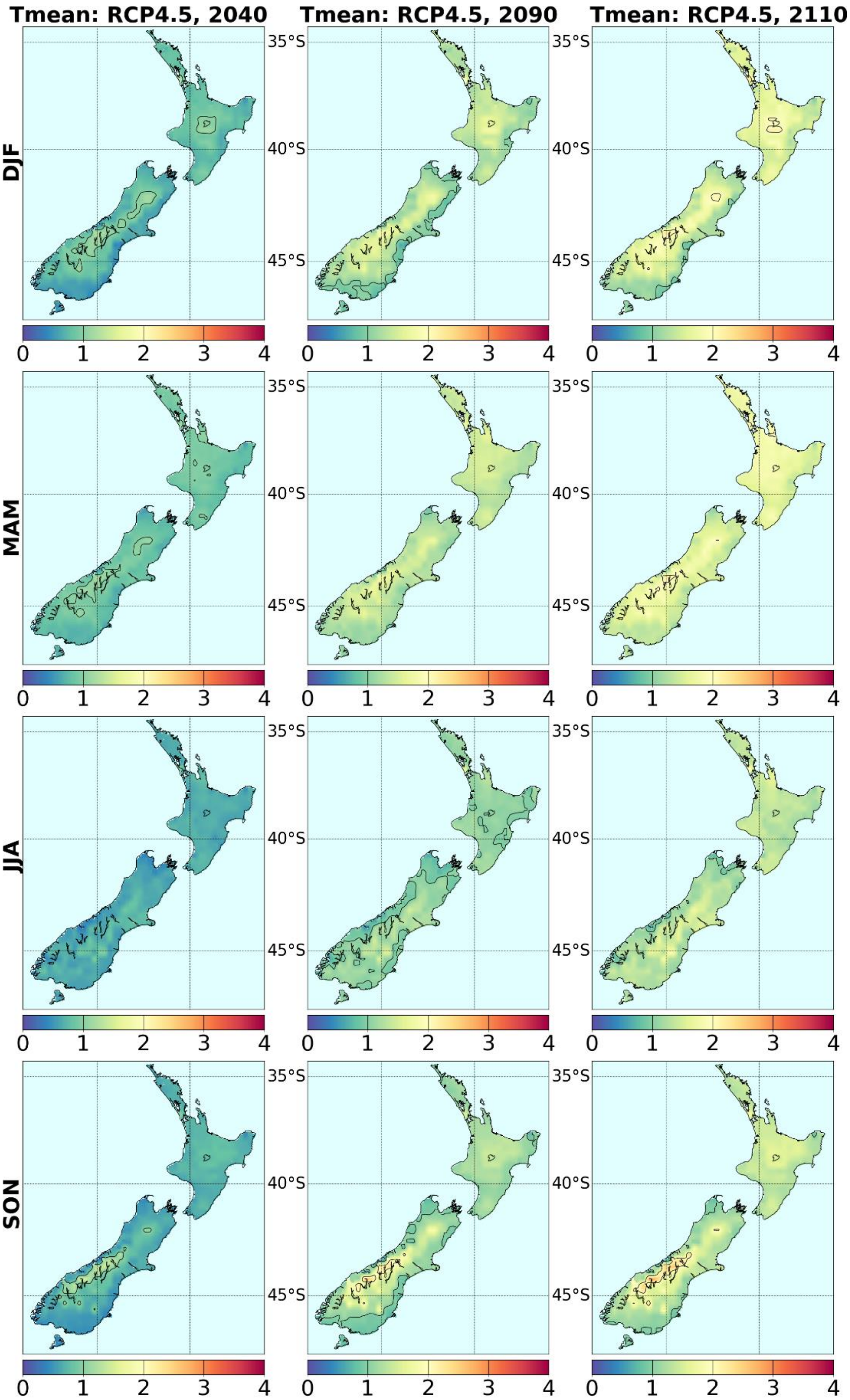
5.1.3 Water Temperature Trends

Understanding potential future changes in river water temperature is important due to the impact of water temperature on freshwater ecosystems. Some invertebrate and fish species have narrow tolerance ranges in regards to temperature, so water temperature increases influenced by climate change-related air temperature increases could have a detrimental impact on these species. Preliminary modelling work has been carried out which suggests water temperature in New Zealand rivers will increase with projected climate change-induced air temperature increases (Doug Booker, NIWA, pers. comm.). The amount of warming will vary depending on river elevation, catchment size, water source and so on.

According to the IPCC (Reisinger et al., 2014), there is high confidence that climate change is already affecting the oceans around New Zealand, with warming observed in the Tasman Sea off northern New Zealand. The western Tasman Sea is warming at a rate of four times the global average due to changes in the East Australian Current (Royal Society of New Zealand, 2016).

5.1.4 Northland compared with other regions: Temperature

New Zealand-wide temperature projections for RCP 4.5 and RCP 8.5 for 2040 and 2090 are presented in Figure 5-6. These projections, based on the larger ensemble of CMIP5 models, have been dynamically downscaled with NIWA's Regional Climate Model. For all seasons and all RCPs in Figure 5-6, the general warming signal has north-south and east-west gradients, with the strongest warming (compared to 1986-2005) over the north eastern North Island (including Northland). Strong warming is also evident over higher elevations in all seasons, but is most prominent in spring and summer. Across the country, winter is the season where the least warming is observed. The warming trend is not observed to abate in any season for the scenarios illustrated.


Tmean: RCP4.5, 2040
Tmean: RCP4.5, 2090
Tmean: RCP4.5, 2110
DJF
MAM
JJA
SON
35°S
40°S
45°S
0 1 2 3 4

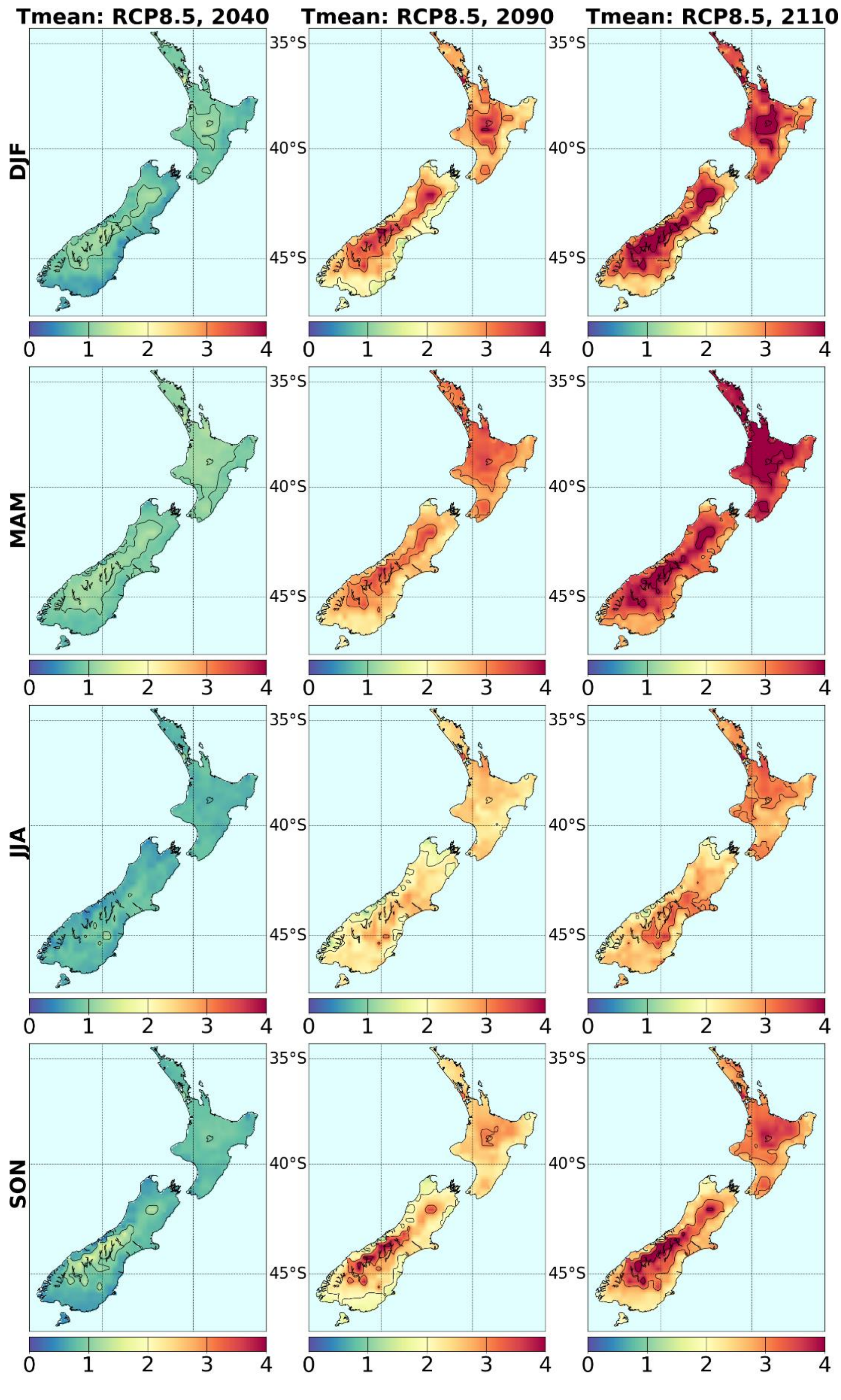
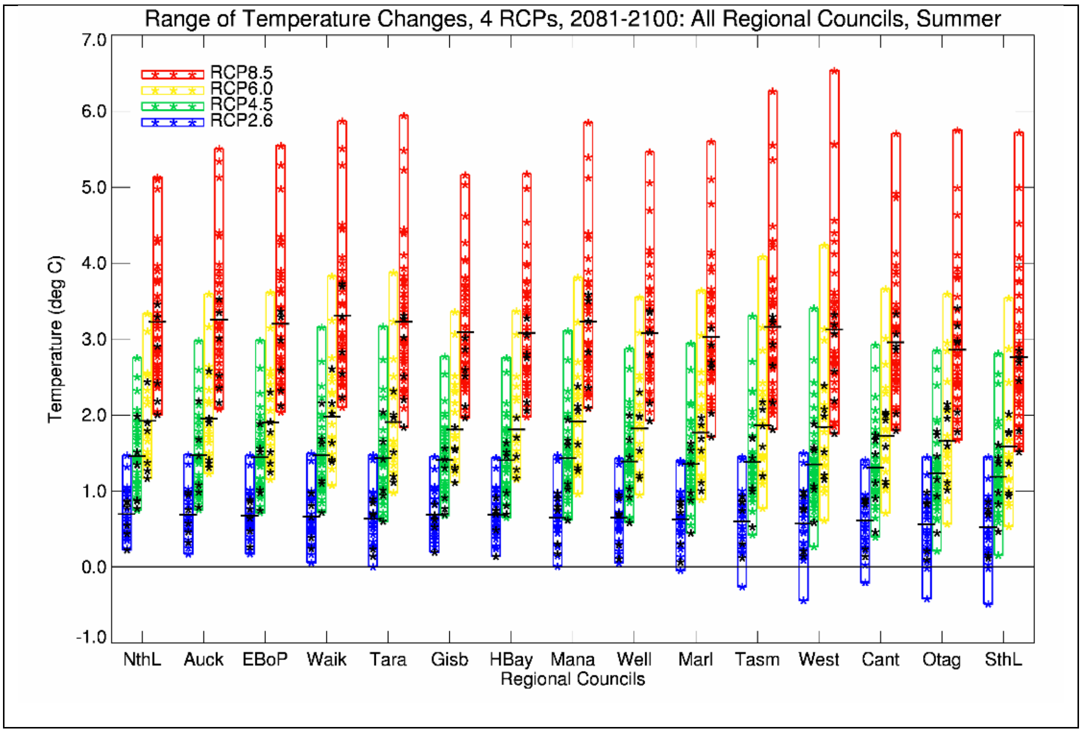


Figure 5-6: Seasonal changes in mean temperature (in °C), for three future time periods under RCP 4.5 (top panel) and RCP 8.5 (bottom panel). Derived by downscaling CMIP5 models via NIWA's Regional Climate Model. After Mullan et al. (2016).

Illustrated by Figure 5-7 are the temperature projections for the summer and winter seasons and RCPs, for the two time periods of 2040 and 2090, for all regional council regions. The temperature changes are averaged over all VCSN grid-points within the regional council region. The coloured vertical bars, and inset stars, show all the individual models, so the complete range is displayed. Figure 5-7 is an excellent way of not only demonstrating the difference with season and RCP, but also the range of model sensitivity. The black stars within each vertical bar represent the results of the six RCM simulations; the RCM projections tend to be in the lower half of the statistically-downscaled results, owing to the bias-correction applied to the raw RCM output.

Having all the regions on one graph in Figure 5-7 makes it easy to compare the range of projections in different regions of New Zealand. There is not a great deal of difference between regions for temperature, but it is apparent that the north of the country warms slightly faster than the south (see black horizontal bars for model averages), but also that some southern regions have a larger uncertainty in the projected change (longer bars). The model uncertainty range for the lower RCP 2.6 pathway crosses zero in all South Island regions in summer, indicating that at least one model simulates similar temperatures to the current climate.

If the IPCC Fifth Assessment "likelihood" definitions (IPCC, 2013) are applied to the temperature projections, and the model spread is used to calculate the probabilities of a particular outcome, then it can be said that a rise in temperature above the present-day is *virtually certain* (99-100% probability) for almost all locations and seasons at 2040 and 2090. There are a few exceptions for the 2090 projections under the RCP 2.6 pathway where a warmer future is *very likely* (90-100%); for example, all South Island regions in the summer season (Figure 5-7). Obviously, other temperature thresholds could be assessed in the same way.



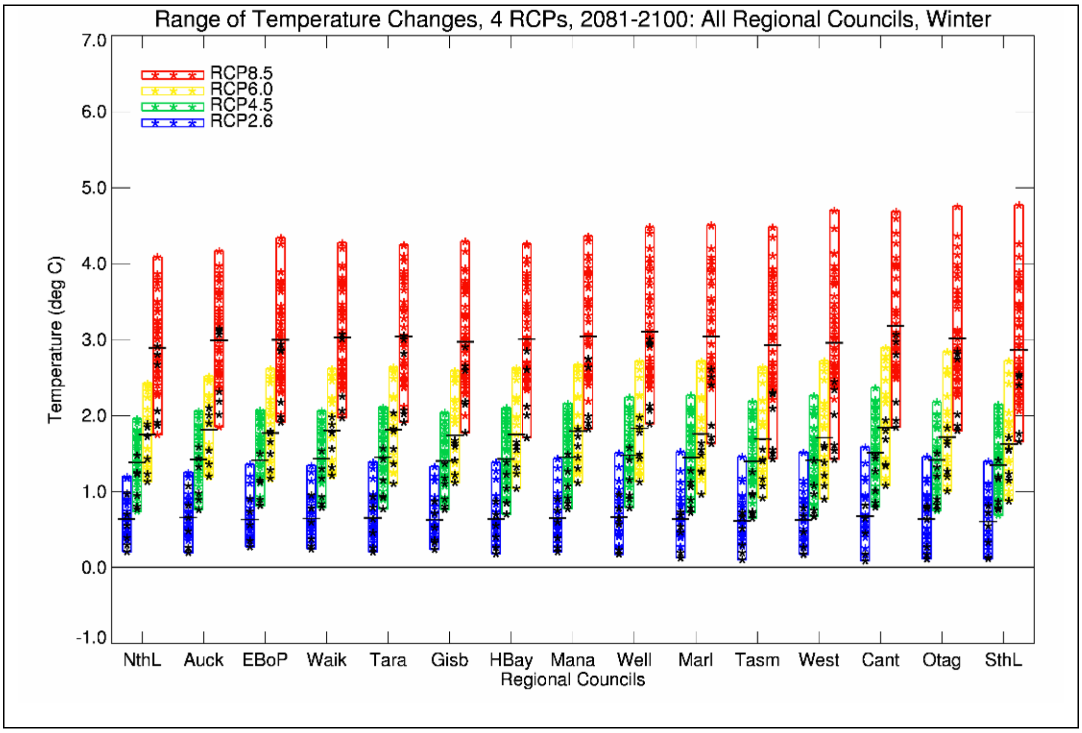


Figure 5-7: Projected temperature changes for all Regional Council area for 2090, for summer (top panel) and winter (bottom panel) seasons, for all RCPs (bars) and all models (coloured stars), as derived by statistical downscaling. The black stars correspond to the 6-model RCM-downscaling. The Regional Council abbreviations (in order) represent: Northland, Auckland, Environment Bay of Plenty, Waikato, Taranaki, Gisborne, Hawkes Bay, Horizons Manawatu-Wanganui, Wellington, Marlborough, Tasman (including Nelson City), West Coast, Environment Canterbury, Otago, and Southland. After Mullan et al. (2016).

5.2 Projections for Frosts and Hot Days under Climate Change

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

For this report, high temperature extremes (i.e. ‘hot days’) are considered as the number of days per year of 25°C or above, and low temperature extremes (i.e. ‘cold nights’ or frosts) are considered as the number of nights per year of 0°C or below. These extremes were determined by adding the monthly statistically downscaled temperature offsets to the daily VCSN[2] maximum temperature (for ‘hot days’) and to daily VCSN minimum temperature (for ‘cold nights’) for each model; then counting the exceedances (greater than or equal to 25°C, or less than or equal to 0°C, for hot days and cold nights, respectively) for the selected RCP and time period. Finally the changes were averaged over the number of years (20) and the number of models (37 for RCP 4.5 and 41 for RCP 8.5).

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

The projected increase in the number of hot days per year at 2040 (2031-2050) and 2090 (2081-2100) relative to 1986-2005, for RCP 4.5 and RCP 8.5 is shown in Figure 5-8. At 2040 under RCP 4.5 there is projected to be increases in the number of hot days for up to 20 days across most of the region, with up to 30 days increase along the eastern coastal margin and up to 10 days increase in the hill country of the central west of the region. Under RCP 8.5 at 2040, most of the region is expected to have increases in hot days of up to 30 days per year. By 2090 under RCP 4.5, most of the northern, eastern and southern part of the region is projected to experience up to 40 more hot days per year. Under RCP 8.5 at 2090, the north of the region and the east coast north of the Bay of Islands is expected to experience up to 90 more hot days per year, and most of the rest of the region up to 80 more hot days per year. The western hill country north of Dargaville is projected to experience up to 50 more hot days per year under this scenario.

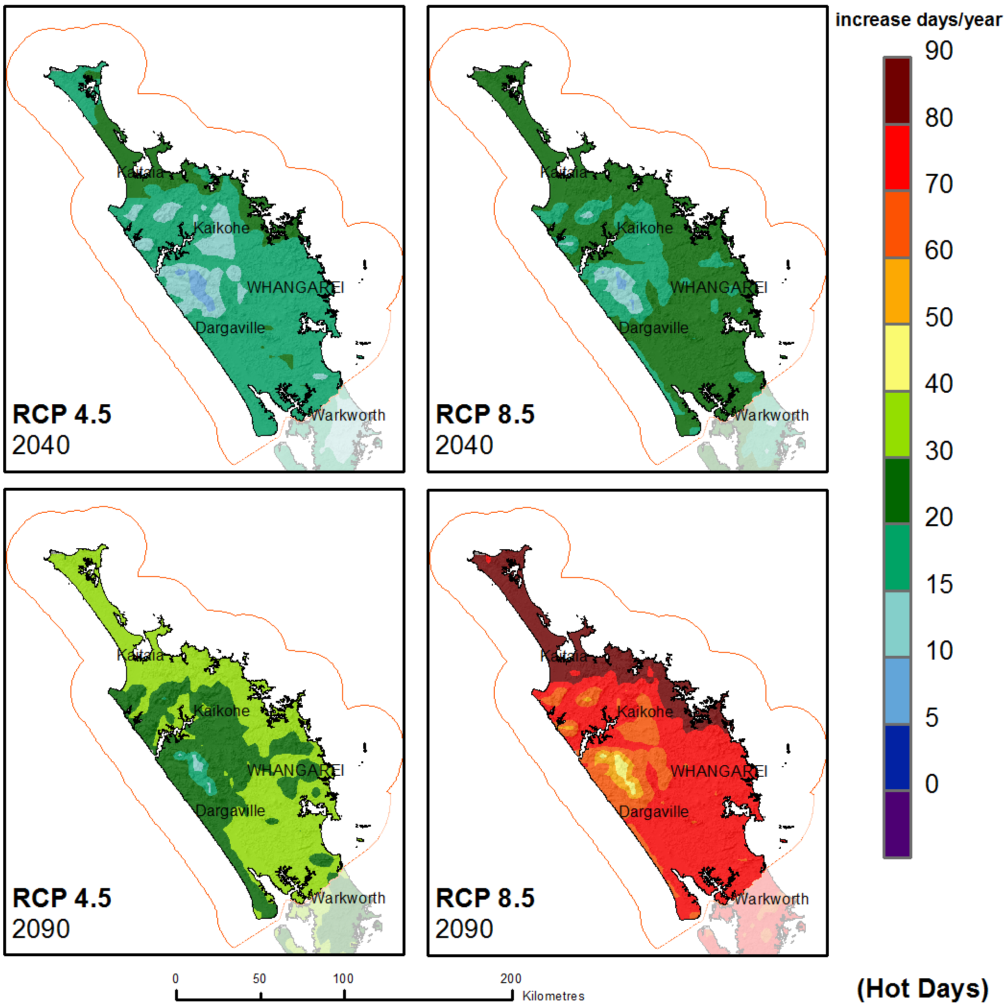


Figure 5-8: Projected increase in number of hot days per year (Tmax >25°C) at 2040 & 2090 for RCP 4.5 (left panels) and RCP 8.5 (right panels), for Northland Region. Projected change in hot days is relative to 1986-2005. The numbers on the scale refer to the *increase* in the number of hot days, e.g. the north-east coast of Northland is projected to experience an increase in the number of hot days by 80-90 days by 2090 under RCP8.5 (lower right panel). © NIWA.

At present, Northland does not experience many frosts (minimum temperatures below 0°C). The current frequency of frosts over the whole region on average is 0.5 cold nights per year, or one every two years (this varies at the local scale). Figure 5-9 shows the projected decrease in cold nights per year over the Northland region. Table 5-2 shows that projections suggest a decrease in the annual number of cold nights (or frosts) on average across Northland Region, with a decrease from one frost every two years during 1986-2005 to one frost every five years by 2040 under RCP 4.5 and RCP 8.5, and one frost day every ten years by 2090 under both RCPs. In many parts of the region, frosts will no longer occur by the late 21st century.

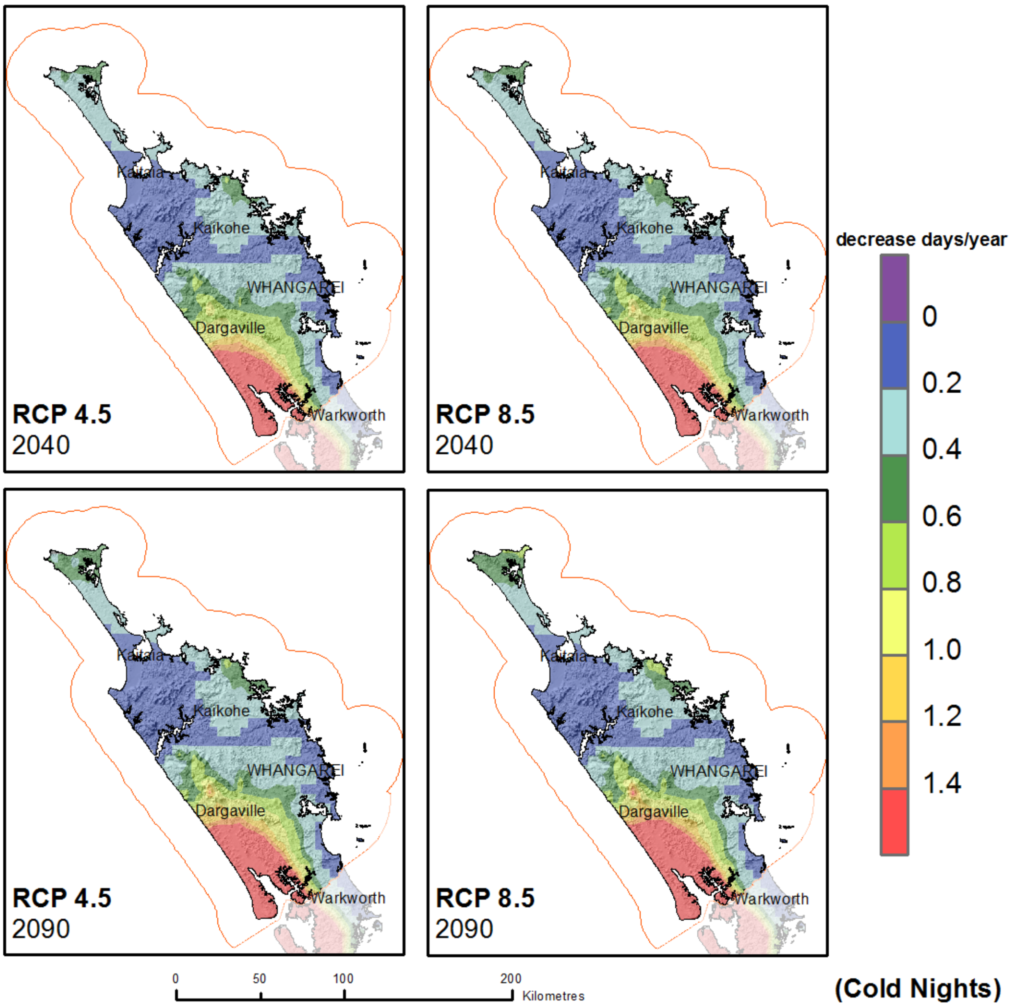


Figure 5-9: Projected decrease in number of cold nights per year (Tmin <0°C) at 2040 & 2090 for RCP 4.5 (left panels) and RCP 8.5 (right panels). Projected change in cold nights is relative to 1986-2005. The numbers on the scale refer to the *decrease* in the number of cold nights, e.g. the south-west part of Northland is projected to experience a decrease in the number of cold nights by over 1.4 nights per year by 2090 under both RCP 4.5 and RCP 8.5 at 2040 and 2090. © NIWA.

The number of hot days is projected to increase significantly, with perhaps 74 more hot days by 2090 under RCP 8.5 (an increase from 25 days per year during 1986-2005 to 99 days per year during 2081-2100 under RCP 8.5). The values in Table 5-2 are a calculated average over the Northland Region for all VCSN points below 500m altitude; hence the projected changes are lower (or higher) than some of the local-scale changes in Figure 5-8.

There is a much higher chance of extended heatwaves in Northland under both RCPs towards the end of the 21st century, with the number of hot days doubling under RCP 4.5 at 2090 and quadrupling under RCP 8.5 at 2090, compared with the historical period (Table 5-2).

Table 5-2: Projected changes in the number of hot days and cold nights (frosts) at 2040 and 2090 for Northland Region. Model results from RCP 4.5 and RCP 8.5 are compared to the historical period (1986-2005). The projected changes were averaged over all VCSN points across the Northland Region below 500m elevation. After Mullan et al. (2016).

		Historical period days	2040 number of days	2040 change	2090 number of days	2090 change
Hot days	**RCP 4.5**	25	42	+17	55	+30
	RCP 8.5		46	+21	99	+74
Cold nights	**RCP 4.5**	0.5	0.2	-0.3	0.1	-0.4
	RCP 8.5		0.2	-0.3	0.1	-0.4

5.2.1 Northland compared with other regions: Hot Days and Cold Nights

The spatial distribution of the changes in hot days and cold nights across New Zealand is shown in Figure 5-10, for the present day and at 2090 for the most extreme warming pathway (RCP 8.5). The largest increase in hot days occurs for the northern half of the North Island and for coastal Gisborne and Hawkes Bay. Frosty nights continue to occur at higher altitudes in both the North and South Islands.

A breakdown of hot day and cold night projections is shown in Table 5-3 and Table 5-4 for regional council regions of New Zealand, by RCP, for two different time periods (tables from Mullan et al. (2016)). “Hot days” increase everywhere and with all RCPs. For example (Table 5-3), in the Northland region at 2090, the number of hot days increases by 13 days (~52% increase) for RCP 2.6, and by 75 days per year under RCP 8.5 (over 4 times as many hot days as occur currently). By 2090 under RCP 8.5, Southland is projected to have as many hot days as Northland does in the current climate (about 24 days per year). As with the mean temperature change, the increase in hot days is most pronounced in northern North Island. At present, Northland has the 4th-highest number of hot days per year (after Hawke’s Bay, Canterbury, and Gisborne). However, at 2090 under all RCPs, Northland is expected to have the highest number of hot days of any region in the country.

Conversely, the frequency of cold days (or cold nights) decreases everywhere, varying from a typical reduction of about 50% at 2090 under RCP 2.6, through to a 70-80% reduction throughout the South Island under RCP 8.5 at 2090 (Table 5-4, Figure 5-10). There is no need, of course, for a seasonal breakdown to be shown: the hot days will occur in the summer (December-February), with extensions to the shoulder seasons of autumn and spring in some instances; the cold nights will likewise be concentrated in the winter months (June-August).

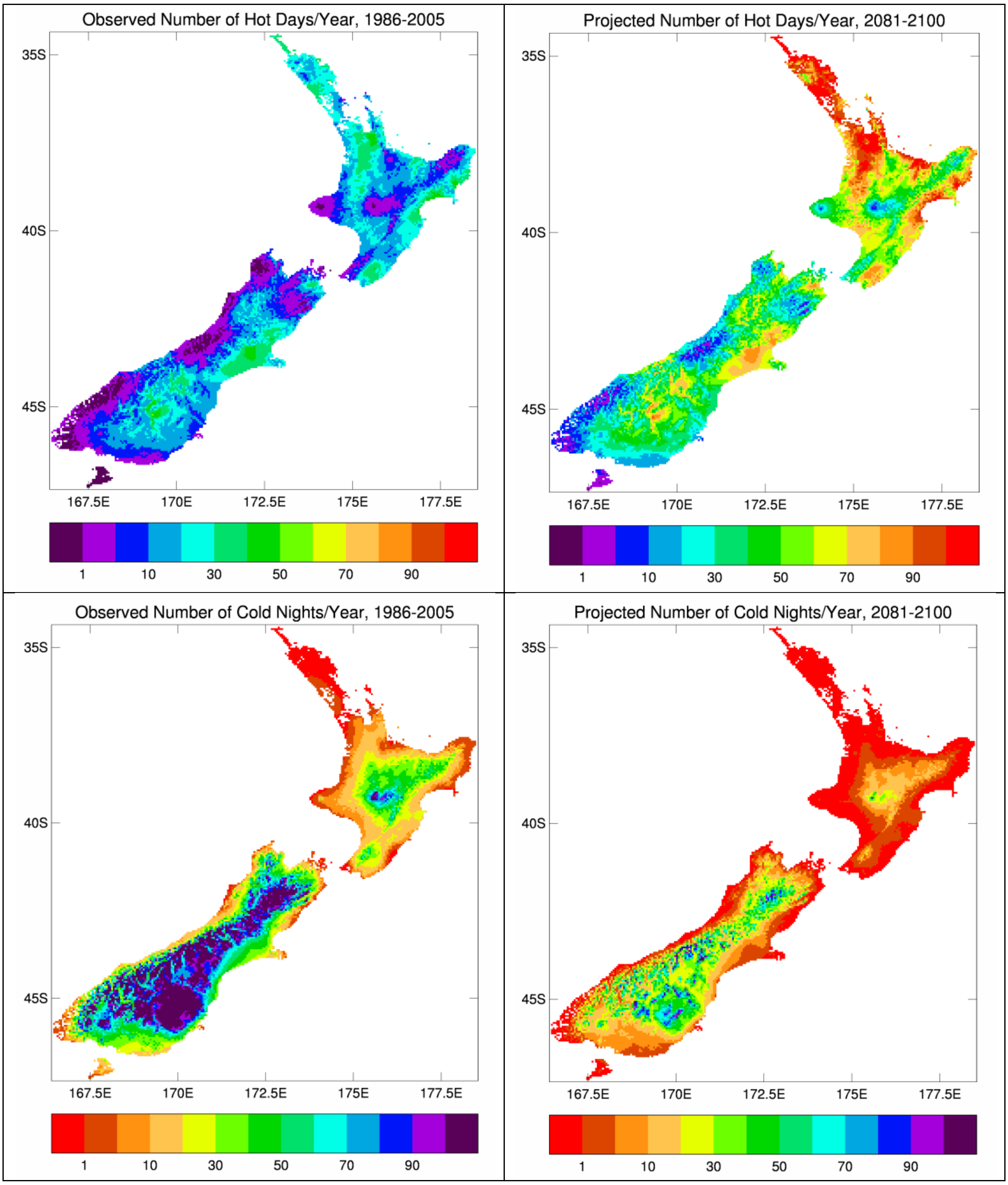


Figure 5-10: Number of days per year of "hot days" (maximum temperature of 25°C or above, top row) and "cold nights" (minimum temperature of 0°C or below, bottom row): 'current' climate (1986-2005), left; 2090 climate under RCP8.5 (right). After Mullan et al. (2016).

Table 5-3: Average number of "Hot Days" per year (maximum temperature ≥25°C), by Region, for the present day (1986-2005) and for two future periods (2040, 2090) under the four RCPs. The averages are calculated over all models but only for VCSN grid-points below 500m altitude. Results are based on statistical downscaled projections. After Mullan et al. (2016).

Council	Present	2031-2050 period				2081-2100 period			
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Northland	24.5	38.1	42.1	41.1	46.0	37.2	55.1	67.3	99.3
Auckland	19.7	32.0	35.5	34.8	39.1	30.7	47.6	59.3	89.7
Bay of Plenty	16.3	26.1	28.6	28.4	31.8	25.1	38.6	48.4	75.6
Waikato	23.6	34.9	37.8	37.5	40.9	33.3	47.8	57.7	84.0
Taranaki	6.5	12.0	13.5	13.4	15.3	11.1	19.7	26.6	47.7
Gisborne	24.2	32.7	35.2	34.5	37.8	32.3	43.6	51.5	75.5
Hawkes Bay	27.5	36.3	38.8	38.2	41.6	36.1	47.6	55.2	78.1
Manawatu	18.6	26.9	29.0	28.8	31.3	25.7	36.7	44.2	65.5
Wellington	20.1	26.8	28.6	28.3	30.6	26.3	35.2	41.3	60.1
Marlborough	14.0	19.7	21.2	21.0	23.0	19.3	27.3	33.1	51.8
Tasman	11.0	17.1	18.5	18.7	20.5	16.0	25.2	32.5	53.9
West Coast	8.0	12.3	13.1	13.4	14.4	11.3	17.7	23.1	39.4
Canterbury	27.3	33.5	34.8	34.6	36.8	33.1	40.9	45.9	62.3
Otago	17.8	21.9	22.6	22.7	23.9	21.4	26.8	30.3	42.3
Southland	7.6	10.1	10.5	10.6	11.3	9.7	13.1	15.5	24.0

Table 5-4: Average number of "Cold Nights" per year (minimum temperature ≤0°C), by Region, for the present day (1986-2005) and for two future periods (2040, 2090) under the four RCPs. The averages are calculated over all models but only for VCSN grid-points below 500m altitude. Results are based on statistical downscaled projections. After Mullan et al. (2016).

Council	Present	2031-2050 period				2081-2100 period			
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Northland	0.5	0.2	0.2	0.2	0.2	0.3	0.1	0.1	0.1
Auckland	1.9	0.9	0.8	0.9	0.7	1.0	0.5	0.3	0.1
Bay of Plenty	17.3	11.5	10.3	10.9	9.2	11.9	7.3	5.7	2.3
Waikato	15.2	10.3	9.2	9.7	8.2	10.6	6.5	5.0	1.9
Taranaki	6.3	3.1	2.5	2.8	2.0	3.3	1.4	0.9	0.2
Gisborne	8.5	4.9	4.2	4.6	3.6	5.1	2.7	2.0	0.7
Hawkes Bay	16.0	10.1	8.9	9.4	7.8	10.4	5.9	4.4	1.2
Manawatu	18.2	12.0	10.6	11.3	9.4	12.4	7.2	5.5	1.7
Wellington	14.4	9.0	7.8	8.4	6.8	9.3	5.1	3.8	1.1
Marlborough	21.7	14.5	13.0	13.8	11.6	15.0	9.2	7.3	2.8
Tasman	36.2	26.8	24.8	25.7	22.9	27.4	19.3	16.3	8.2
West Coast	21.0	13.6	12.1	12.9	10.7	14.1	8.4	6.7	2.6
Canterbury	46.7	33.7	30.9	32.3	28.1	34.2	23.4	19.4	8.8
Otago	64.6	51.0	48.0	49.6	45.0	51.3	39.4	34.8	20.1
Southland	37.0	26.4	24.1	25.4	22.0	26.7	18.2	15.4	7.0

5.3 Northland Climate Change Precipitation Projections

Precipitation projections show more spatial variation than the temperature projections. Again, the magnitude of the projected change will scale up or down with the different RCPs, and will also differ between climate models. Figure 5-11 and Figure 5-12 show the projected seasonal patterns of precipitation change over the Northland Region and surrounding areas at 2040 and 2090 for RCP 4.5 (averaging 37 climate models), and Figure 5-13 and Figure 5-14 show the same for RCP 8.5 (averaging 41 climate models).

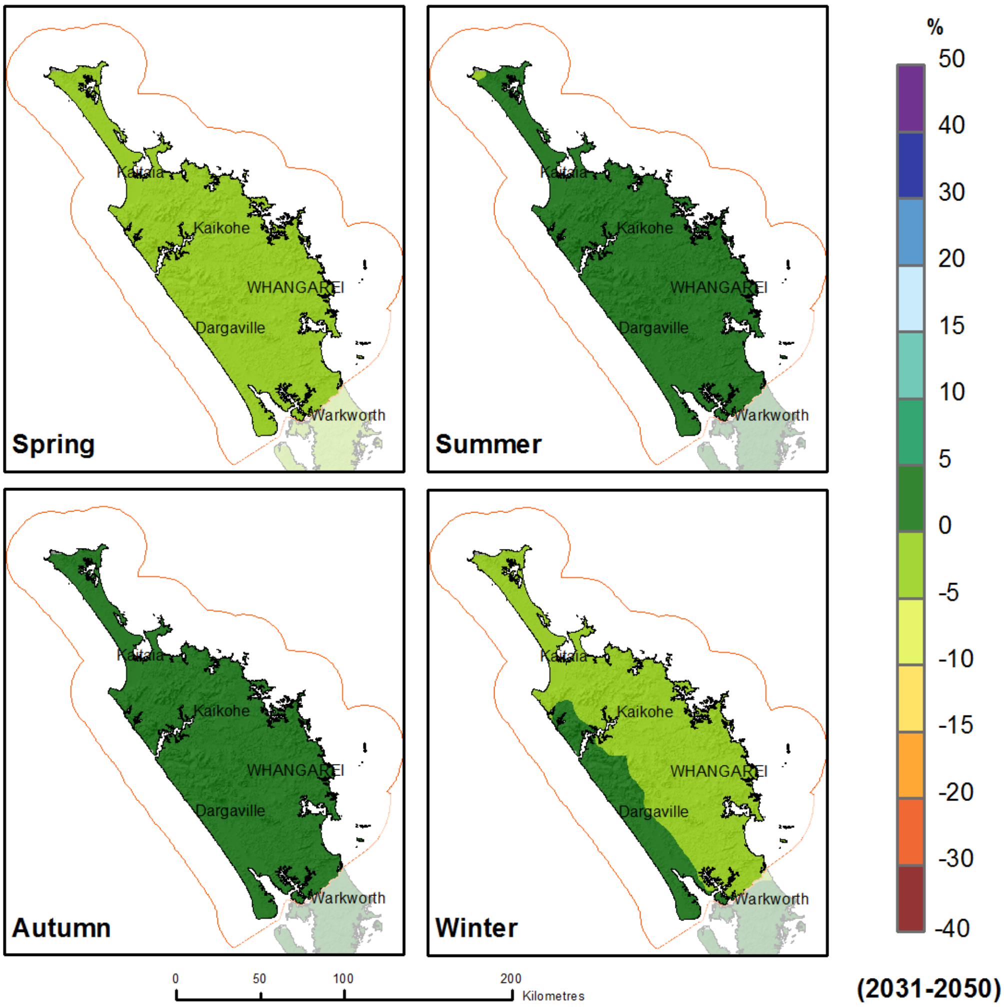


Figure 5-11: Projected seasonal precipitation changes (in %) at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP 4.5 scenario, averaged over 37 climate models. ©NIWA.

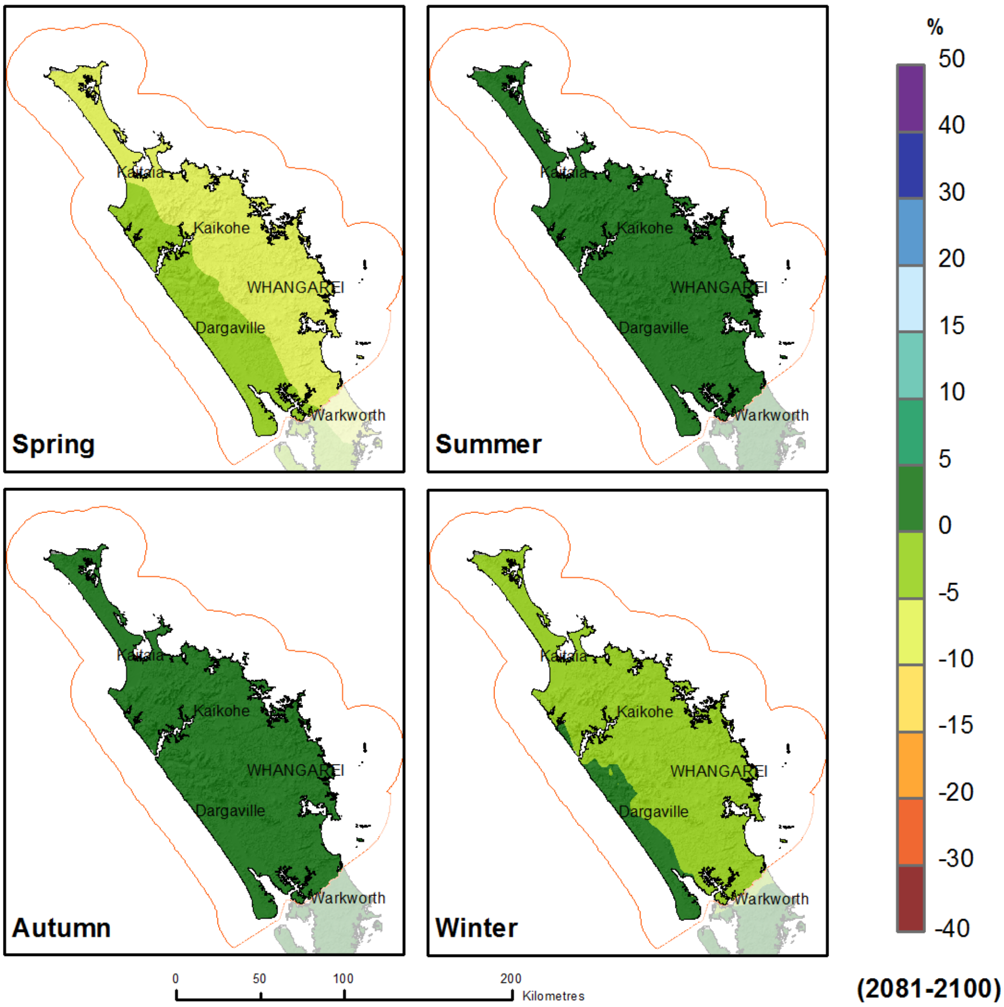


Figure 5-12: Projected seasonal precipitation changes (in %) at 2090 (2081-2100 average). Relative to 1986-2005 average, for the RCP 4.5 scenario, averaged over 37 climate models. ©NIWA.

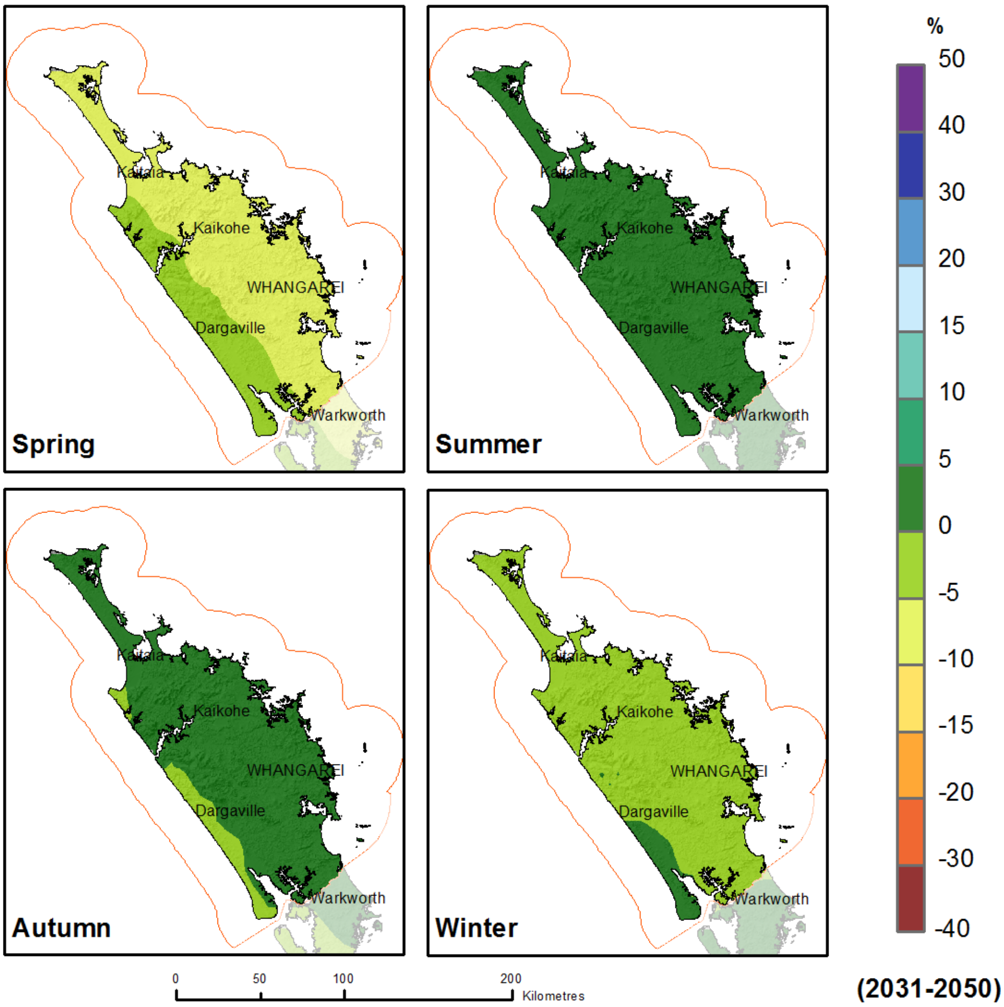


Figure 5-13: Projected seasonal precipitation changes (in %) at 2040 (2031-2050 average). Relative to 1986-2005 average, for the IPCC RCP 8.5 scenario, averaged over 41 climate models. ©NIWA.

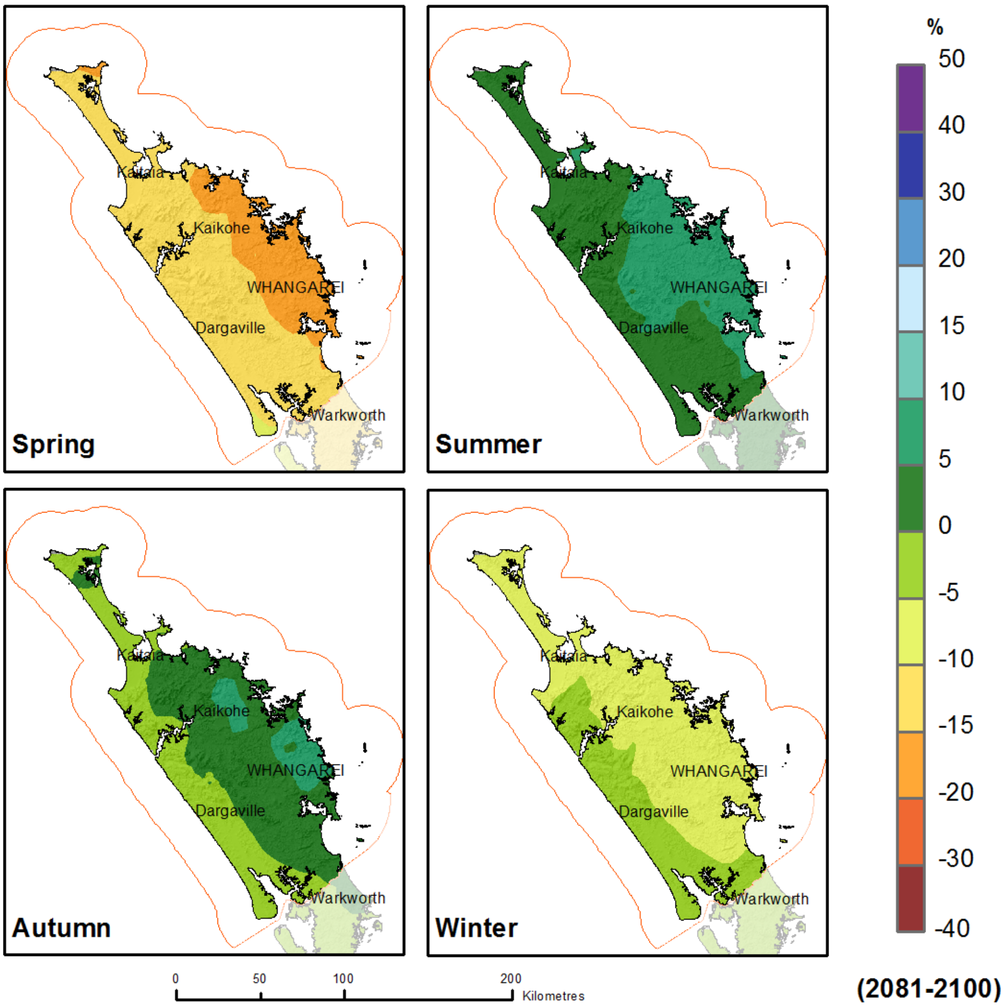


Figure 5-14: Projected seasonal precipitation changes (in %) at 2090 (2081-2100 average). Relative to 1986-2005 average, for the IPCC RCP 8.5 scenario, averaged over 41 climate models. ©NIWA.

The RCP 4.5 projections to 2040 (Figure 5-11) indicate minimal changes of within 5% (increase or decrease) in each season. By 2090 for RCP 4.5, (Figure 5-12), up to 10% less rainfall is projected across northern and eastern parts of the region in spring, but the remaining seasons show less than 5% change in precipitation (increase or decrease). For RCP 8.5 at 2040, the projections are quite similar to those of RCP 4.5 at 2090 (Figure 5-13) (up to 10% decrease in spring for northern and eastern areas and minimal change in other seasons). However, by 2090 for RCP 8.5, significant changes are evident (Figure 5-14), with the largest decreases in precipitation projected in spring (up to 20% decrease for eastern areas and 15% decrease elsewhere). Precipitation may decrease by up to 10% in eastern and northern parts of Northland in winter by 2090. In contrast, autumn and summer precipitation may increase by up to 10% in eastern areas by 2090 under RCP 8.5.

The full range of model-projected precipitation change (in %) is given for Kaitaia and Whangarei. Model-projected changes are given for 2031-2050 (2040) in Table 5-5 and for 2081-2100 (2090) in Table 5-6. The precipitation changes are relative to the baseline period 1986-2005. Hence the projected changes at 2040 and 2090 should be thought of as 45-year and 95-year trends.

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

Region	Summer	Autumn	Winter	Spring	Annual
Kaitaia					
rcp 8.5	1 (-6, 13)	1 (-6, 10)	-1 (-12, 7)	-5 (-12, 4)	-1 (-8, 4)
rcp 6.0	1 (-12, 24)	3 (-5, 10)	1 (-9, 7)	-3 (-12, 8)	0 (-5, 8)
rcp 4.5	1 (-12, 14)	2 (-7, 3)	0 (-11, 8)	-3 (-12, 8)	0 (-6, 5)
rcp 2.6	1 (-8, 12)	1 (-5, 10)	1 (-5, 7)	-2 (-11, 6)	0 (-3, 5)
Whangarei					
rcp 8.5	1 (-8, 10)	2 (-7, 13)	-2 (-15, 10)	-7 (-16, 5)	-2 (-8, 5)
rcp 6.0	2 (-12, 25)	4 (-10, 13)	-2 (-17, 11)	-3 (-19, 14)	0 (-7, 11)
rcp 4.5	1 (-12, 13)	3 (-9, 17)	-2 (-15, 9)	-4 (-18, 10)	-1 (-7, 6)
rcp 2.6	1 (-8, 13)	1 (-9, 10)	0 (-14, 11)	-4 (-17, 8)	-1 (-7, 6)

Table 5-6: Projected changes in seasonal and annual precipitation (in %) between 1986-2005 and 2081-2100. for selected locations within the Northland region, as derived from statistical downscaling. The changes are given for four RCPs (8.5, 6.0, 4.5 and 2.6), where the ensemble-average is taken over (41, 18, 37, 23) models respectively. The values in each column represent the ensemble average, and in brackets the range (5 percentile to 95 percentile) over all models within that ensemble. After Mullan et al. (2016).

Region	Summer	Autumn	Winter	Spring	Annual
Kaitaia					
rcp 8.5	4 (-14, 29)	0 (-12, 9)	-6 (-19, 8)	-12 (-27, 1)	-4 (-14, 7)
rcp 6.0	6 (-13, 28)	4 (-4, 21)	0 (-15, 15)	-5 (-17, 6)	1 (-10, 9)
rcp 4.5	2 (-12, 19)	2 (-6, 13)	-1 (-13, 10)	-5 (-14, 8)	-1 (-8, 6)
rcp 2.6	3 (-11, 14)	2 (-4, 11)	1 (-3, 8)	-1 (-8, 5)	1 (-2, 4)
Whangarei					
rcp 8.5	6 (-11, 30)	5 (-7, 16)	-9 (-28, 14)	-17 (-38, -2)	-4 (-15, 12)
rcp 6.0	6 (-8, 26)	4 (-10, 15)	-5 (-35, 12)	-11 (-53, 9)	-2 (-25, 8)
rcp 4.5	2 (-11, 19)	3 (-7, 16)	-3 (-25, 11)	-7 (-18, 8)	-2 (-12, 6)
rcp 2.6	2 (-12, 13)	1 (-8, 13)	-1 (-7, 10)	-3 (-14, 8)	0 (-4, 5)

The seasonal and annual ensemble average projection (the number outside the brackets) in Table 5-5 and Table 5-6 is the precipitation increase (in %) for the given locations for 2040 and 2090, respectively, averaged over all 23 models for RCP 2.6, 37 models for RCP 4.5, 18 models for RCP 6.0, and 41 models for RCP 8.5 analysed by NIWA. The bracketed numbers give the range (5th and 95th percentile) for each RCP for each season and the annual projection.

Most seasons have an unclear precipitation signal, even at 2090 under RCP 8.5. The ensemble-average is often less than ±5%, with the model range (the 5th and 95th percentile values) varying between quite large (>10%) increases and decreases. By 2040 (2031-2050, relative to 1986-2005), spring is the season with the most precipitation change, with a small decrease in the ensemble-average at most locations (up to 7% at Whangarei under RCP 8.5).

By 2090 (2081-2100, relative to 1986-2005), there is a slightly clearer precipitation signal. For both locations, spring is still the season with the most precipitation change, with Whangarei projecting decreases in the ensemble average at around 17% and Kaitaia around 12% under RCP 8.5.

5.4 Temperature and precipitation comparisons within RCPs

The average picture of projected temperature and rainfall changes in the tables and maps in Sections 5.1 to 5.3 obscures significant variations between the individual models run under each RCP on the projected seasonal changes. Figure 5-15 and Figure 5-16 show seasonal temperature projections from all the models individually averaged over the Northland Region for 2040 and 2090, respectively. The coloured vertical bars, and inset stars, show the individual models, so the complete range is displayed (unlike Table 5-1, where the 5th to 95th percentile range has been calculated). Figures Figure 5-15 and Figure 5-16 show an excellent way of not only demonstrating the difference with season and RCP, but also the range of model sensitivity. The black stars within each vertical bar represent the results of the 6 Regional Climate Model (RCM) simulations; the RCM projections tend to be in the lower half of the statistically-downscaled results, owing to the bias-correction applied to the raw RCM output.

For 2040 (Figure 5-15), all four RCPs project quite similar changes on average (model-average warming – the black horizontal line on the bars – is within about 0.5°C). The models for RCP 8.5 have the greatest spread, particularly in summer (the red bar). However, the models all agree on the direction of change (i.e. warming). For 2090 (Figure 5-16), the model spread is much larger, with the models for summer for RCP 8.5 spread across over 3°C of warming (from ~2.0°C to ~5.1°C). All of the models agree on the direction of change (i.e. warming).

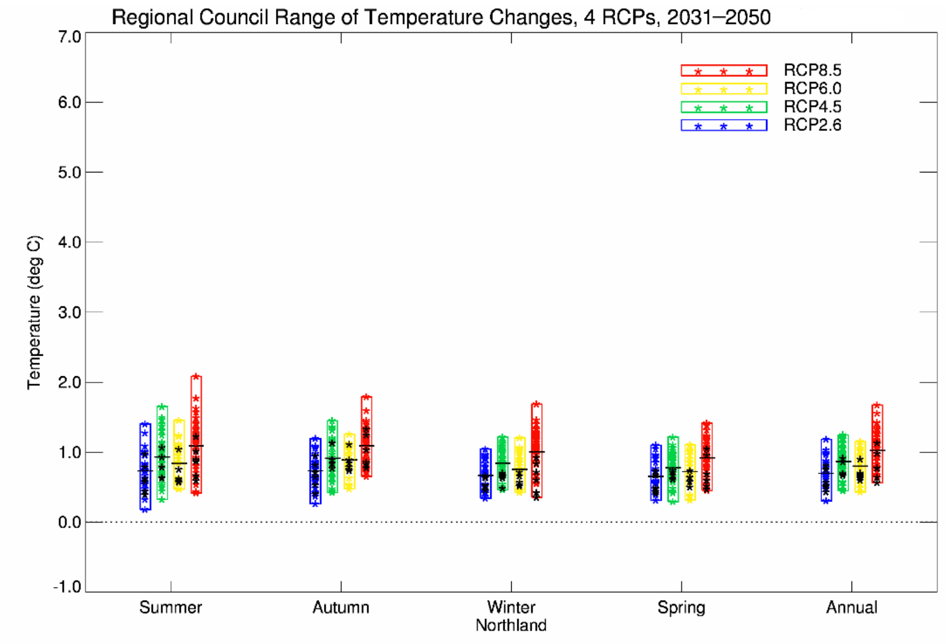


Figure 5-15: Projected seasonal temperature changes by 2040 (2031-2050) averaged over the Northland Region, for the four RCPs. The vertical coloured bars show the range over all climate models used, and coloured stars the projected changes for each model individually (results from statistical downscaling). The black stars represent the 6-model dynamical downscaling changes. The short horizontal line is the model-average warming over all statistical and dynamical models. Blue = RCP 2.6, 23 models; green = RCP 4.5, 37 models; yellow = RCP 6.0, 18 models; red = RCP 8.5, 41 models. © NIWA.

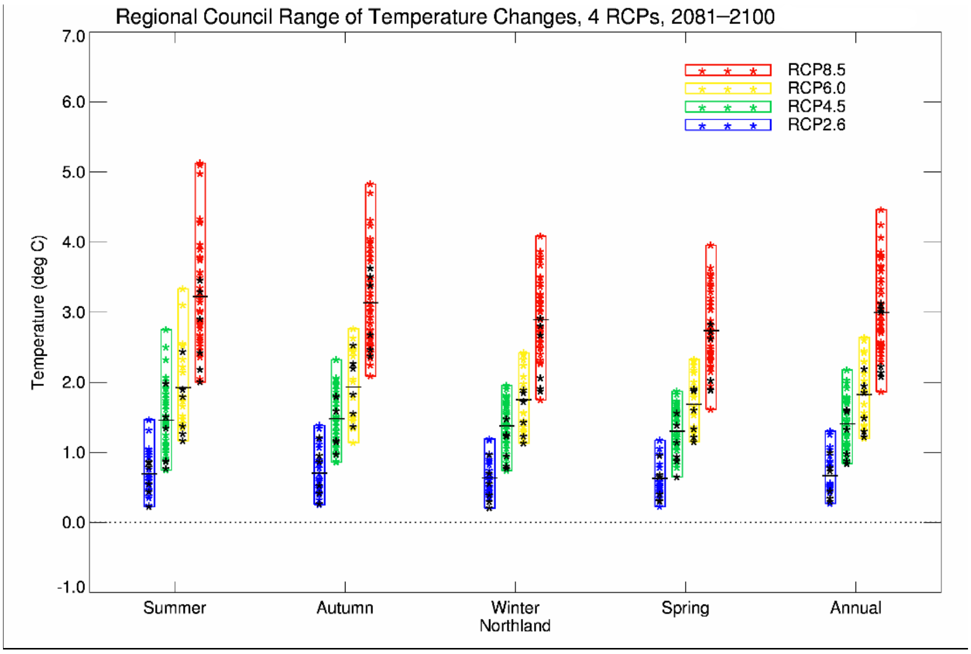


Figure 5-16: Projected seasonal temperature changes by 2090 (2081-2100) averaged over the Northland Region, for the four RCPs. The vertical coloured bars show the range over all climate models used, and coloured stars the projected changes for each model individually (results from statistical downscaling). The black stars represent the 6-model dynamical downscaling changes. The short horizontal line is the model-average warming over all statistical and dynamical models. Blue = RCP 2.6, 23 models; green = RCP 4.5, 37 models; yellow = RCP 6.0, 18 models; red = RCP 8.5, 41 models. © NIWA.

Figure 5-17 and Figure 5-18 show seasonal rainfall projections from all the models individually for the Whangarei grid point only for 2040 and 2090, respectively. There is disagreement between the models as to the direction of projected rainfall changes, as identified in Table 5-5 and Table 5-6 for the different RCPs. However, for 2040 in Figure 5-17, the model-average rainfall projections are quite similar for summer and autumn, and for winter and spring. The spread of the models under each RCP is quite large (spread across approximately -15% to +30% precipitation change for summer and autumn and -20% to +10% for winter and spring). For 2090 (Figure 5-18), the model spread under each RCP is much larger than in Figure 5-17 and the model-averages between each RCP are quite varied.

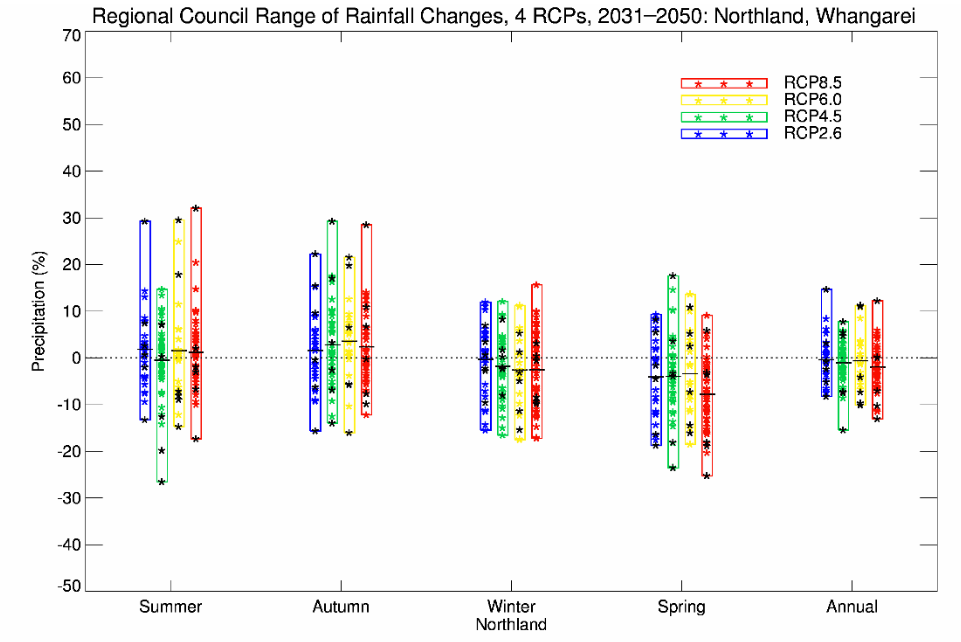


Figure 5-17: Projected seasonal rainfall changes by 2040 (2081-2100) for Whangarei, for the four RCPs. The vertical coloured bars show the range over all climate models used, and coloured stars the projected changes for each model individually (results from statistical downscaling). The black stars represent the 6-model dynamical downscaling changes. The short horizontal line is the model-average rainfall over all statistical and dynamical models. Blue = RCP 2.6, 23 models; green = RCP 4.5, 37 models; yellow = RCP 6.0, 18 models; red = RCP 8.5, 41 models. © NIWA.

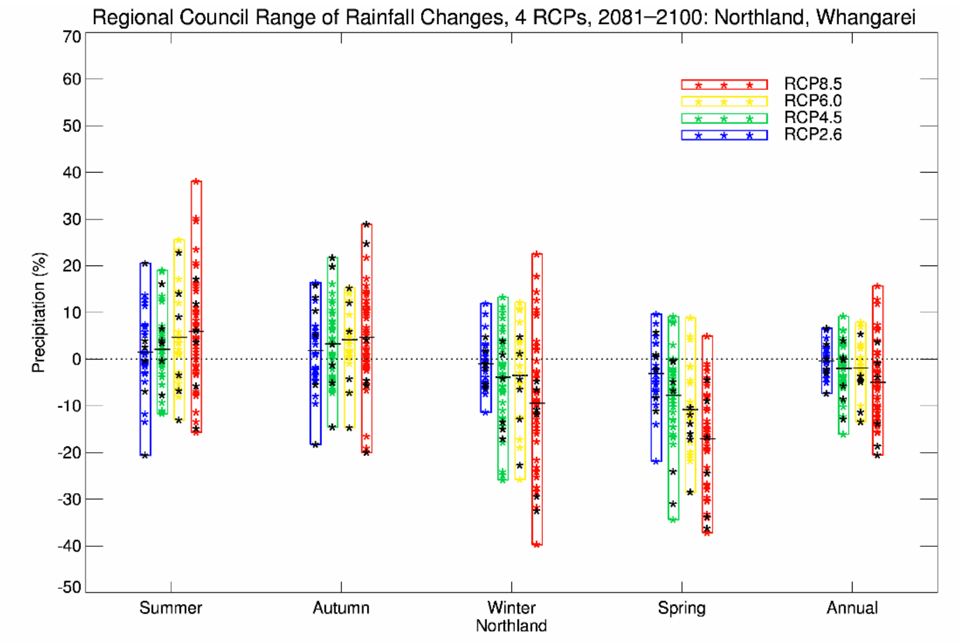


Figure 5-18: Projected seasonal rainfall changes by 2090 (2081-2100) for Whangarei, for the four RCPs. The vertical coloured bars show the range over all climate models used, and coloured stars the projected changes for each model individually (results from statistical downscaling). The black stars represent the 6-model dynamical downscaling changes. The short horizontal line is the model-average rainfall over all statistical and dynamical models. Blue = RCP 2.6, 23 models; green = RCP 4.5, 37 models; yellow = RCP 6.0, 18 models; red = RCP 8.5, 41 models. © NIWA.

Figure 5-19 and Figure 5-20 show seasonal rainfall projections from all the models individually for the Kaitaia grid point only for 2040 and 2090, respectively. The ensemble averages (black horizontal line) for all seasons are very close to zero (no change in precipitation on average). However, there is some disagreement between the individual models as to the direction and magnitude of projected rainfall changes – the spread within each RCP coloured bar is quite large, for example, ranging from a ~20% decrease to a ~40% increase in rainfall during summer for under RCP 8.5 at 2090 (Figure 5-20). The model spread is larger for Whangarei than for Kaitaia for all RCPs at both 2040 and 2090.

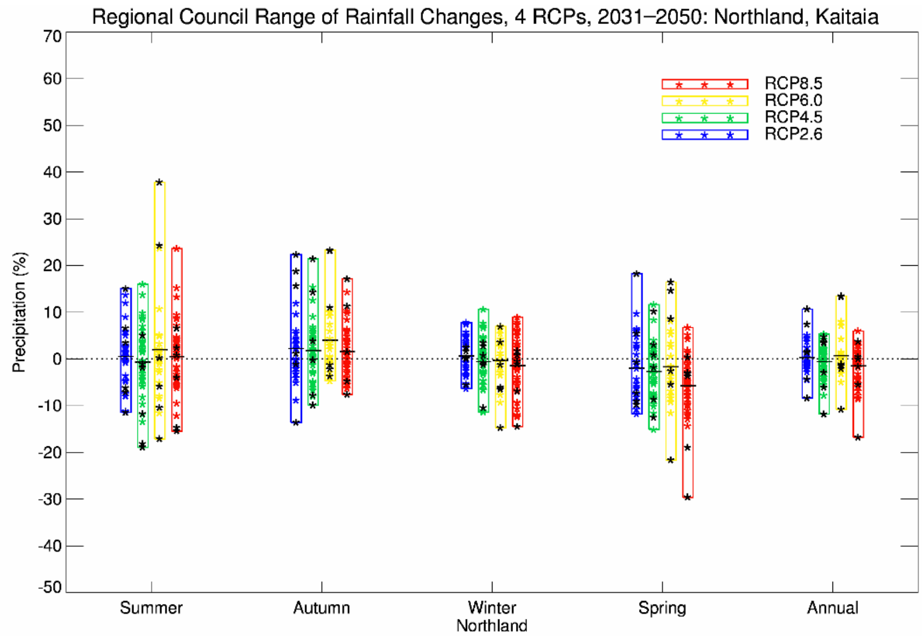


Figure 5-19: Projected seasonal rainfall changes by 2040 (2081-2100) for Kaitaia, for the four RCPs. The vertical coloured bars show the range over all climate models used, and coloured stars the projected changes for each model individually (results from statistical downscaling). The black stars represent the 6-model dynamical downscaling changes. The short horizontal line is the model-average rainfall over all statistical and dynamical models.Blue = RCP 2.6, 23 models; green = RCP 4.5, 37 models; yellow = RCP 6.0, 18 models; red = RCP 8.5, 41 models. © NIWA.

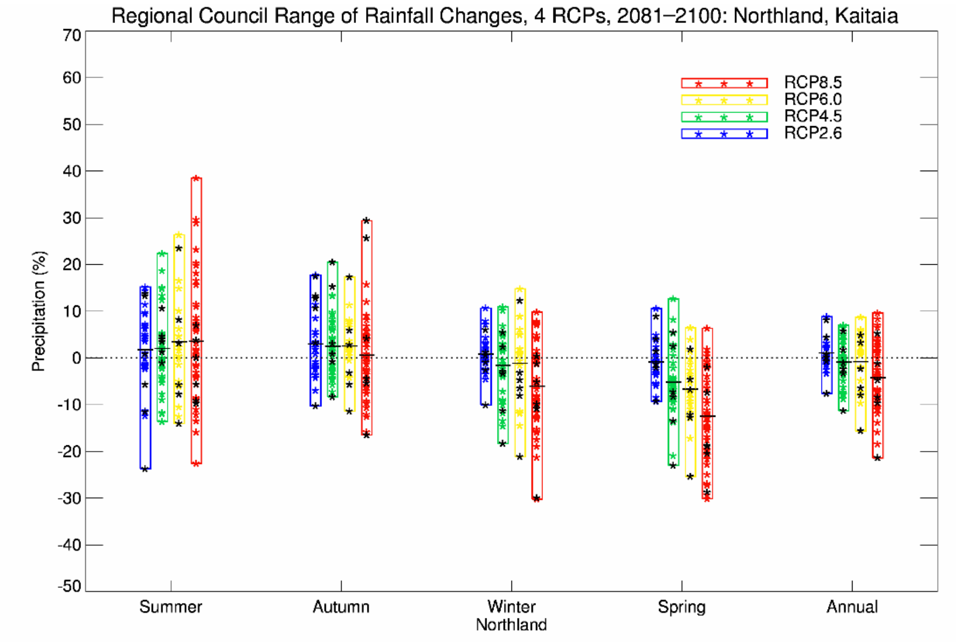


Figure 5-20: Projected seasonal rainfall changes by 2090 (2081-2100) for Kaitaia for the four RCPs. The vertical coloured bars show the range over all climate models used, and coloured stars the projected changes for each model individually (results from statistical downscaling). The black stars represent the 6-model dynamical downscaling changes. The short horizontal line is the model-average rainfall over all statistical and dynamical models. Blue = RCP 2.6, 23 models; green = RCP 4.5, 37 models; yellow = RCP 6.0, 18 models; red = RCP 8.5, 41 models. © NIWA.

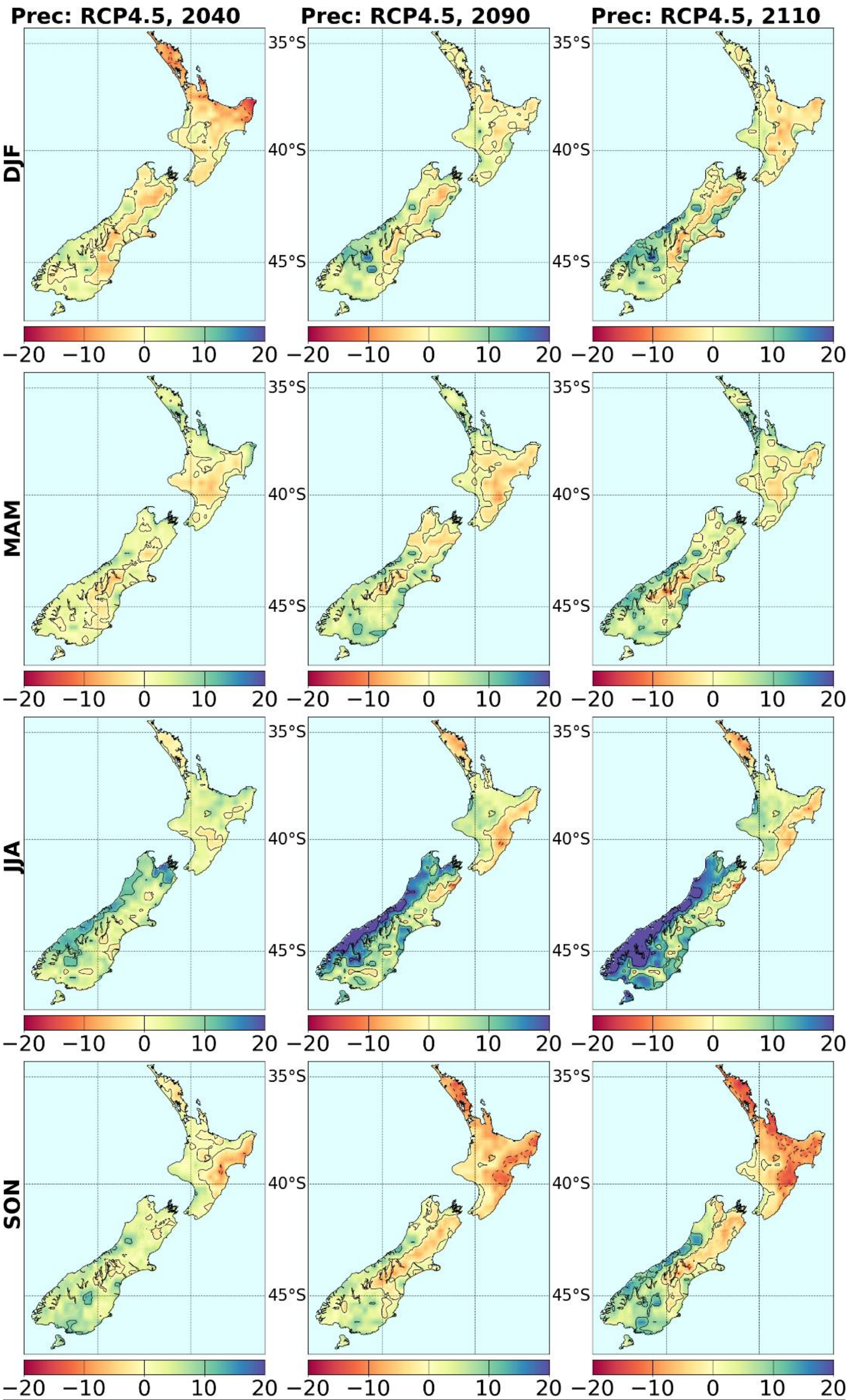
Note that Figure 5-17 to Figure 5-20 show the model variability at two grid points only (Whangarei and Kaitaia), rather than a regional average (as was done for temperature). This is because the projected changes to rainfall vary greatly over the region. These figures can be replicated for any grid point in the Northland Region, upon request.

5.4.1 Northland compared with New Zealand: Precipitation

New Zealand-wide precipitation projections for RCP4.5 and RCP8.5 for 2040 and 2090 are presented in Figure 5-21. These projections, based on the larger ensemble of CMIP5 models, have been dynamically downscaled with NIWA's Regional Climate Model. For a number of regions of New Zealand, there is no clear direction of precipitation change, even at 2090 under RCP 8.5. The ensemble-average is often smaller than ±5%, with the model range (the 5-percentile and 95-percentile model values) varying between quite large (>10%) decreases and increases. The largest changes of all occur for the West Coast of the South Island in the winter season, with area-average changes up to a 30% increase under RCP 8.5 by 2090.

The magnitudes (positive and negative) of the precipitation projections generally increase with time and with the strength of the radiative forcing (RCP). The largest precipitation changes by the end of the century are seen at the seasonal scale:

- In spring, decreases for Northland, Auckland, and Bay of Plenty, and increases for Otago (Queenstown) and Southland;
- In winter, decreases for Waikato, Gisborne, Hawke's Bay and Canterbury (Christchurch and Hanmer), and increases for Tasman-Nelson (Nelson), West Coast, Canterbury (Tekapo), Otago (Dunedin), Southland and Chatham Islands.



Prec: RCP4.5, 2040
Prec: RCP4.5, 2090
Prec: RCP4.5, 2110
DJF
MAM
JJA
SON
35°S
40°S
45°S
−20 −10 0 10 20

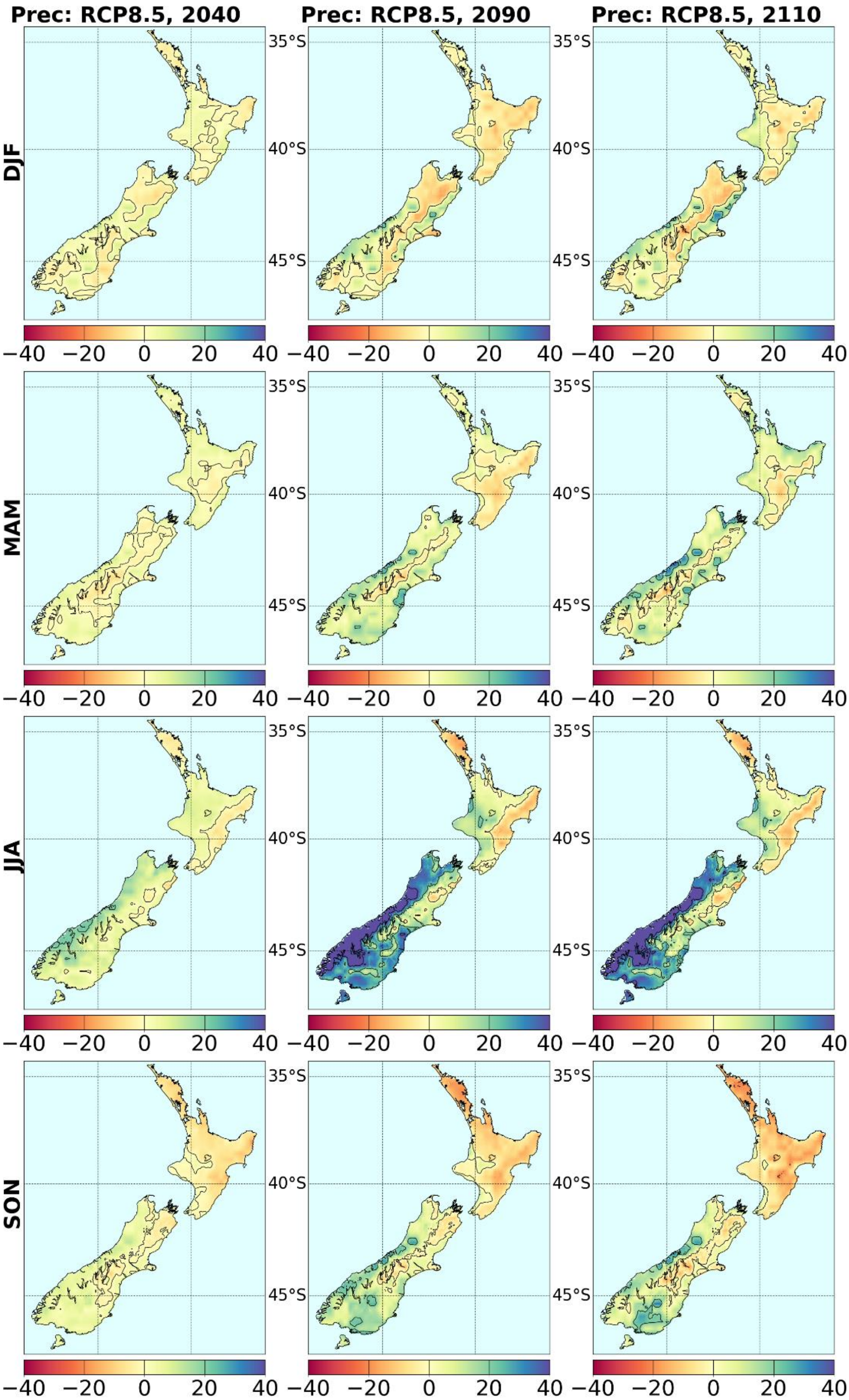


Figure 5-21: Seasonal changes in precipitation (in %) for three future time periods under RCP4.5 and RCP8.5. Derived by downscaling CMIP5 models via NIWA's Regional Climate Model. After Mullan et al. (2016).

Figure 5-22 presents a similar picture to Figure 5-21, except that the extreme seasons (summer and winter) are shown for selected sites in all regional council regions on a single graph. This makes it easy to compare the range of projections in different regions of New Zealand. It may appear that there is no clear precipitation signal anywhere, since every bar graph crosses zero (i.e., there is at least one model projecting a decrease in precipitation and at least one projecting an increase). However, a model-average change of about 10% (increase or decrease) could be considered as a significant change.

The clearest signals of change occur for the highest concentration pathway (RCP 8.5) for particular sites and seasons: for example, in summer, precipitation is most likely to increase on the east coast of the North Island (Gisborne and Hawke's Bay regions); in winter, precipitation is most likely to decrease in the same locations, but increase in Hokitika, Tekapo and Queenstown.

If the IPCC Fifth Assessment "likelihood" definitions are applied to the precipitation projections, and the model spread is used to calculate the probabilities of a particular outcome, then likelihoods of precipitation increase or decrease can be described as follows:

- Simulated 'natural variability' in the models is too large to give much of a precipitation signal at 2040. By 2090, the signal has risen above the noise in a number of locations.
- At 2090 in the summer season, it is *likely* (66-100% probability) to have increases in precipitation, especially at higher greenhouse gas concentrations, at: Kaitaia, Whangarei, Tauranga, Taihape, Gisborne, Napier, Masterton, Blenheim, Nelson, Christchurch, Hanmer, Tekapo, Dunedin, and Queenstown. Nowhere, are there higher likelihoods (i.e., *very likely* or higher) of a precipitation increase.
- In summer at 2090, none of the sites in Figure 5-22 are *likely* to receive decreased precipitation.
- At 2090 in the winter season, it is *very likely* (90-100%) to have increases in mean precipitation under the higher greenhouse gas concentrations at: Taumarunui, Hokitika, Tekapo, Queenstown, and Invercargill. It is *likely* there will be precipitation increases at: Ruakura, Taupo, New Plymouth, Paraparaumu, Wellington, Blenheim, Nelson, and Dunedin.
- At 2090 in winter, it is *likely* (66-100%) to have decreased precipitation at: Kaitaia, Whangarei, Gisborne, Napier, Masterton, Christchurch, and Hanmer.
- In general, the spring season tends to be similar to winter, and the autumn season is intermediate between summer and winter.

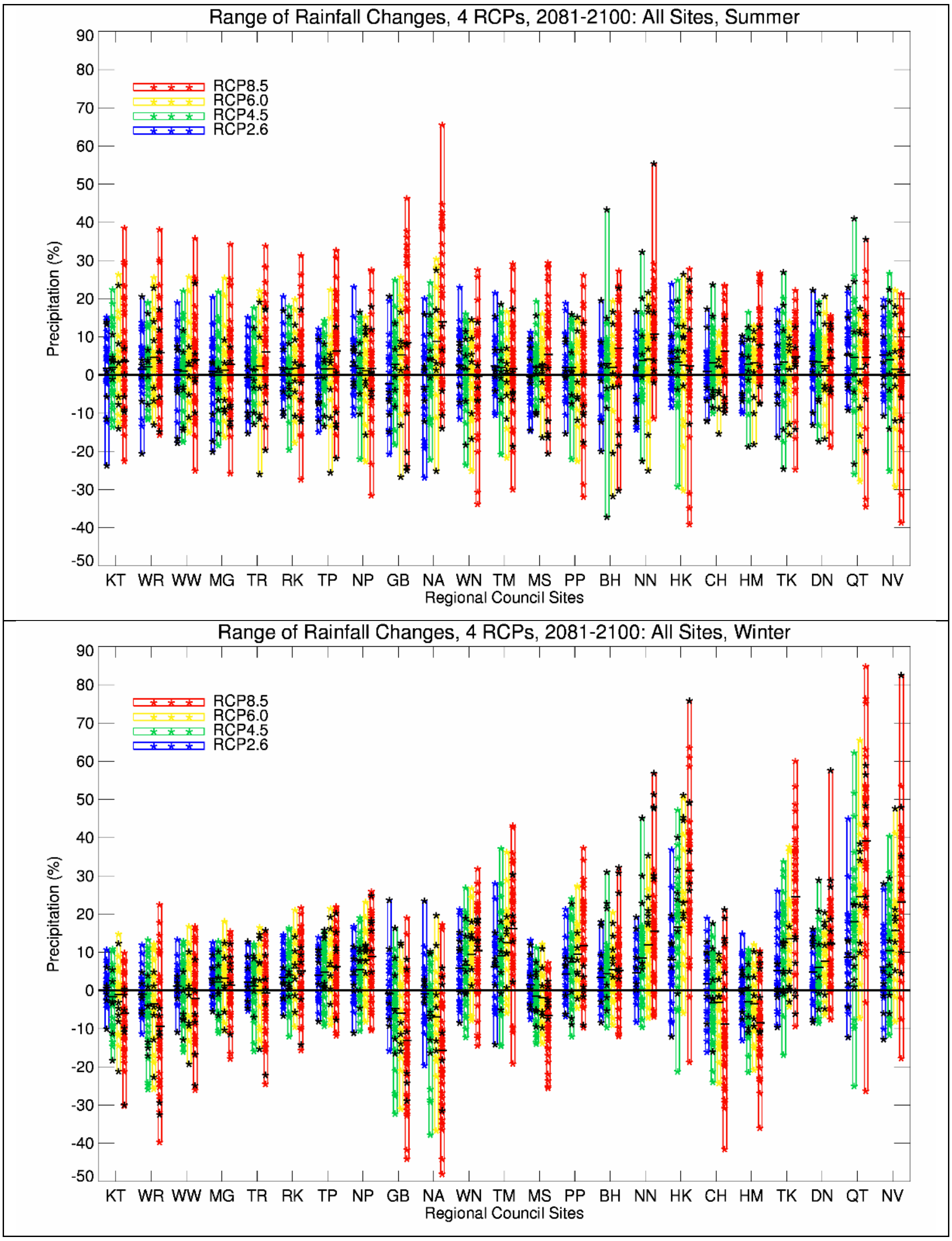


Figure 5-22: Projected precipitation changes for selected sites within all Regions for 2090, for summer (top panel) and winter (bottom panel) seasons, for all RCPs (bars) and all models. Coloured stars refer to statistical downscaling, whereas the black stars correspond to the 6-model RCM-downscaling. The sites chosen (and Regions) are: Kaitaia [KT] and Whangarei [WR] (Northland), Warkworth [WW] and Mangere [MG] (Auckland), Tauranga [TR] (Environment Bay of Plenty), Ruakura [RK] and Taupo [TP] (Waikato), New Plymouth [NP] (Taranaki), Gisborne [GB] (Gisborne), Napier [NA] (Hawkes Bay), Wanganui [WN] and Taumarunui [TM] (Horizons Manawatu-Wanganui), Masterton [MS] and Paraparaumu [PP] (Wellington), Blenheim [BH] (Marlborough), Nelson [NN] (Tasman), Hokitika [HK] (West Coast), Christchurch [CH], Hanmer [HM] and Tekapo [TK] (Canterbury), Dunedin [DN] and Queenstown [QT] (Otago) , and Invercargill [NV] (Southland). After Mullan et al. (2016).

5.5 Scenarios for Changes in Extreme Rainfall

A warmer atmosphere can hold more moisture (about 8% more for every 1°C increase in temperature), so there is potential for heavier extreme rainfall with global increases in temperatures under climate change. In its Fifth Assessment Report, the IPCC concluded that the frequency of heavy precipitation events is "very likely" to increase over most mid-latitude land areas (this includes New Zealand) (IPCC, 2013, Table SPM.1). Given the mountainous nature of New Zealand, spatial patterns of changes in rainfall extremes are expected to depend on changes in atmospheric circulation and storm tracks.

NIWA produced guidance on changes in heavy rainfall to be used for "screening assessments"[3] in New Zealand, for the 2008 update to the Local Government Guidance manual (Ministry for the Environment, 2008a). The manual recommends use of a geographically uniform relationship between projected changes in temperature and changes in extreme rainfall return period statistics. An overview of the process for producing heavy rainfall statistics for screening analyses, with a detailed example of its application for Whangarei, is provided here. This method uses augmentation amounts for various rainfall return intervals and durations set out in Table 5-7, which is a reproduction of Table 5.2 of the revised Guidance Manual (Ministry for the Environment, 2008a). The recommendation in the Local Government Guidance manual is that if a screening analysis using statistics produced through this process indicates changes in heavy rainfall could lead to problems for a particular asset or activity, then further guidance should be sought from a science provider for a more detailed risk analysis.

Rainfall depth-duration-frequency statistics for Whangarei under current conditions are provided in Table 5-8. Statistics for screening studies under mid-range and high-end temperature scenarios for 2100 are provided in Table 5-9 to Table 5-11.

Table 5-7: Augmentation factors (percentage increases per degree of warming) used in deriving changes in extreme rainfall for preliminary scenario studies. [Note: In preparing this table, all reasonable skill and care was exercised, using best available methods and data. Nevertheless, NIWA does not accept any liability, whether direct, indirect, or consequential, arising out of its use].

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

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

Table 5-8: Current rainfall depth-duration-frequency statistics for Whangarei from HIRDS V3. Numbers in the body of the table are in mm.

ARI (years)	Duration									
	10m	**20m**	**30m**	**60m**	**2h**	**6h**	**12h**	**24h**	**48h**	**72h**
2	10.8	15.3	18.8	26.7	37.0	61.9	85.7	118.6	146.1	165.0
5	13.6	19.4	23.8	33.8	46.6	77.8	107.5	148.6	183.0	206.7
10	15.9	22.6	27.8	39.4	54.4	90.6	125.0	172.5	212.4	239.9
20	18.5	26.3	32.2	45.8	63.1	104.8	144.4	199.0	245.1	276.8
30	20.1	28.6	35.1	49.9	68.7	114.0	156.9	216.0	266.1	300.5
50	22.4	31.8	39.1	55.5	76.4	126.6	174.1	239.4	294.9	333.1
100	25.9	36.8	45.2	64.2	88.1	145.8	200.2	275.1	338.8	382.7

Table 5-9: Projected rainfall depth-duration-frequency statistics for Whangarei in 2100, for a low-range temperature scenario (1°C warming), from HIRDS V3.

ARI (years)	Duration									
	10m	**20m**	**30m**	**60m**	**2h**	**6h**	**12h**	**24h**	**48h**	**72h**
2	11.7	16.5	20.2	28.5	39.3	65.2	89.8	123.7	151.7	170.8
5	14.7	20.9	25.6	36.2	49.7	82.5	113.7	156.6	192.2	216.6
10	17.2	24.4	29.9	42.3	58.3	96.8	133.1	183.4	225.4	254.1
20	20.0	28.4	34.7	49.3	67.9	112.6	154.9	213.3	262.5	296.2
30	21.7	30.9	37.9	53.9	74.2	123.1	169.5	233.3	286.9	323.6
50	24.2	34.3	42.2	59.9	82.5	136.7	188.0	258.6	318.5	359.7
100	28.0	39.7	48.8	69.3	95.1	157.5	216.2	297.1	365.9	413.3

Table 5-10: Projected rainfall depth-duration-frequency statistics for Whangarei in 2100 for a mid-range temperature scenario (2°C warming), from HIRDS V3.

ARI (years)	Duration									
	10m	**20m**	**30m**	**60m**	**2h**	**6h**	**12h**	**24h**	**48h**	**72h**
2	12.5	17.7	21.5	30.3	41.6	68.5	93.9	128.8	157.2	176.6
5	15.8	22.4	27.3	38.6	52.8	87.3	120.0	164.6	201.3	226.5
10	18.4	26.1	32.0	45.2	62.2	102.9	141.2	194.2	238.3	268.2
20	21.5	30.5	37.2	52.9	72.7	120.3	165.5	227.7	279.9	315.6
30	23.3	33.2	40.7	57.9	79.7	132.2	182.0	250.6	307.6	346.8
50	26.0	36.9	45.4	64.4	88.6	146.9	202.0	277.7	342.1	386.4
100	30.0	42.7	52.4	74.5	102.2	169.1	232.2	319.1	393.0	443.9

Table 5-11: Projected rainfall depth-duration-frequency statistics for Whangarei in 2100, for a higher-end temperature scenario (3°C warming), from HIRDS V3.

ARI (years)	**Duration**									
	10m	**20m**	**30m**	**60m**	**2h**	**6h**	**12h**	**24h**	**48h**	**72h**
2	13.4	18.8	22.9	32.1	43.9	71.7	98	133.9	162.8	182.3
5	16.9	23.9	29.1	41	56	92	126.2	172.7	210.4	236.5
10	19.7	27.9	34.1	48.1	66.2	109.1	149.4	205.1	251.3	282.4
20	22.9	32.6	39.7	56.4	77.5	128.1	176	242	297.3	334.9
30	24.9	35.5	43.5	61.9	85.2	141.4	194.6	267.8	328.4	369.9
50	27.8	39.4	48.5	68.8	94.7	157	215.9	296.9	365.7	413
100	32.1	45.6	56	79.6	109.2	180.8	248.2	341.1	420.1	474.5

Projected rainfall depth-duration-frequency tables for other locations in Northland Region can be produced using HIRDS (High Intensity Rainfall System) software package (www.hirds.niwa.co.nz) and the process is described in the revised Local Government Guidance Manual (Ministry for the Environment, 2008a). Note that a significant update to HIRDS is currently underway (as at mid 2016).

Mullan et al. (2016) calculated projected changes in extreme precipitation using the same models as in Section 5.3. The frequency of extreme precipitation, as quantified by the changes in the 99th percentile of the daily precipitation distribution (i.e. the top 1% of rain days), shows a systematic increase in much of the South Island, with both time and increasing greenhouse gas concentration (different RCPs used) (Figure 5-23). Over the North Island, however, projected changes are small and erratic. To some degree, this is because a 20-year period is too short to obtain a robust signal in the precipitation extremes. However, this preliminary analysis at least suggests that some regional variation may be expected in future return periods of extreme rainfall.

Focussing on the 2090 changes under RCP 8.5 (the strongest forcing), the only coherent regions to show a decrease in daily extreme rainfall are Northland and parts of the Wairarapa and Hawke's Bay on the east coast of the North Island. These areas also show the largest reductions in winter precipitation (the wettest season) (Figure 5-14). As a cautionary aside, the climate models being used do not have the resolution to realistically simulate tropical cyclones, and thus extreme rainfall from these phenomena are likely to be underestimated in these results.

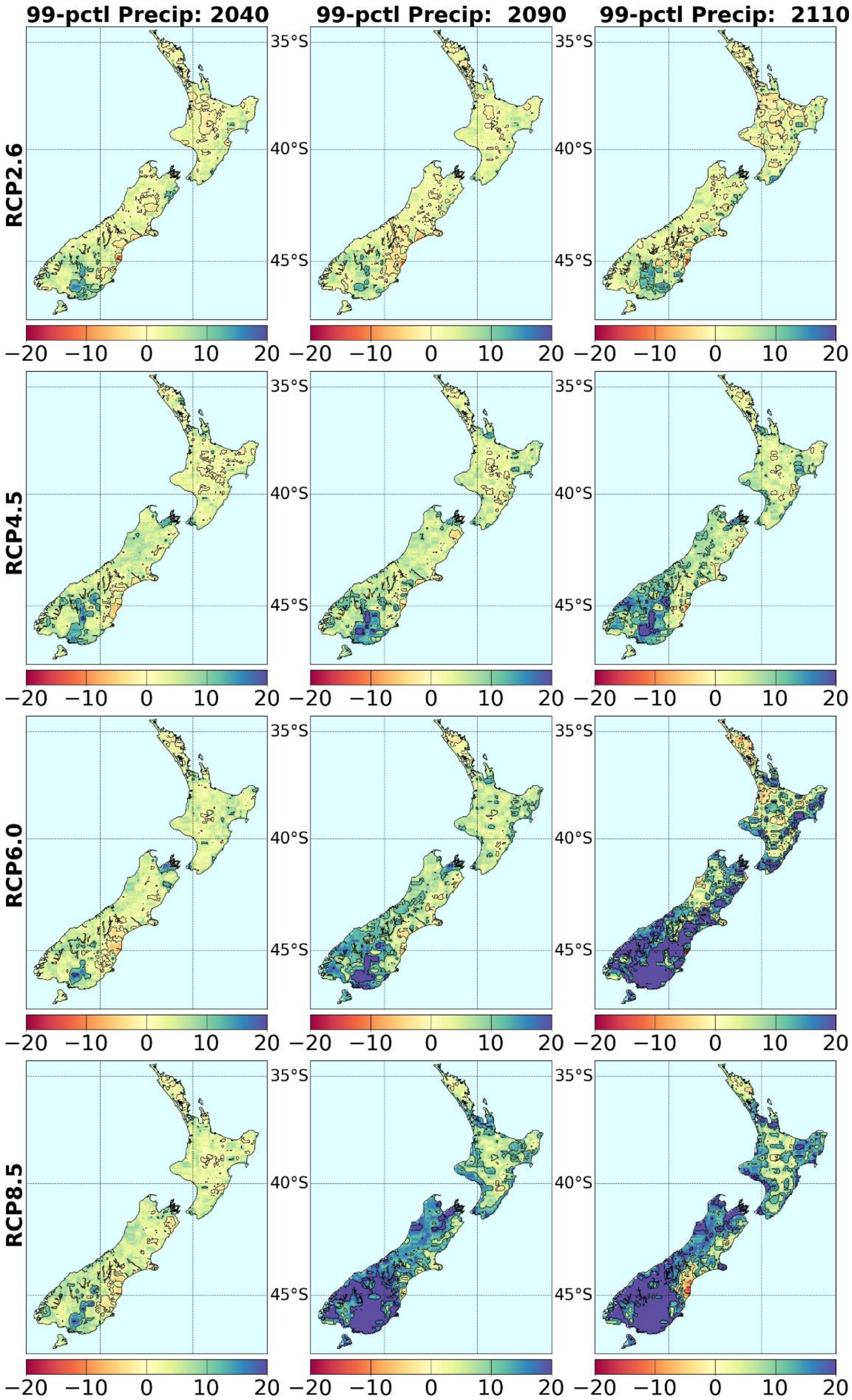


Figure 5-23: Change in the magnitude of the 99th percentile of daily precipitation (in %). For all four RCPs and three future time periods, relative to the daily 99th percentile in the baseline 1986-2005 period. The red colours indicate a decrease in extreme rainfall, orange little change, and green, blue, and purple a progressive increase in extremes. After Mullan et al. (2016).

5.5.1 Ex-Tropical Cyclones

Northland is occasionally affected by cyclones of tropical origin, which may bring heavy rain and strong winds to the region. Ex-tropical cyclones have the potential to cause flooding, generate primary and secondary wind damage to vegetation, and higher-than-normal wave heights and coastal storm surges. Approximately one ex-tropical cyclone comes within 550 km of Auckland during each tropical cyclone season (November-April) (Lorrey et al., 2014), and this number would be similar for Northland, due to Auckland's proximity to the Northland region.

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

Overall, there is significant uncertainty surrounding projections of tropical cyclones into the future. However, it is likely that storms making landfall will be stronger and cause more damage. However, the IPCC (2013) projections are for tropical cyclones – storms that are in the tropics and thus at their full strength, not ex-tropical cyclones that have undergone extratropical transition where they begin to lose their strength, as they do upon their southwards path where they may influence New Zealand. Therefore, the frequency with which ex-tropical cyclones and other tropical depressions may reach Northland in the future is uncertain.

5.6 Evaporation, Soil Moisture and Drought

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

Potential evapotranspiration deficit (PED) is the cumulative difference between potential evapotranspiration (PET) and rainfall from 1 July of a calendar year to 30 June of the next year, for days of soil moisture under half of available water capacity (AWC), where an AWC of 150mm for silty-loamy soils is consistent with estimates in previous studies (e.g. Mullan et al., 2005). PED, in units of mm, can be thought of as the amount of rainfall needed in order to keep pastures growing at optimum levels. As a rule of thumb, an increase in PED of 30 mm or more corresponds to an extra week of reduced grass growth.

A regional map of projected changes in potential evapotranspiration deficit is presented in Figure 5-24. The maps are plotted with a range of up to 60 mm of accumulated PED anomaly with respect to the historical average.

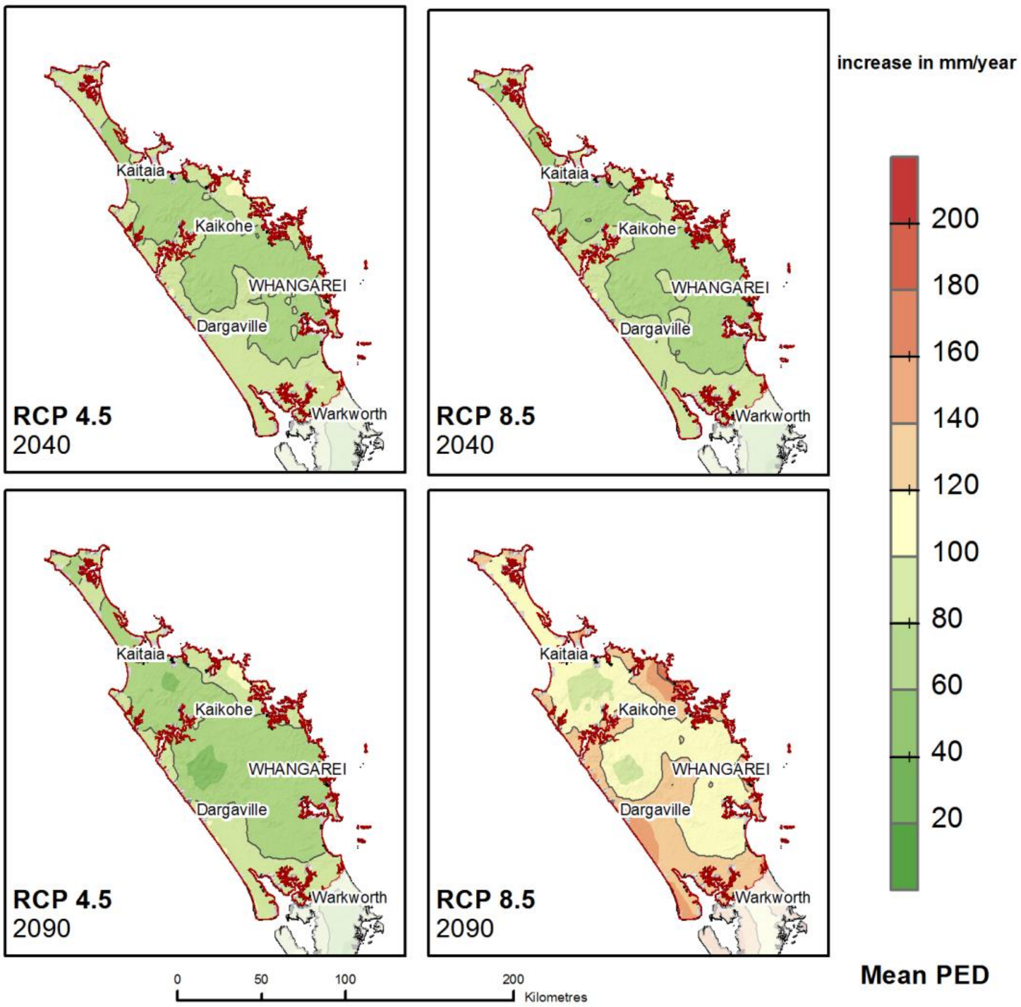


Figure 5-24: RCM-projected changes in Potential Evapotranspiration Deficit (PED, in mm accumulation over the July-June 'hydrologic year') for Northland Region. With respect to the baseline 1995 period, for RCP 4.5 and RCP 8.5, for 2040 and 2090. The black contour lines are at 40, 80, 120 and 160 mm/year intervals.

Northland Region has been separated into four sub-regions for the purposes of analysing changes to PED (and corresponding potential drought risk).

Northern Northland sub-region (north of Kaitaia)

At 2040 and 2090 under RCP 4.5, increases in PED of 60-100 mm/year are projected for the Aupouri Peninsula. The patterns are similar for both 2040 and 2090 under RCP 4.5, and also for 2040 under RCP 8.5. However, at 2090 under RCP 8.5 there is projected to be an increase in PED of 100-120 mm/year in most of the sub-region and some small pockets of 120-140 mm/yr in the northern Aupouri Peninsula.

East coast Northland sub-region (eastern coastal margin from Karikari Peninsula to Mangawhai)

At 2040 under RCP 4.5 and RCP 8.5, most of the east coast is projected to experience increases in PED of 60-80 mm/year, with some places projected to experience increases of around 100 mm/year. The patterns are similar for 2040 and 2090 under RCP 4.5, with a few more places experiencing increases in PED of up to 100 mm/year (in particular, around the northern Bay of Islands and Whangaroa Harbour) by 2090. By 2090 under RCP 8.5, however, much larger increases in PED are projected for the east coast, with most places projecting increases of over 120 mm/year, and an area north of the Bay of Islands projecting increases of up to 160 mm/year.

West coast Northland sub-region (Ahipara to Kaipara Heads)

At 2040 under RCP 4.5 and RCP 8.5, and also at 2090 under RCP 4.5, the west coast sub-region is projected to experience increases in PED of 80-100 mm/year. However, by 2090 under RCP 8.5 most of the west coast sub-region is projected to experience increases in PED of 120-140 mm/year, with some pockets south of Dargaville projected to experience increases in PED of over 140 mm/year.

Inland Northland sub-region (whole region south of Kaitaia, inland from coast)

The inland part of Northland region is generally expected to experience smaller increases in PED than the coastal sub-regions. At 2040 under RCP 4.5 and RCP 8.5, as well as at 2090 under RCP 4.5, increases in PED are projected to be up to 40 mm/year. Under RCP 8.5 at 2090, however, most of the inland sub-region is projected to experience increases in PED of over 100 mm/year (small pockets with 80-100 mm/year increase). Some central and southern parts of the sub-region are projected to experience increases in PED of 120-140 mm/year by 2090 under RCP 8.5.

Overall, the east coast sub-region, the west coast sub-region and the southern inland sub-region are most at risk of future drought due to the larger projected increases in PED.

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

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

During this century, evidence for increases in time spent in drought is apparent for Canterbury, Hawke’s Bay, Gisborne, and Northland (Clark et al., 2011). Under the most likely mid-range emissions scenario the projected increase in percentage of time spent in drought from 1980-99 levels is about 7% for 2030-2050 and 10% for 2070-2090 for the Northland Region. This can be interpreted as: for a site that is currently in drought 5% of the time in Northland, in 2030-2050 it is likely that this same location will be in drought 12% of the time (i.e. an additional 7%), and in 2070-2090 that location is likely to be in drought 15% of the time (an additional 10%).

Mullan et al. (2016) calculated the number of dry days (days with rainfall <1mm) for different RCPs (Figure 5-25). Blue and green shading indicates a decrease in dry days (i.e., more rain days), yellow little change, and orange and red an increase in the number of dry days per year. The frequency of dry days increases with time and RCP for much of the North Island, and for high altitude inland regions in the South Island. The frequency of dry days decreases on the west and east coastal regions in the South Island. For Northland, there is projected to be an increase in dry days of about 20 days per year for most of the region by 2090 under RCP 8.5.

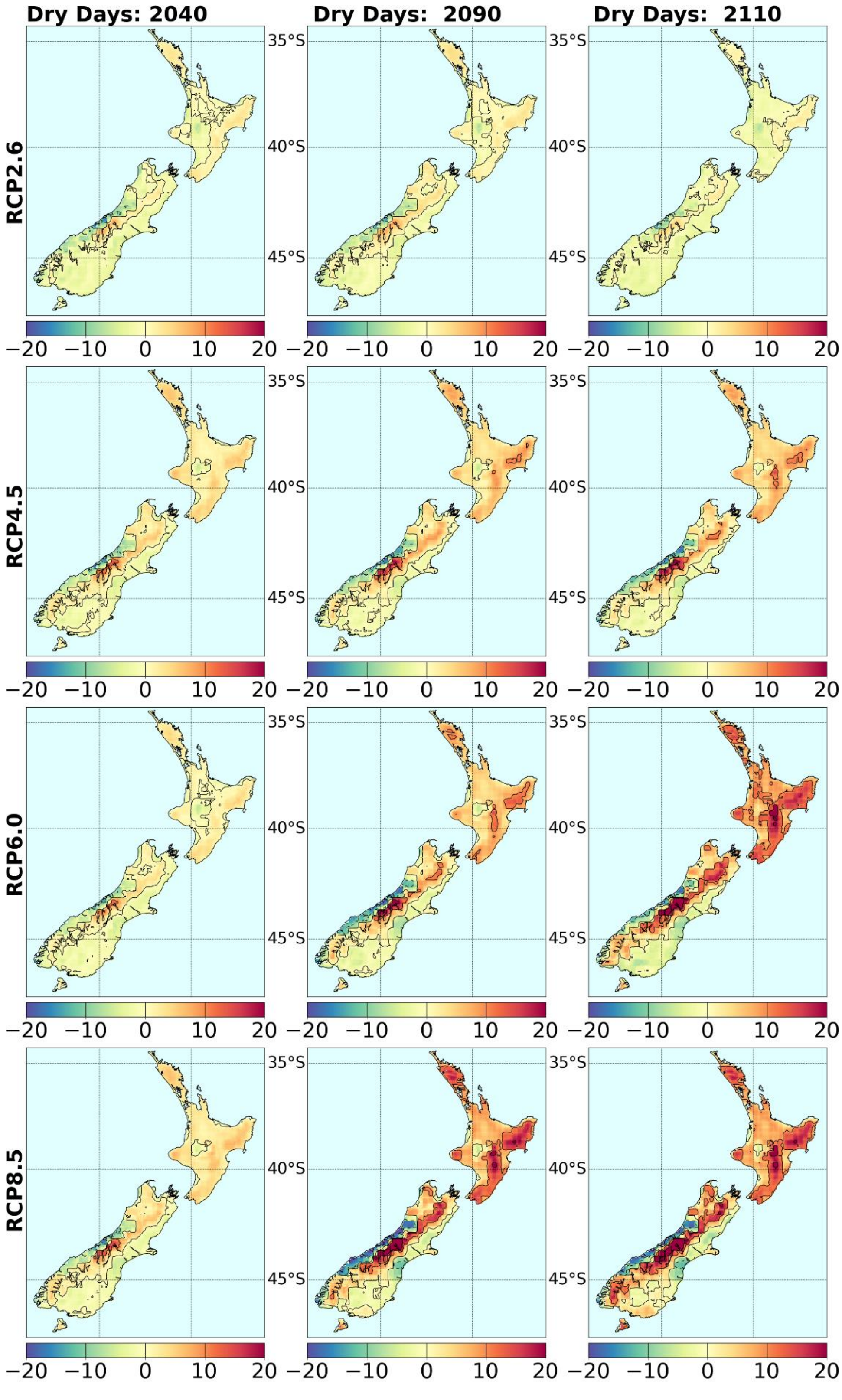


Figure 5-25: RCM-projected changes in the annual number (in days) of "dry days" (precipitation below 1 mm/day). With respect to the baseline 1995 period, for all four RCPs and three future time periods. Blue shades indicate a decrease in dry days and red shades indicate an increase in dry days. After Mullan et al. (2016).

5.7 Pressure and Wind

Mean sea-level pressure and wind projections have been derived from the Regional Climate Model (RCM) simulations by Mullan et al. (2016). The RCM simulations provide much more information about weather parameters than is readily available from statistical downscaling. In all cases, there is a maximum of six models available for analysis for each RCP and time period; four models are available beyond 2100 for RCPs 2.6 and 8.5, five models for RCP 4.5, and only one model for RCP 6.0.

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

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

The 99th percentile of daily-mean wind speed was evaluated over the historical 1986-2005 period at each VCSN grid-point in the downscaled (but not bias-corrected) regional model output data, by Mullan et al. (2016). Figure 5-26 maps how the 99th percentiles at future periods differs from the current climate for each of the four RCPs.

In Figure 5-26, yellow shading means little or no change from present, green a decrease in extreme wind speed, and red an increase. For most of the RCPs and time periods, the southern half of the North Island and all the South Island are shown as having stronger extreme daily winds in future. This is especially noticeable in the South Island east of the Southern Alps. The regional model is able to resolve speed-up in the lee of the mountain ranges, and shows increases of up to 10% or greater in Marlborough and Canterbury by the end of the century under the highest RCP8.5 forcing. However, there is a decrease in extreme winds in the North Island from Northland to Bay of Plenty, probably because of increasing anticyclonic conditions.

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

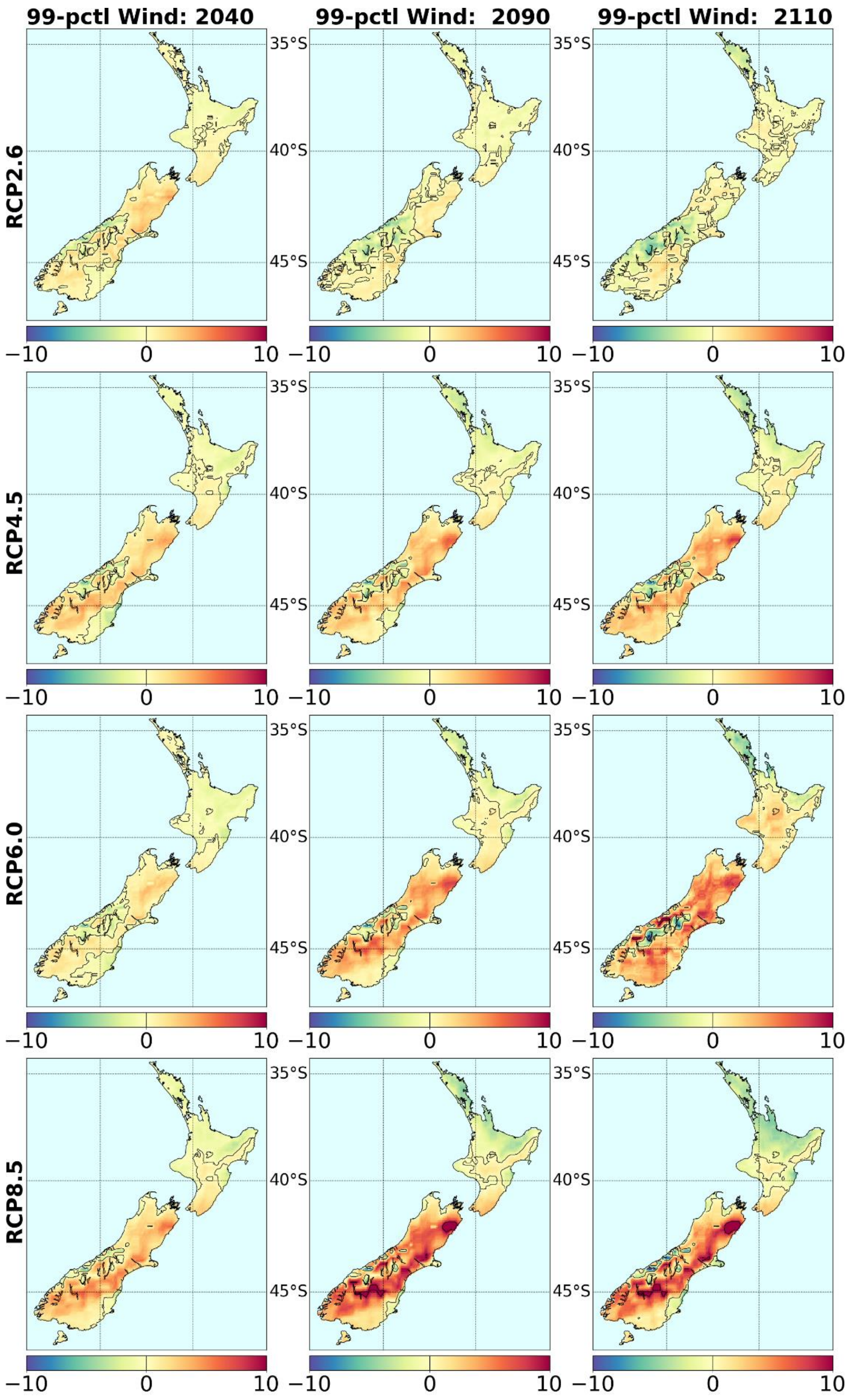


Figure 5-26: Change in the magnitude of the 99th percentile of daily-mean wind speed, for all four RCPs and three future time periods. Relative to the daily 99th percentile in the baseline 1986-2005 period. Blue and green shades indicate a decrease in wind speed and red shades indicate an increase in wind speed. After Mullan et al. (2016).

5.8 Solar Radiation

Mullan et al. (2016) produced projections of solar radiation for the four RCPs at different periods during the 21st century.

The geographic distribution of solar radiation depends not only on astronomical factors but also local rainfall (and cloudiness) patterns. The highest solar radiation levels are recorded in Nelson-Marlborough and in central Otago regions in summer months, and in northern North Island and Nelson-Marlborough in winter months. Astronomical factors will not change over the projection period but cloud will.

The seasonal patterns of projected changes are clearest for the most extreme RCP (RCP 8.5). The solar radiation projection suggests increases of up to 10% on the West Coast in summer, and smaller increases elsewhere with notable exception of the coastal Canterbury where sunshine is predicted to decrease. Autumn solar radiation patterns are similar but weaker to those of summer. The winter changes are almost the reverse of the summer ones: about a 5% decrease in radiation in western parts of the North Island, and 10% or more in western and southern South Island. Eastern North Island is projected to have an increase in winter sunshine levels. In spring, most of the North Island, and the northern third of the South Island, displays an increase in radiation, with decreases further south.

For more detail on solar radiation projections, see Mullan et al. (2016).

5.9 Climate Change and Sea Level

Sea levels will continue to rise over the 21st century and beyond, primarily because of thermal expansion within the oceans and loss of ice sheets and glaciers on land. The basic range of projected global sea-level rise estimated in the IPCC's Fifth Assessment Report (IPCC, 2013) is for a rise of 0.26 m-0.82 m for 2081-2100 (2080s and 2090s) relative to the average sea level over the period 1986-2005, as shown in Figure 5-27. This is based on projections from IPCC AR5 climate model projections in combination with process-based models of glacier and ice sheet surface mass balance for the four different RCP emissions scenarios. Global mean sea level rise for the scenarios will likely be in the 5 to 95% ranges characterising the spread of the model results (bars on the right hand side of Figure 5-27).

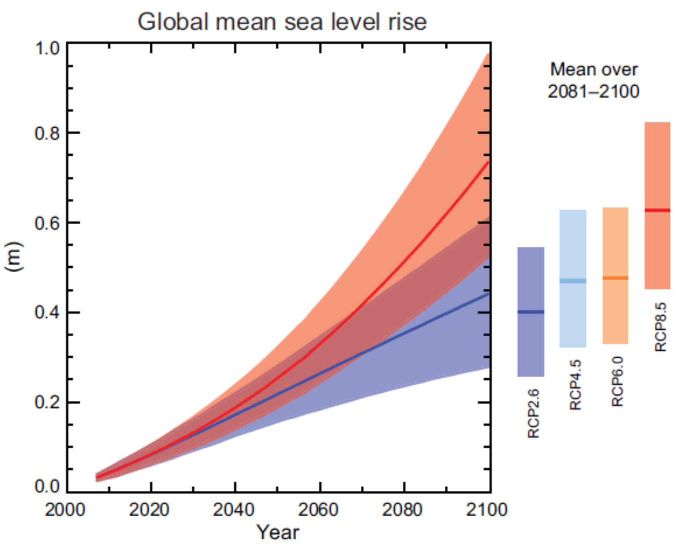


Figure 5-27: Projections of global mean sea level rise over the 21st century relative to 1986-2005. Projections are from the combination of the Coupled Model Intercomparison Project (CMIP5) ensemble with process-based models, for RCP2.6 and RCP8.5. The assessed likely range is shown as a shaded band. The assessed likely ranges for the mean over the period 2081-2100 for all RCP scenarios are given as coloured vertical bars, with the corresponding median value given as a horizontal line. After IPCC (2013).

In all emissions scenarios, thermal expansion is the largest contribution to global mean sea-level rise, accounting for about 30-55% of the total. Glaciers are the next largest, accounting for 15-35% of total sea level rise. By 2100, 15-55% of the present glacier volume is projected to be eliminated under the lowest emissions scenario, and 35-85% under the highest emissions scenario. The increase in surface melting in Greenland is projected to exceed the increase in accumulation, and there is high confidence that the surface mass balance changes on the Greenland ice sheet will make a positive contribution to sea-level rise over the 21st century. On the Antarctic ice sheet, surface melting is projected to remain small.

Figure 5-28 shows Wellington and Auckland annual mean sea level measurements spliced with global-mean sea-level rise projections for two of the RCPs (RCP 2.6 and RCP 8.5) from IPCC (2013). Note that IPCC provided a caveat that further collapse of Antarctica ice sheets could cause global sea level to rise substantially above the *likely* ranges by 2100 (shown as dashed lines in Figure 5-28), with medium confidence that the additional contribution would not exceed several decimetres of sea-level rise by 2100. The RCP projections from IPCC have been extended out from 2100 to 2120, to assist with the application of the NZ Coastal Policy Statement that requires coastal hazards and climate change effects be assessed over "at least 100 years". Both measurements from the two ports and the projections are relative to a baseline averaged from 1986–2005 (centred on 1996).

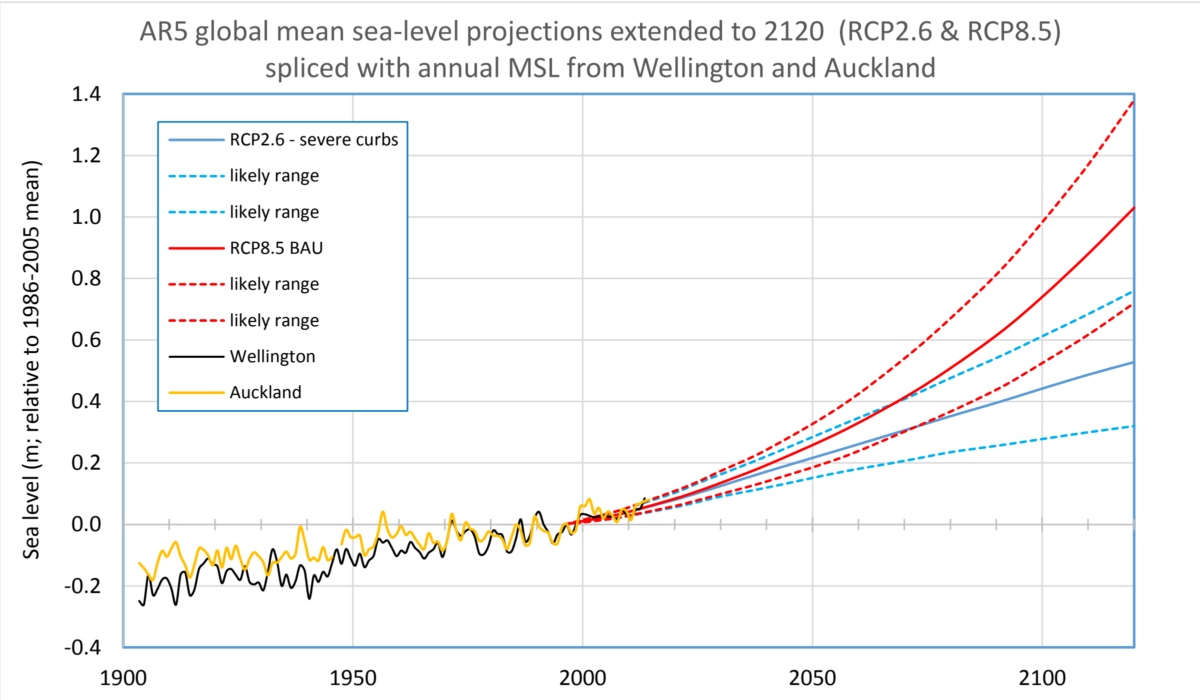


Figure 5-28: AR5 global mean sea-level projections extended to 2120 spliced with annual MSL from Wellington and Auckland. Dashed lines show the upper and lower bounds of the *likely* range for each RCP shown, which in the calibrated language of IPCC means there is a 33% change the SLR could lie outside those bounds (Church et al., 2013a). Source: QA for annual MSL for historic NZ ports undertaken by Prof. John Hannah and NIWA – data sourced originally from the port companies and obtained from the Land Information

NZ archives. The global-mean SLR projections were interpolated by data from Table 13.5 (Church et al., 2013b) and from Figure SPM.9 in the IPCC AR5 Summary for Policymakers (IPCC, 2013).

Sea level rise will have an impact on sediment redistribution, the partitioning of habitats within estuaries, salinity, tidal range, and submergence periods, with consequences for biological communities in the estuaries as well as human communities that exist nearby (Wong et al., 2014). Estuaries and coastal lagoons may shrink because landward migration is restricted due to human occupation, or extend due to the drowning of marshes and coastal wetlands.

A manual for local government on coastal hazards and climate change was published in 2008 (Ministry for the Environment, 2008b). This guidance manual uses projections based on the IPCC's Fourth Assessment Report. By the end of 2016, it is expected that an updated report will be published using projections based on the IPCC Fifth Assessment Report projections, but in this report the 2008 report will be referenced.

The Coastal Hazards and Climate Change Guidance Report includes suggestions on changes in mean sea-level for use in future planning and decisions. Numbers for use in such guidance depend on risk management considerations as well as scientific assessment. The guidance manual advocates the use of a risk assessment process to assist incorporating sea-level rise and the associated uncertainties, within local government planning and decision-making. This requires a broader consideration of the potential impacts or consequences of sea-level rise on a specific decision or issue. Rather than define a specific climate change scenario or sea-level rise value to be accommodated, it is recommended in the manual that the magnitude of sea-level rise accommodated is based on the acceptability of the potential risk.

To aid this risk assessment process, the manual recommends that allowance for sea-level rise is based on the IPCC Fourth Assessment Report, and that consideration be given to the potential consequences from higher sea-levels due to factors not included in current global climate models[4].

For planning and decision timeframes out to the 2090s (2090-2099):

a. A base value sea level rise of 0.5 m relative to the 1980-1999 average should be used, along with:

b. An assessment of the potential consequences from a range of possible higher sea-level rises (particularly where impacts are likely to have high consequence or where additional future adaptation options are limited). At the very least, all assessments should consider the consequences of a mean sea-level rise of at least 0.8 m relative to the 1980-1999 average.

For planning and decision timeframes beyond 2100 where, as a result of the particular decision, future adaptation options will be limited, an allowance of sea-level rise of 10 mm per year beyond 2100 is recommended (in addition to the above recommendation). Climate change will also impact on other coastal hazard drivers, such as tides, storm surge, waves, swell, and coastal sediment supply. The potential changes and their impacts are at present much less well understood, but the manual provides pragmatic guidance informed by expert judgement and the current state of scientific knowledge.

A small amount of research has been completed within Northland Region concerning the effects of sea-level rise on coastal environments and communities. A research project was completed at

[4] Such factors relate to uncertainties associated with increased contribution from the Greenland and Antarctica ice sheets, carbon cycle feedbacks, and possible differences in mean sea level when comparing the New Zealand region with the global average.

Mitimiti on the west coast, north of Hokianga Harbour, by King et al. (2013). This project focused on community vulnerability to climate change, in particular to changes in flooding and sea-level rise. A2 (mid-high range) and B2 (mid-low range) climate change scenarios from the IPCC's Fourth Assessment Report were used as well as projected 0.4m of sea-level rise by 2040 and 0.8m of sea-level rise by 2090. The report found that a creeping of tide is likely by 2040, especially for areas surrounding stream channels that discharge onto the beach at Mitimiti. By 2090, the MHWS-10 (mean high water spring which is exceeded by 10% of high tides) tidal limit pushes further inland, leading to an increase in the width of stream channels and the inundation of existing pasture land in some cases.

5.9.1 Effect of Sea-Level Rise on High Tide Exceedance Frequency

The Coastal Hazards and Climate Change guidance manual (Ministry for the Environment, 2008b) provides information on tide ranges and frequency of high tides. Tidal ranges and the timing of high and low tides in shallow harbours, river mouths and estuaries could be altered by changes in channel depth due to climate change. These changes could occur through either the deepening of channels where sea-level rise exceeds the rate of sediment build-up, or conversely by the formation of shallower channels where rates of sediment build-up (i.e. from increased runoff due to more intense rainfall events) exceeds sea-level rise.

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

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

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

An example of the effect that future sea-level rise has on the frequency of high tides exceeding certain points at Opua, Bay of Islands is shown on Figure 5-29 and Table 5-12. The black line in Figure 5-29 shows the present-day sea levels and the upper curves are for different levels of sea-level rise. Currently, 10% of high tides exceed the MHWS-10 level (Mean High Water Spring level that 10% of high tides exceed, excluding weather and climate effects). With 0.4 m of sea-level rise, approximately 84% of high tides will exceed this level and with 0.8 m of sea-level rise 100% of high tides will exceed this level, again excluding weather and climate effects such as storm surge.

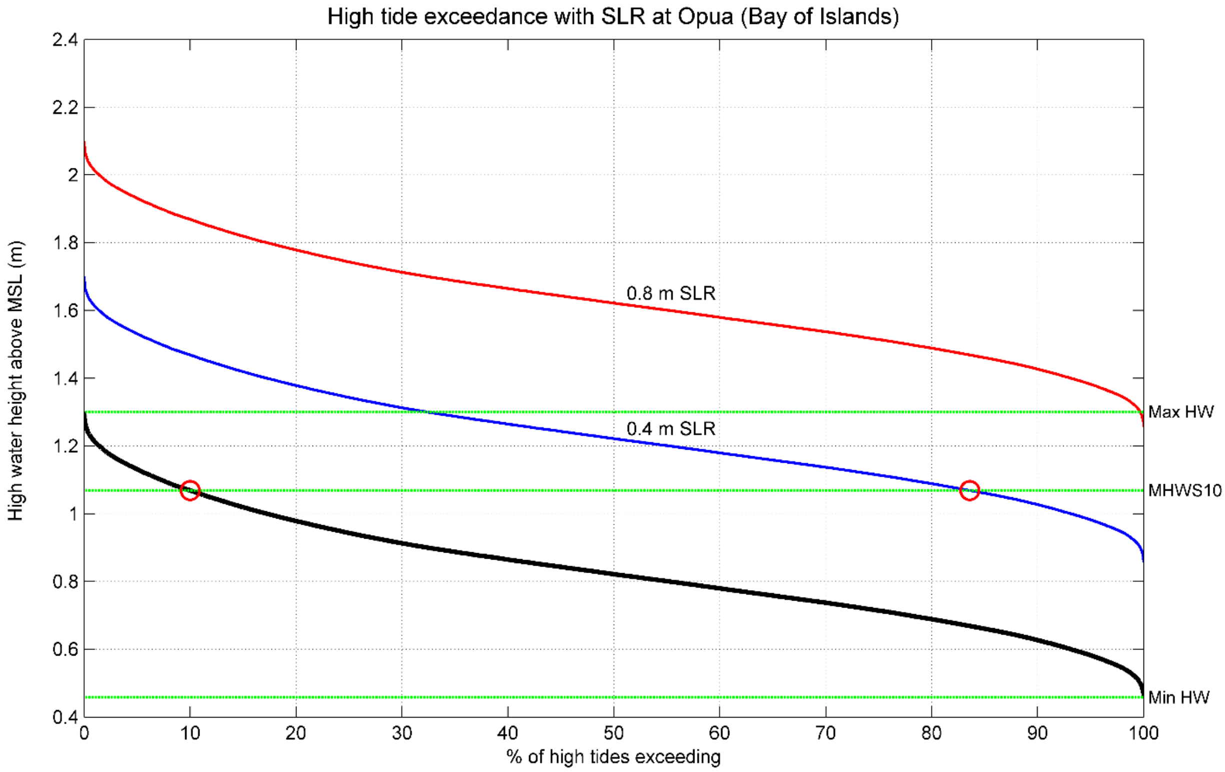


Figure 5-29: The frequency of occurrence of high tides exceeding different present day tide marks at Opua, Bay of Islands. The tide marks for the present is shown by the heavy line, 0.4m of sea-level rise (blue line) and 0.8m of sea-level rise (red line). ©NIWA.

Table 5-12: Data analysis of effect of sea-level rise at Opua on components of tide.

Maximum HW	1.301 m
MHWPS (Mean High Water at Perigean Spring) 1.0954 m exceeded by	7.65%
Pragmatical MHWS for 10% exceedance	1.069 m
MHWS (Mean High Water Spring)	0.9368 m exceeded by: 26.0%
MHWN (Mean High Water Neap)	0.6952 m exceeded by: 78.7%
MHWAN (Mean High Water at Apogean Neap)	0.5366 m exceeded by: 98.5%
Minimum HW	0.457 m
Minimum SLR for ALL high tides to exceed present MHWPS	0.64 m
Minimum SLR for ALL high tides to exceed present MHWS-10%ile	0.61 m

% of high tides that would exceed current MHWS-10 for 0.4 m SLR	83.6%
% of high tides that would exceed current MHWS-10 for 0.8 m SLR	100%

5.10 Climate Change Impacts on Other Coastal Hazard Drivers

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

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

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

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

Limited research to date has been completed in Northland Region regarding the effect of sea-level rise on high tide exceedance frequency and other coastal drivers such as storm surge and waves. NIWA reports for other regional councils (e.g. Goodhue et al., 2012b) have used the IPCC emissions scenarios to run simulations of storm surge, storm tide height, and significant wave height under climate change to 2100. Northland Regional Council administers a large section of coastline on both east and west coasts, and many communities and infrastructure are placed near the coast. Therefore, such research could be useful for the region, in order to better understand the potential impacts of climate-induced changes to the region's coasts.

5.11 Hydrological Impacts of Climate Change

The climate projections used to drive the hydrological model TopNet in order to make future projections of hydrological changes in New Zealand rivers are from the Regional Climate Model (RCM) simulations by Mullan et al. (2016). Results are presented in Table 5-13 for the mouth of the Wairoa River in Northland in terms of percentage changes relative to modelled historical conditions

(1986-2005) for six different global climate models, four RCPs and two projection timelines (2031-2050: ‘2040’ and 2081-2010: ‘2090’). Interpretation of each variable follows the table. Due to the log-normality of streamflow generation processes, results will be presented in terms of change of median rather than of change in average (as per the climate section). There are large differences between some of the model outputs (large range in the brackets) because the models are highly sensitive to rainfall – where and when rain falls in the catchment can drastically change the model output.

Table 5-13: Projected changes in flow variables of the Wairoa River (in %) between 1986-2005 and 2031-2050 (2040) and 2081-2100 (2090). The changes are given for four RCPs, where the ensemble median is taken over six models. The values in each column represent the ensemble median, and in brackets the range (minimum to maximum) over all models within that ensemble.

Variable and RCP	2040 Median (min, max)	2090 Median (min, max)
Mean annual flow		
rcp 8.5	-3 (-17, 11)	-11 (-26, 37)
rcp 6.0	-7 (-9, 14)	-4 (-19, 3)
rcp 4.5	1 (-15, 9)	-2 (-15, 2)
rcp 2.6	-2 (-7, 14)	0 (-6, 6)
Mean annual flood		
rcp 8.5	-3 (-27, 21)	22 (-24, 63)
rcp 6.0	-7 (-29, 31)	-8 (-25, -41)
rcp 4.5	5 (-20, 27)	8 (-21, 27)
rcp 2.6	4 (0, 26)	2 (-23, 58)
Mean annual low flow (Q10)		
rcp 8.5	-15 (-24, -2)	-24 (-39, 199)
rcp 6.0	-11 (-31, 37)	-11 (-15, 4)
rcp 4.5	-14 (-35, 29)	-4 (-28, 25)
rcp 2.6	-7 (-21, 25)	1 (-46, 32)
Average seasonal flow: DJF		
rcp 8.5	-17 (-19, 55)	-10 (-37, 22)
rcp 6.0	-14 (-21, 46)	-6 (-24, 51)
rcp 4.5	-12 (-35, 3)	-10 (-16, 35)
rcp 2.6	-9 (-21, 62)	-13 (-35, 24)
Average seasonal flow: MAM		
rcp 8.5	4 (-22, 26)	2 (-31, 31)
rcp 6.0	7 (-19, 37)	0 (-20, 25)
rcp 4.5	4 (-15, 28)	2 (-20, 27)
rcp 2.6	11 (-13, 29)	12 (-20, 23)
Average seasonal flow: JJA		
rcp 8.5	-2 (-15, 3)	-10 (-35, -2)
rcp 6.0	-4 (-14, 4)	-6 (-21, 8)
rcp 4.5	0 (-9, 3)	-7 (-18, 4)

Variable and RCP	2040 Median (min, max)	2090 Median (min, max)
rcp 2.6	1 (-6, 4)	0 (-6, 4)
Average seasonal flow: SON		
rcp 8.5	-7 (-22, 4)	-21 (-30, -7)
rcp 6.0	-2 (-15, 18)	-16 (-25, -6)
rcp 4.5	0 (-16, 25)	-9 (-28, -1)
rcp 2.6	-2 (-16, 9)	-1 (-13, 9)
FRE3: Number of hours above FRE3		
rcp 8.5	5 (-2, 27)	7 (1, 13)
rcp 6.0	1 (-10, 5)	-4 (-12, 19)
rcp 4.5	7 (-7, 28)	1 (-18, 23)
rcp 2.6	2 (-10, 10)	2 (-11, 11)

Mean annual flow: Mean river flows change in response to shifts in precipitation patterns. The median result across all climate models of the mean flow changes are generally negative, in other words projecting a decrease in mean annual flow (Table 5-13). This is generally consistent with projected decreases in precipitation (Section 5.3) in Northland, although precipitation changes are quite variable between models. However it should be noted that there is a large range between the different model results, reflecting the uncertainties in precipitation projections and river flow responses.

Mean annual flood: The mean annual flood is the average of the maximum flood discharges experienced in a particular river, which should have a recurrence interval of once every 2.33 years. Table 5-13 shows some variability in the projections for mean annual flood. At 2040, the two higher RCPs (6.0 and 8.5) show a decrease in the median of mean annual flood model projections, whereas the two lower RCPs (2.6 and 4.5) show an increase in mean annual flood. At 2090, a large increase in mean annual flood (22%) is projected under RCP 8.5, whereas the projections are smaller and the direction of change is mixed between the other RCPs.

Mean annual low flow (Q10): The mean annual low flow (taken as Q10) is defined as the flow that is exceeded 90% of the time, independently of recurrence. The median ensemble results show projected decreases in mean annual low flow for all RCPs at both time periods except for RCP 2.6 at 2090 (median = 1). The largest median ensemble change is projected for 2090 under RCP 8.5, which is a reduction in mean annual low flow of 24%. However, the range of model results is quite large.

Average seasonal flow: Examining average seasonal flows shows a more nuanced picture of changing flow patterns than at the annual time scale. The projections for summer, winter and spring at 2040 and 2090 are dominated by decreases in average seasonal flow, although some of the decreases are minimal (less than -5%). The summer months (DJF) show the largest decreases, which has implications for water allocation for irrigation. In contrast, the projections for autumn are mostly for increases in average seasonal flow, although a number of the changes are less than +5%.

Number of hours above FRE3: FRE3 is described by Booker (2013) as the average number of high flow events (freshes or floods) per year that exceed three times the median flow. FRE3 has been used as an index relating to flow-driven disturbance in ecological studies of in-stream biota. A decrease (increase) in FRE3 would mean fewer (more) floods capable of disturbing aquatic ecosystems, suggesting an increase (decrease) in periphyton cover. Table 5-13 shows small projected increases in median FRE3 under both time periods for all RCPs, except for a small decrease under RCP 6.0 at 2090. However, the projected change is less than +5% in many cases.

The following caveats that should be noted alongside the river flow projections presented in Table 5-13:

- This analysis was completed to provide guidance on what climate change-induced trend in river flows could look like at this location only. The model used is uncalibrated, and it is suggested that a calibrated model be used for planning purposes.
- All results have been reported as percentage changes. There has been no attempt made by NIWA to bias correct or otherwise adjust the TopNet model output, based on observed flows.
- Low flows are taken to be the flow that is exceeded 90% of the time. There were no attempts in this analysis to define change in term of the 7 days Mean Annual Low Flow (MALF).
- FRE3 are reported as the occurrence of discharge above three times the median flow. As per the low flow characteristics, there was no attempt made in this analysis to correctly define a FRE3 event.
- The changes are reported in terms of the change to the median of an ensemble of six RCM runs. The maximum and minimum rate of change are provided across all RCPs only as a potential indication of the range of change.

A study by McMillan et al. (2010) revealed that for a catchment in Northland (Waihou River that drains into the Hokianga Harbour), a decrease in annual rainfall is projected to 2100 (15-20% under A2 scenario, 10-15% under B2 scenario). However, extreme daily rainfalls are likely to increase with the most pronounced increases during the summer period. This increase in extreme daily rainfalls has an impact on projected flood frequency. Under the A2 scenario (high emissions), floods at all return periods were expected to be larger, approximately 1.4 times the discharge for current conditions. Under the B2 scenario (moderate emissions), floods at less than 3-year return periods are similar to current conditions, and floods at 4- to 15-year return periods will increase to approximately twice the current discharge. Floods at the extreme 30-year return period are shown to become up to 2.6 times the current discharge; however, this result is highly uncertain as it relies on the most extreme event predicted by the models.

5.12 Ocean Acidification

Since the beginning of the industrial era, the pH of global ocean surface water has decreased by 0.1, corresponding to a 26% increase in hydrogen ion concentration (IPCC, 2013). It is virtually certain that the increased storage of carbon by the ocean will increase acidification in the future, continuing the observed trends of the past decades. Ocean acidification in the surface ocean will follow atmospheric CO_2 and it will also increase in the deep ocean as CO_2 continues to penetrate the abyss (Figure 5-30).

A global increase in ocean acidification is projected under all RCP scenarios, due to the increasing uptake of carbon by the ocean. The corresponding decrease in surface ocean pH by the end of the

21st century is in the range of 0.06-0.07 for RCP 2.6, 0.14-0.15 for RCP 4.5, 0.20-0.21 for RCP 6.0, and 0.30-0.32 for RCP 8.5.

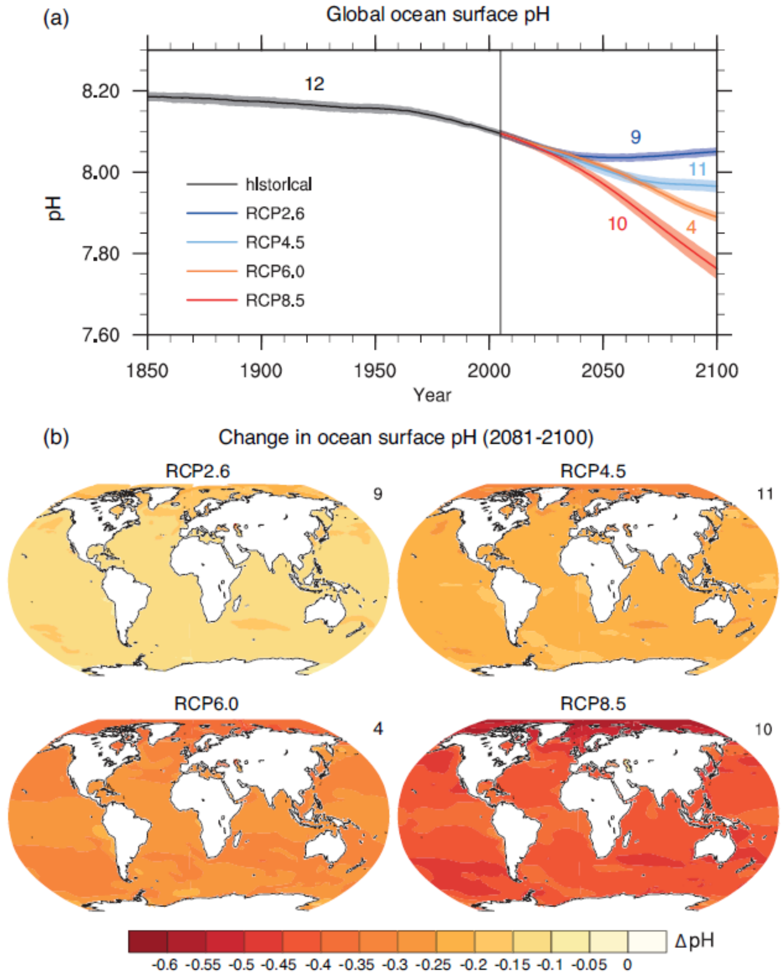


Figure 5-30: Change in ocean surface pH. Time series (model averages and minimum to maximum ranges and (b) maps of multi-model surface ocean pH for the scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 in 2081-2100. The maps in (b) show change in global ocean surface pH in 2081-2100 relative to 1986-2005. The number of CMIP5 models to calculate the multi-model mean is indicated in the upper right corner of each panel. Figure after (IPCC, 2013).

Figure 5-31 shows the projected pH decrease to 2100, using RCP 8.5, in New Zealand's Exclusive Economic Zone (EEZ). The pH decrease, from current values of ~8.08 to 7.95 by mid-century and 7.75 by 2100, is consistent with global trends of a decline by 0.3-0.4 by the end of the century. The sinusoidal pattern reflects the seasonal shift within each year of higher pH in summer (when phytoplankton growth removes CO_2) and lower pH in winter (when growth is low and mixing raises surface water CO_2).

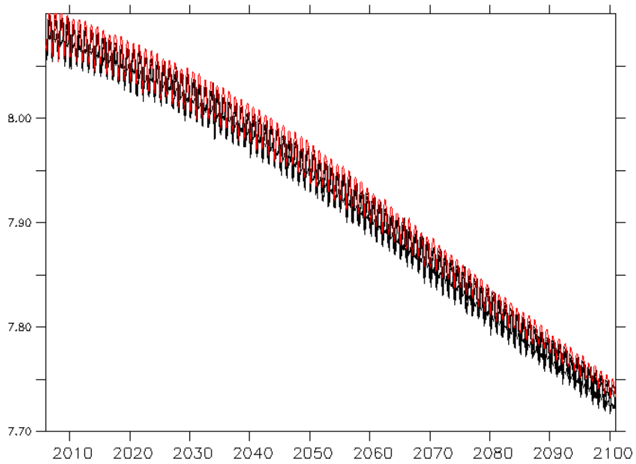


Figure 5-31: Projected mean surface pH for the NZ EEZ open ocean from a suite of six CMIP5 models, using the RCP8.5 scenario. The outputs from the models that show the closest fit to carbonate observations in the NZ EEZ during the present period are highlighted in red (S. Mikaloff-Fletcher, NIWA).

The 15-year Munida time-series in Figure 5-32 shows that ocean acidification of NZ waters is already evident, with an increase in dissolved surface CO_2 and associated decreases in surface pH and carbonate saturation state. The increase in dissolved CO_2 is consistent with the regional increase in atmospheric CO_2 recorded at the NIWA Baring Head Atmospheric Station. The observed decline in pH and carbonate saturation are consistent with observations at 6 other time-series stations in the global ocean, although the rate of change of pH at the Munida station is the lowest.

The variability and rate of change in pH will differ in coastal waters as these are also influenced by terrestrial factors and run-off. The rate and magnitude of acidification in coastal waters is being monitored by the recently initiated New Zealand Ocean Acidification Observing Network (NZOA-ON) of 14 stations around the coast.

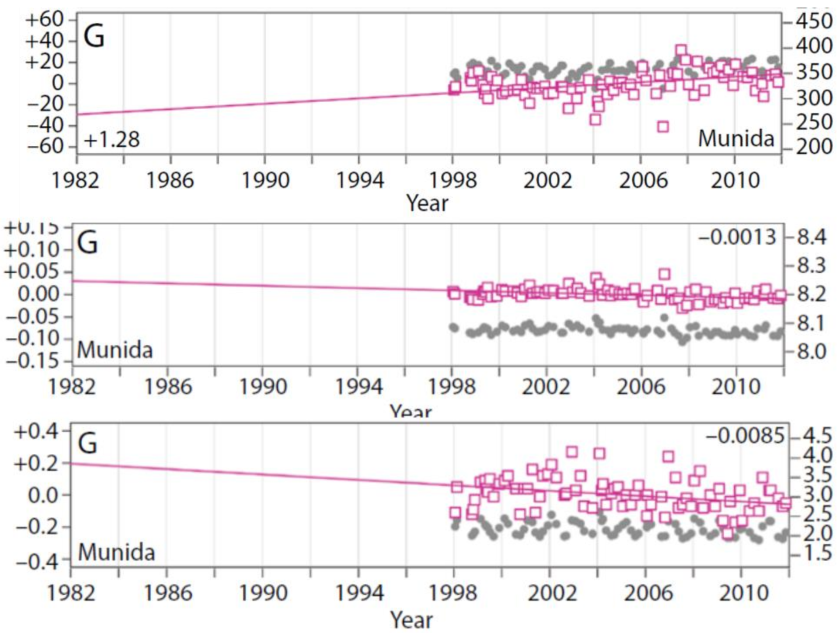


Figure 5-32: Time series of Surface seawater pCO2 (µatm, top panel), pH (middle panel), and saturation state of the carbonate mineral, aragonite (lower panel). This time series is from Sub-Antarctica water at the

Munida site (Otago shelf). Coloured symbols are the anomalies and the grey symbols the observed data, with the annual trends (yr-1) shown (Bates et al., 2014).

5.12.1 New Zealand-specific Impacts of Ocean Acidification

- There is evidence of an increase in bacterial enzyme activity under increased dissolved CO_2, which increase oxygen removal and decrease carbon uptake in the ocean (Burrell, 2015, Maas et al., 2013).
- Time series studies show no discernible impact of current increases in dissolved carbon dioxide on phytoplankton or zooplankton with carbonate shells in NZ waters currently (S. Nodder & C. Law, pers. comm.), although decreased carbonate production under conditions projected for 2100 in comparative species from other regions suggest they may be detrimentally impacted by the end of the century.
- Nitrogen fixers that live in nutrient-depleted regions are predicted to be "winners" from ocean acidification; however no significant effect of increased dissolved CO_2 was observed in experiments carried out on mixed plankton communities in NZ subtropical waters (Law et al., 2012).
- Macroalgae community structure in coastal regions may be altered in response to ocean acidification with a decline in encrusting coralline algae that use carbonate, while red algae found in deeper waters may benefit from an increase in dissolved CO_2 (Hepburn et al., 2011, Tait, 2014). Changes in the biomineralisation or species distribution of Coralline red algae may occur in response to ocean acidification, particularly in species producing high-Mg calcite (James et al., 2014, Smith et al., 2013).
- Sponges may benefit from ocean acidification (Bell et al., 2013) although those that produce calcite of high magnesium content, or aragonite may be vulnerable to dissolution (Smith et al., 2013).
- The projected decrease of carbonate saturation in the deep ocean may cause a decline in the abundance and distribution of cold water corals, which support important ecosystems in regions such as the Chatham Rise (Bostock et al., 2015). It is suggested that seamounts and topographic features may be important future refugia for cold water corals (Thresher, 2015, Tittensor et al., 2010).
- There is clear evidence of malformation of Sea Urchin larvae, in tropical to Antarctic species including from NZ, under higher dissolved CO_2. This may result in smaller larvae and an increased duration in the planktonic phase, reducing the chances of survival to the adult stage (Byrne et al., 2013, Clark et al., 2009).
- Experimental work on the impacts of acidification in New Zealand waters on juvenile paua has shown that while survival was not affected, growth was significantly reduced, and dissolution of the shell surface was evident (Cunningham, 2013). Similar effects were found for growth and shell surfaces of flat oysters (Cummings et al., 2013, Cummings et al., 2015). This is consistent with observed negative effects of ocean acidification on the function and metabolism of Antarctic bivalves (Bylenga et al., 2015, Cummings et al., 2011).

- The behaviour of Australian reef fish is affected by ocean acidification, with olfaction, hearing, visual risk assessment and activity altered due to the impact on neurotransmitter function (Munday et al., 2014). MPI funding has supported studies of the impacts of ocean acidification on Kingfish, and this work will be extended to Snapper.

5.13 Considering both Anthropogenic and Natural Changes

Much of the material in Sections 5.1 to 5.12 focuses on the projected impact on the climate of Northland Region over the coming century of increases in global anthropogenic greenhouse gas concentrations. But natural variations, such as those described in Section 4.3 (associated with for example El Niño, La Niña, the Interdecadal Pacific Oscillation, the Southern Annular Mode, and "climate noise"), will also continue to occur. As noted at the beginning of Section 5, those involved in (or planning for) climate-sensitive activities in Northland Region will need to cope with the sum of both anthropogenic change and natural variability.

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

Over the 1900-2014 historical period, the 7-station curve lies within the 41-model ensemble, in spite of the model temperatures including air temperature over the sea, which is expected to warm somewhat slower than over land (Mullan et al., 2016). For the future 2015-2100 period, the RCP 2.6 ensemble shows very little warming trend after about 2030, whereas the RCP 8.5 ensemble 'takes off' to be anywhere between +2°C and +5°C by 2100. The *miroc5* model is deliberately chosen to sit in the middle of the ensemble, and illustrates well how interannual variability dominates in individual years: the *miroc5* model under RCP 8.5 is the warmest of all models in the year 2036 and the coldest of all models in the year 2059, but nonetheless has a long-term trend that sits approximately in the middle of the ensemble.

Figure 5-33 should not be interpreted as a set of specific predictions for individual years. But it illustrates that although we expect a long term overall upward trend in temperatures (at least for RCP8.5), there will still be some relatively cool years. However for this particular example, a year which is unusually warm under our present climate could become the norm by about 2050, and an "unusually warm" year in 30-50 years' time (under the higher emission scenarios) is likely to be warmer than anything we currently experience.

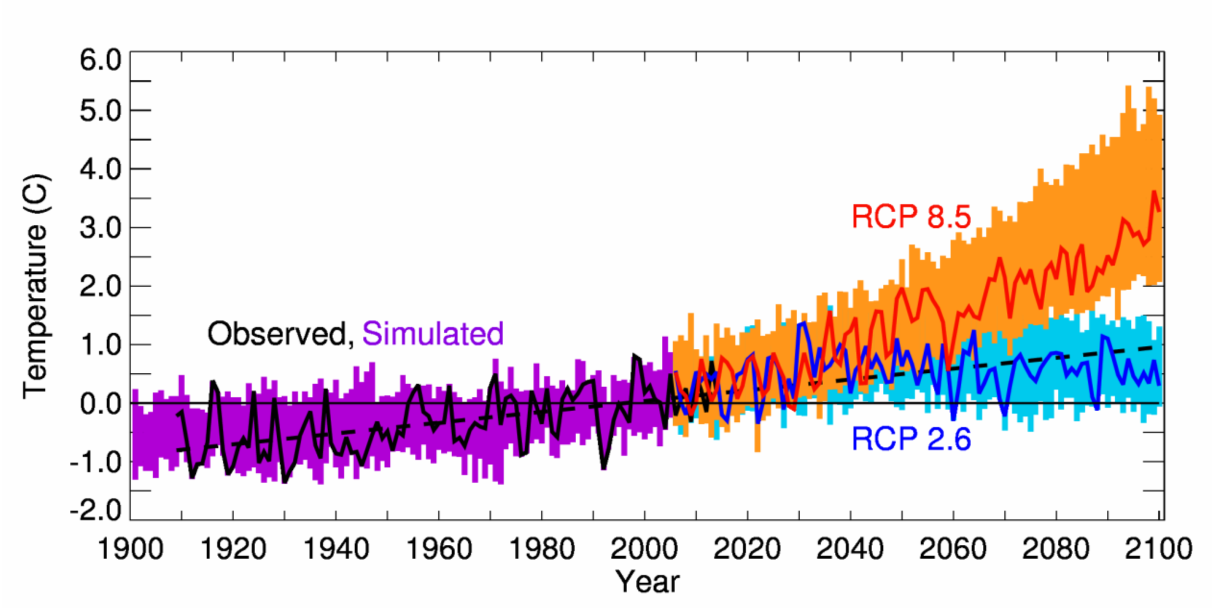


Figure 5-33: New Zealand Temperature - historical record and an illustrative schematic projection illustrating future year-to-year variability. (See text for full explanation). After Mullan et al. (2016).

For rainfall, the fact that we have recently moved into a negative phase of the Interdecadal Pacific Oscillation (Figure 4-13) may be just as important for the Northland Region over the next 2-3 decades as the effects of anthropogenic climate change. From Section 4.3.1, it can be seen that periods of negative SOI (e.g. El Niño) may on average experience below normal rainfall in the eastern part of Northland Region during summer, pushing rainfall in these directions in the opposite direction as expected from anthropogenic factors, which projects increasing rainfall in summer for the eastern part of Northland (Section 5.3). A subsequent further reversal of the IPO in 20-30 years' time could have the opposite effect, enhancing part of the anthropogenic trend in rainfall for a few decades.

As discussed in Section 4.3, the IPO and the El Niño/La Niña cycle have an effect on New Zealand sea level. So the sea levels we experience over the coming century will also result from the sum of anthropogenic trend and natural variability.

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

6 Commentary on other climate change impacts in Northland Region

The main purpose of this report has been to draw together existing information on how Northland Region's climate may change in the future. At Northland Regional Council's request, we have compiled some information on climate change impacts on important industries for Northland: aquaculture, agriculture, horticulture, forestry, biosecurity (aquatic and terrestrial), and groundwater. The resourcing did not extend to undertaking new research on the likely impacts of climate change on these industries, what is presented here is a compilation of existing research in Northland, New Zealand, and internationally.

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

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

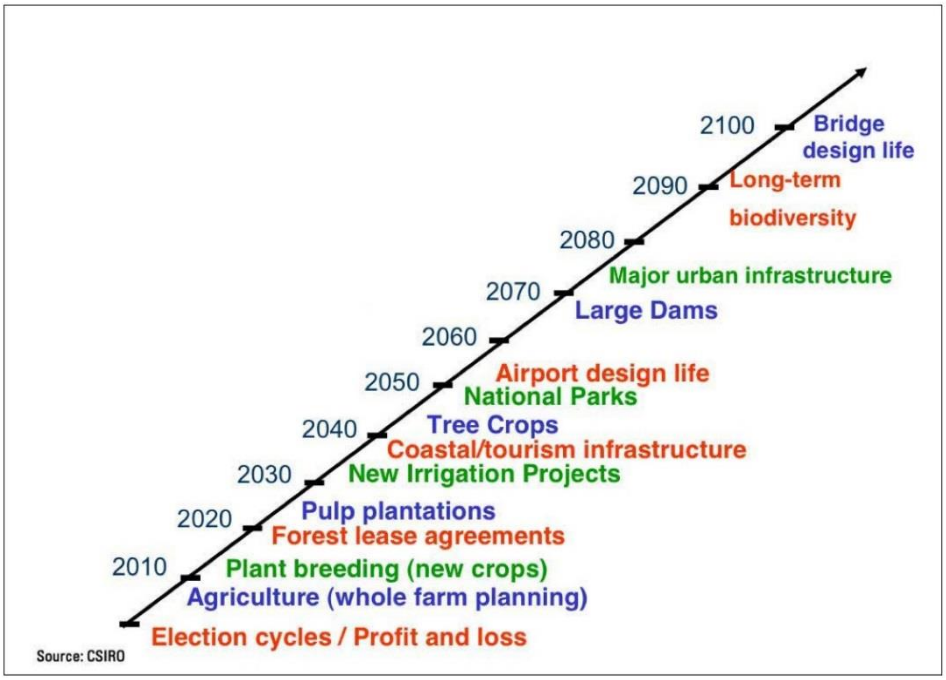


Figure 6-1: Time scales and adaptation. Planning for human-induced climate change becomes increasingly important as one moves right along this line. Source: R. Jones, CSIRO.

6.1 Agriculture, Horticulture and Forestry

Climate change is likely to have the largest impact on primary industries such as agriculture, horticulture, and forestry through changes in climate variability and climate extremes. Mean temperatures are likely to increase in Northland, frost occurrence is projected to decrease, and drought occurrence is likely to increase for some parts (Section 5). In response, farmers and growers in Northland are likely to increase their usage and dependence on existing subtropical plant species and introduce new commercial species that are heat and drought-tolerant (Kean et al., 2015).

In pastoral agriculture, warmer temperatures are likely to shift the competitive balance in pastures towards subtropical grasses that have a C_4 photosynthetic pathway (these species are more efficient under higher temperatures and drier conditions) and it is expected that these species will spread and increase in dominance over large areas of the North Island in response to climate change (Kean et al., 2015). Kikuyu grass (*Pennisetum clandestinum)* is likely to become the most prevalent forage grass as it spreads readily and forms dense swads, out-competing most other pasture species. Chicory (*Cichorium intybus*) and plantain (*Plantago lanceolata*) are two other pasture grass species that are deep-rooted and drought tolerant, which may increase in abundance in Northland. Pasture production will generally increase, especially in winter, through higher CO_2 levels in the atmosphere, higher temperatures and an extended growing season (Kenny, 2001). However, higher incidence of drought (lower soil moisture) in Northland during summer may counteract this extra growth (Renwick et al., 2013).

Heat load is projected to increase to an extent that dairy cows would experience significant thermal stress in many areas of New Zealand, particularly Northland due to higher mean temperatures at present which are likely to rise further (Renwick et al., 2013), as well as a large increase in the number of hot days in the region. Heat stress responses may have a detrimental impact on production, reproduction, and welfare. Wratt et al. (2008) considered productivity and economic impacts for the pastoral farming industry. For the climate scenarios modelled (based on the IPCC Third Assessment Report), both average and worst year production for sheep/beef and dairy were projected to decline for a number of east coast regions as well as Northland. However, the modelling did not consider CO_2 fertilisation of pasture, which could increase production.

For arable cropping in Northland, climate change is likely to be generally positive (Kenny, 2001). Higher temperatures will allow earlier sowing of crops, and they will generally reach maturity faster (depending on sowing time). Higher temperatures could lead to decreased yields, but the fertilising effect of higher levels of CO_2 will potentially offset this, resulting in yield increases for temperate crops such as wheat and barley. Crops such as maize, which utilise CO_2 differently to temperate crops, show little or no yield response to higher levels of CO_2 (Kenny, 2001). The greatest risk for arable cropping will be the availability of water, which is projected to decrease due to increased evaporation and reduced rainfall (thereby increasing risk). Therefore, irrigation costs will probably increase. New (for New Zealand) arable crop species (for example soybeans and rice) may become increasingly viable in some areas.

In horticulture, subtropical crops such as persimmon and macadamia have become commercially viable in northern New Zealand, and it is expected that new subtropical (and possibly tropical) crops will begin to be commercially grown as the climate warms in Northland. The kiwifruit industry in Northland (around Kerikeri) is currently marginal, as winter temperatures do not always provide significant chilling for adequate bud break and flowering, in particular for the Hayward variety (Kenny, 2001). This has led to a decline in the kiwifruit industry in Northland and presumably will continue to do so with projected increases in temperature.

In contrast to the pastoral agriculture and horticulture industries, the forestry sector does not expect to invest in new subtropical crops. The long-term nature of forestry crops means that changes in the species grown can only be done very gradually. In addition, it appears that the main current crop, *Pinus radiata,* will probably perform even better in a warmer New Zealand than it currently does (Kean et al., 2015). Productivity is likely to increase by approximately 30-40% (depending on modelled scenario chosen) due to increased atmospheric CO_2 (Renwick et al., 2013).

Fires are likely to become a larger issue for northern New Zealand with projected increasing temperatures and decreasing rainfall (Reisinger et al., 2014, Pearce et al., 2010). The number of days per year of Very High and Extreme Forest Fire Danger is projected to increase by 40-50% for

Northland to 2050 and 2090 and (from 5.9 days/year to 8.2 days/year for Kaitaia, and from 2.2 days/year to 3.1 days/year for Dargaville) (Pearce et al., 2010). In addition, higher CO_2 may also enhance fuel loads by increasing vegetation productivity. In Northland, commercial forestry is particularly at risk of increased fire weather.

Changes in pests and diseases will also be an important factor for agriculture, and this is discussed below.

6.1.1 Terrestrial biosecurity

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

Although climate change may affect organisms and ecosystems in a range of ways, the most important driver of pest invasion is likely to be temperature, modified by rainfall, humidity and carbon dioxide (Kean et al., 2015). In addition, changes in large-scale weather patterns will influence the frequency and intensity of extreme weather events (e.g. flooding, drought, frost) and regional winds and currents which in turn may affect the ability of potential invaders to reach New Zealand and establish.

The increased usage of subtropical plants (as discussed in Section 6.1) will make Northland more susceptible to invasion by subtropical pests and diseases and new host/pest associations (Kean et al., 2015). The shift towards reliance on drought and heat tolerant plants (in particular, pasture grasses) may cause new pest species to spread. The 2014 emergence of two native moths (*Epyaxa rosearia* and *Scopula rubraria)* as major plantain (a variety of pasture grass) pests demonstrates how a large increase in usage elevated these previously harmless species to pest status. In addition, as kikuyu grass is likely to become the most prevalent forage grass with increasing temperatures, pests that affect kikuyu grass are likely to be important. Some pest species from Australia (e.g. the *Sphenophorus venatus vestitus* weevil) has already been recorded on kikuyu in Northland.

It is important to note that although much of the biosecurity risk with climate change will come from beyond New Zealand's borders, many of the future's pest and disease problems are currently 'sleeping' in New Zealand, awaiting some perturbation, such as climate change, to allow them to spread and flourish. These types of pests are often weeds but may also be invertebrates.

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

- Migratory locust *Locusta migratoria,* found in grassland in Northland. Because existing temperatures are not usually high enough to trigger swarming behaviour, the insect currently is not regarded as a pest. However, the locusts have retained the capacity to swarm with a small swarm observed near Ahipara in the 1980s.
- Tropical armyworm *Spodoptera litura.* While this pest can be found through many lowland North Island districts, epidemic outbreak populations, when caterpillars move 'like an army' through crops and pastures, are rare. However, the combination of events that precipitate

outbreaks will be more common under projected climate change scenarios and include above average summer and autumn temperatures, allowing for additional generations to develop.

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

6.2 Aquaculture

Aquaculture is an important industry for Northland. As an industry that is sensitive to environmental changes, it is important to understand potential risks the industry may be exposed to under future climate change. Kovats et al. (2014) state that aquaculture can be affected by climate change as the areal extent of some habitats that are suitable or used for aquaculture can be reduced by sea-level rise. In addition, it is commonly accepted that warmer sea and fresh water temperatures modify host-pathogen interactions, by increasing host susceptibility to disease (Castinel et al., 2014). Ocean acidification may also have impacts on the early developmental stages of shellfish (see Section 5.12). Sea temperatures are projected to increase around New Zealand, particularly to the west of the country, and seawater is likely to decrease in pH (Royal Society of New Zealand, 2016).

Climate change may also reinforce parasitic diseases and impose severe risks for aquatic animal health. In the Iberian Atlantic, the harvesting period for the mussel aquaculture industry has sometimes been reduced because of harmful algal blooms resulting from changes in phytoplankton communities linked to a weakening of Iberian upwelling (i.e. warmer sea surface temperatures). In freshwater systems, heat waves in summer may boost the development of harmful cyanobacterial blooms (Kovats et al., 2014).

According to Reisinger et al. (2014), no climate change impacts on fisheries in New Zealand have so far been reported, although this may be due to insufficient monitoring. However, although evidence of climate change impacts on coastal habitats is limited to date, confidence is high that negative impacts will arise with continued climate change. Changes in temperature, rainfall, and sea-level are expected to lead to secondary effects, including erosion, landslips and flooding, affecting coastal habitats and their dependent species. Such shifts suggest potentially substantial changes in production and profit of both wild fisheries and aquaculture species such as salmon, mussels, and oysters.

For Pacific oysters (*Crassostrea gigas*) in New Zealand, oyster herpesvirus (OsHV-1) outbreaks are exacerbated in warmer waters, as is the transmission of the parasite *Martelia refringens,* which affects flat oysters (*Ostrea chilensis*) and blue mussels (*Mytilus spp.*) (Castinel et al., 2014). In addition, there are concerns about the future of paua (*Haliotis spp.*) farming in Northland due to warmer waters creating a higher stress environment and potential spread of pathogens for these animals (A. Forsythe, NIWA, pers. comm.).

As stated in Section 5.13, ocean acidification may have impacts on species that are important to Northland's aquaculture industry, for example paua and flat oysters. Experimental work has shown that growth of juveniles of these species was significantly reduced and dissolution of the shell surface was evident in water with higher acidity levels (Cummings et al., 2013, Cummings et al., 2015, Cunningham, 2013).

6.2.1 Aquatic biosecurity

The primary source of entry for aquatic biosecurity risk organisms into New Zealand is and will remain to be through international shipping, whether these risk organisms are contained within ballast water or attached to the hulls of ships. However, changes in water temperature and ocean currents into the future, as a result of climate change, may result in species, including pests and pathogens, not usually seen in New Zealand waters to arrive and establish.

Long-term changes in environmental parameters, such as seawater temperature, may lead to new ecological compatibilities and may alter existing host-pathogen interactions. Such changes could contribute to the emergence of aquatic diseases in new regions (Castinel et al., 2014). Of particular concern for Northland is a strengthening East Auckland Current off the east coast of the region. This strengthening current is expected to promote establishment of tropical or subtropical species that currently occur as vagrants in warm La Niña years (Willis et al., 2007). The establishment of these species may have negative impacts on wild fisheries and also on aquaculture operations.

As is discussed in Section 6.1.1 for agriculture, organisms already established within the New Zealand region that are not currently pests may become problematic under changed environmental conditions with climate change – these are called 'sleeper pests'.

6.3 Groundwater (Recharge and Salinity)

Northland's groundwater resources are primarily contained among 17 coastal and inland aquifers (Cameron et al., 2001) and are abstracted for a mix of agricultural, industrial and municipal purposes (Aqualinc, 2010). Typical seasonal fluctuations see groundwater levels rise in the winter and fall in the summer, due to the combination of seasonal recharge and abstraction, with long-term fluctuations reflecting above- or below-average rainfall amounts. A long-term decline in groundwater level within the Aupouri aquifer system may also have been due in part to afforestation with *Pinus radiata*. In the absence of focused groundwater modelling, one may make inferences about potential groundwater levels and salinisation based on projections of temperature, precipitation, potential evaporation deficit, river flow, and sea level rise – each of which are documented in Section 5.

Groundwater recharge essentially occurs when the ground is near saturation - specifically, above field capacity in terms of soil properties - but recharge may also occur beneath rivers or through fractured rock. With projected increases in potential evaporation deficit (PED) (Section 5.6), one may infer that the soil moisture conditions necessary to allow drainage of water below the root zone towards the underlying aquifer will become less frequent, leading to less recharge. This stems from the combination of higher temperatures (Section 5.1) and, particularly in spring, lower rainfall (Section 5.3). This is further reflected in the surface hydrological simulations of the Wairoa catchment (Section 5.11), which sees declines in mean discharge and, more pertinently, in mean annual low flow, which is a strong reflection of groundwater contributions to baseflow. The amount of relative change in groundwater recharge would be modulated by the aquifer properties; Northland's greywacke catchments may be expected to experience a smaller percentage reduction in recharge than the region's sandy aquifer systems. A quantitative estimate of any reduction in recharge cannot be made without a more process-based model of the recharge process, although groundwater modelling per se would not be necessary.

Towards the coast, groundwater levels are influenced also by sea level, as it is the sea level that sets the water level towards which groundwater flows. This is most relevant to the Aupouri aquifer system. As the sea level rises - projected to range from 0.26-0.82 m by 2081-2100 relative to 1986-

2005 conditions - coastal groundwater levels would increase to match. This would not mean an increase in groundwater yield from the aquifer, per se, but a reduction in groundwater flow velocities. How far this effect extends from the coast depends on aquifer properties, flow velocities, and the amount of sea-level rise. This change could also be associated with an increase in salinisation of the coastal aquifers, which is presently a concern for the Taipa, Ngunguru and Russell aquifers during summer when recharge drops and abstraction increases. It should be noted that these statements are somewhat uncertain without having undertaken groundwater modelling exercises for the region.

6.4 Final points

Some particular impact, vulnerability, and adaptation issues to which Northland Regional Council may wish to give consideration include:

- Implications of sea-level rise and coastal change for planning and development in coastal areas.
- Implications of river flow and sedimentation changes, as well as changing flood regimes for river engineering planning.
- Implications of potential changes in rainfall and of drought frequency for water demand, availability in surface and ground water storage, and allocation (including planning for irrigation schemes and storage).
- Implications of projected changes in extreme rainfall, erosion risk and coastal hazards for council roading and stormwater drainage infrastructure, lifelines planning, and civil defence and emergency management.
- Opportunities which climate change may bring for new horticultural crops – and infrastructure and land-use issues that might arise.
- Implications of climate change (including potential changes in flood frequency, extreme rainfall (influencing hillslope and riverbank erosion) and in coastal hazards) for land-use planning (e.g. erosion control measures, Basher et al. (2012), Manderson et al. (2015)).
- Implications for natural ecosystems and their management, both terrestrial and marine. This is especially relevant given the number of forest parks, nationally significant wetlands, and protected marine areas in the region. Reisinger (2014) gives information on the projected impacts on natural ecosystems for New Zealand as a whole.
- Building consideration of climate change impacts and adaptation into council planning as outlined in MfE guidance. Also important is consultation and discussion with stakeholders (e.g. groups of farmers, iwi) to help them identify climate-related risks and ways of building resilience (e.g. King et al. (2013)).

Recommendations for future work that may assist Northland Regional Council in understanding potential climate change-related impacts:

- Calculation of a homogenised temperature series for locations in Northland

- Understanding Northland’s ex-tropical cyclone climatology
- Influence of climate-induced coastal hazard drivers such as sea-level rise, storm surge and wave climate on Northland Region’s coastlines
- Understanding changes in high tide exceedance frequency with climate-induced sea-level rise
- River flow projections for additional locations in Northland Region
- Groundwater modelling exercises for Northland region.

7 Acknowledgements

The following NIWA staff are acknowledged for their assistance in compiling this report: Andrew Tait, Nicolas Fauchereau, Aran Mol, Andrew Forsythe, Doug Booker, Ben Robinson, and Scott Stephens.

8 References

AQUALINC 2010. Update of water allocation data and estimate of actual water use of consented takes 2009-2010, Report No. H10002/3, prepared for the Ministry for the Environment, pp. 118.

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

BELL, J. J., DAVY, S. K. & JONES, T., ET AL. 2013. Could some coral reefs become sponge reefs as our climate changes? *Global Change Biology* 19**,** 2613-2624

BOOKER, D. J. 2013. Spatial and temporal patterns in the frequency of events exceeding three times the median flow (FRE3) across New Zealand. *Journal of Hydrology (NZ),* 52**,** 15-40.

BOSTOCK, H. C., TRACEY, D. M., CURRIE, K. I., DUNBAR, G. B., HANDLER, M. R., MIKALOFF-FLETCHER, S. E., SMITH, A. M. & WILLIAMS, M. J. M. 2015. The carbonate mineralogy and distribution of habitat-forming deep-sea corals in the Southwest Pacific region. . *Deep-Sea Research I* 100**,** 88–104.

BURRELL, T. J. 2015. *Bacterial extracellular Enzyme Activity in a Future Ocean.* PhD thesis, Victoria University of Wellington.

BYLENGA, C., CUMMINGS, V. J. & RYAN, K. 2015. Fertilisation and larval development in the Antarctic bivalve, Laternula elliptica under reduced pH and elevated temperatures. *Marine Ecology Progress Series,* 536**,** 187-201.

BYRNE, M., LAMARE, M., WINTER, D., DWORJANYN, S. A. & UTHICKE, S. 2013. The stunting effect of a high CO2 ocean on calcification and development in sea urchin larvae, a synthesis from the tropics to the poles. *Phil Trans R Soc B* 368.

CAMERON, S., OSBALDISTON, S., SKUSE, G. & REVFEM, C. 2001. Northland. *In:* ROSEN, M. R. & WHITE, P. A. (eds.) *Groundwaters of New Zealand.* New Zealand Hydrological Society Inc.

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

CHAPPELL, P. R. 2013. The climate and weather of Northland. *NIWA Science and Technology Series,* 59**,** 40.

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

CHURCH, J. A., CLARK, P. U., CAZENAVE, A., GREGORY, J. M., JEVREJEVA, S., LEVERMANN, A., MERRIFIELD, M. A., MILNE, G. A., NEREM, R. S., NUNN, P. D., PAYNE, A. J., PFEFFER, W. T., STAMMER, D. & UNNIKRISHNAN, A. S. 2013b. Sea Level Change. *In:* STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M., ALLEN, S., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

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

CLARK, D., LAMARE, M. & BARKER, M. 2009. Response of sea urchin pluteus larvae (Echinodermata: Echinoidea) to reduced seawater pH: a comparison among a tropical, temperate, and a polar species. *Marine Biology* 156**,** 1125-1137.

CUMMINGS, V., HEWITT, J., ALLEN, S., MARRIOTT, P., BARR, N. & HEATH, P. 2013. Ocean acidification: impacts on key NZ molluscs, with a focus on flat oysters (Ostrea chiliensis). Final Research Report for the NZ Ministry of Primary Industries on project ZBD200913. 18 p.

CUMMINGS, V., HEWITT, J., VAN ROOYEN, A., CURRIE, K. & BEARD, S., ET AL. 2011. Ocean Acidification at High Latitudes: Potential Effects on Functioning of the Antarctic Bivalve Laternula elliptica. . *PLoS ONE,* 6**,** e16069.

CUMMINGS, V., SMITH, A., PEEBLES, B. & MARRIOTT, P. 2015. Shell mineralogy of flat oysters under ocean acidification conditions: preliminary report. Progress report to Ministry of Primary Industries Project ZBD201306. June. 9 p.

CUNNINGHAM, S. C. 2013. *The effects of ocean acidification on juvenile Haliotis iris.* Master of Science, University of Otago.

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

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

GOODHUE, N. G., STEPHENS, S. A. & GORMAN, R. G. 2012b. Combined wave and storm tide hazard for southern Tasman Bay. NIWA report HAM2012-087 prepared for Nelson City Council

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

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

HEPBURN, C. D., PRITCHARD, D. W. & CORNWALL, C. E., ET AL. 2011. Diversity of carbon use strategies in a kelp forest community: implications for a high CO2 ocean. . *Global Change Biology* 17**,** 2488-2497.

IPCC 2013. Summary for Policymakers. *In:* STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC 2014a. Summary for Policymakers. *In:* FIELD, C. B., BARROS, V. R., DOKKEN, D. J., MACH, K. J., MASTRANDREA, M. D., BILIR, T. E., CHATTERJEE, M., EBI, K. L., ESTRADA, Y. O., GENOVA, R. C., GIRMA, B., KISSEL, E. S., LEVY, A. N., MACCRACKEN, S., MASTRANDREA, P. R. & WHITE, L. L. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, NY, USA: Cambridge University Press.

IPCC 2014b. Summary for Policymakers. *In:* EDENHOFER, O., R. PICHS-MADRUGA, Y. SOKONA, E. FARAHANI, S. KADNER, K. SEYBOTH, A. ADLER, I. BAUM, S. BRUNNER, P. EICKEMEIER, B. KRIEMANN, J. SAVOLAINEN, S. SCHLÖMER, C. VON STECHOW, T. ZWICKEL & MINX, J. C. (eds.) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

JAMES, R. K., HEPBURN, C. D. & CORNWALL, C. E., ET AL. 2014. Growth response of an early successional assemblage of coralline algae and benthic diatoms to ocean acidification. . *Marine Biology* 161**,** 1687-1696

KEAN, J. M., BROCKERHOFF, E. G., FOWLER, S. V., GERARD, P. J., LOGAN, D. P., MULLAN, A. B., SOOD, A., TOMPKINS, D. M. & WARD, D. F. 2015. Effects of climate change on current and potential biosecurity pests and diseases in New Zealand. Prepared for Ministry for Primary Industries, MPI Technical Paper No: 2015/25. 100p.

KENNY, G. 2001. Climate Change: Likely impacts on New Zealand agriculture, Prepared for the Ministry for the Environment, Report No. ME412, 32p.

KING, D. N., DALTON, W., BIND, J., SRINIVASAN, M. S., HICKS, D. M., ITI, W., SKIPPER, A., HOME, M. & ASHFORD-HOSKING, D. 2013. Coastal adaptation to climate vulnerability and change: examining community risk, vulnerability and endurance at Mitimiti, Hokianga, Aotearoa-New Zealand. NIWA report AKL2013-022.

KOVATS, R. S., VALENTINI, R., BOUWER, L. M., GEORGOPOULOU, E., JACOB, D., MARTIN, E., ROUNSEVELL, M. & SOUSSANA, J.-F. 2014. Europe. *In:* BARROS, V. R., FIELD, C. B., DOKKEN, D. J., MASTRANDREA, M. D., MACH, K. J., BILIR, T. E., CHATTERJEE, M., EBI, K. L., ESTRADA, Y. O., GENOVA, R. C., GIRMA, B., KISSEL, E. S., LEVY, A. N., MACCRACKEN, S., MASTRANDREA, P. R. & WHITE, L. L. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, NY, USA: Cambridge University Press.

LAW, C. S., BREITBARTH, E., HOFFMANN, L. J., MCGRAW, C. M., LANGLOIS, R. J., LAROCHE, J., MARRINER, A. & SAFI, K. A. 2012. No stimulation of nitrogen fixation by non-filamentous diazotrophs under elevated CO2 in the South Pacific. *Global Change Biology,* 18**,** 3004–3014.

LORREY, A. M., GRIFFITHS, G. M., FAUCHEREAU, N., DIAMOND, H. J., CHAPPELL, P. R. & RENWICK, J. A. 2014. An ex-tropical cyclone climatology for Auckland, New Zealand. *International Journal of Climatology,* 34**,** 1157-1168.

MAAS, E. W., HALL, J. A., LAW, C. S., PICKMERE, S., CURRIE, K. I., CHANG, F. H., VOYLES, K. M. & CAIRD, D. 2013. Effect of ocean acidification on bacterial abundance, activity and diversity in the Ross Sea, Antarctica. *Appl. Microbial Ecol.,* 70**,** 1-15.

MANNING, M., LAWRENCE, J., KING, D. N. & CHAPMAN, R. 2014. Dealing with changing risks: a New Zealand perspective on climate change adaptation. *Regional Environmental Change,* 15**,** 581-594.

MCMILLAN, H., JACKSON, B. & POYCK, S. 2010. Flood risk under climate change: A framework for assessing the impacts of climate change on river flow and floods, using dynamically-downscaled climate scenarios - A case study for the Uawa (East Cape) and Waihou (Northland) catchments. NIWA client report prepared for Ministry of Agriculture and Forestry, No. CHC2010-033, 63p.

MINISTRY FOR THE ENVIRONMENT 2008a. Climate Change Effects and Impacts Assessment. A Guidance Manual for Local Government in New Zealand. *In:* MULLAN, B., WRATT, D., DEAN, S., HOLLIS, M., ALLAN, S., WILLIAMS, T., KENNY, G. & MFE (eds.). Wellington: Ministry for the Environment.

MINISTRY FOR THE ENVIRONMENT 2008b. Coastal hazards and climate change. A guidance manual for local government in New Zealand. 2nd edition. Revised by Ramsay, D. and Bell, R. (NIWA). Prepared for Ministry for the Environment. viii+127 p.

MULLAN, A. B., PORTEOUS, A., WRATT, D. & HOLLIS, M. 2005. Changes in drought risk with climate change. NIWA report WLG2005-23 for Ministry for the Environment and Ministry of Agriculture and Fisheries, Wellington.

MULLAN, A. B., SOOD, A. & STUART, S. 2016. Climate Change Projections for New Zealand based on simulations undertaken for the IPCC 5th Assessment. Part A: Atmosphere Changes. NIWA Client Report for Ministry for the Environment, WLG2015-31. June 2016.

MUNDAY, P. L., CHEAL, A. J. & DIXSON, D. L., ET AL. 2014. Behavioural impairment in reef fishes caused by ocean acidification at CO2 seeps. *Nature Climate Change* 4**,** 487-492.

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

REISINGER, A., KITCHING, R. L., CHIEW, F., HUGHES, L., NEWTON, P. C. D., SCHUSTER, S. S., TAIT, A. & WHETTON, P. 2014. Australasia. *In:* BARROS, V. R., FIELD, C. B., DOKKEN, D. J., MASTRANDREA, M. D., MACH, K. J., BILIR, T. E., CHATTERJEE, M., EBI, K. L., ESTRADA, Y. O., GENOVA, R. C., GIRMA, B., KISSEL, E. S., LEVY, A. N., MACCRACKEN, S., MASTRANDREA, P. R.

& WHITE, L. L. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK, and New York, NY, USA: Cambridge University Press.

RENWICK, J. A., MULLAN, A. B., WILCOCKS, L., ZAMMIT, C., STURMAN, J., BAISDEN, T., KELLER, L., KIRSCHBAUM, M., MEASON, D., HARRISON, D., VERKERK, G., COOKE, A., MARSHALL, P. & CLARK, A. 2013. Four degrees of global warming: effects on the New Zealand primary sector. MPI Technical Information Paper No. 2013/49. 180p.

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

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

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

SMITH, A. M., BERMAN, J. & KEY JR, M. M., ET AL. 2013. Not all sponges will thrive in a high-CO2 ocean: Review of the mineralogy of calcifying sponges. *Palaeogeography Palaeoclimatology Palaeoecology,* 392**,** 463-472.

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

TAIT, L. 2014. Impacts of natural and manipulated variations intemperature, pH and light on photosynthetic parameters of coralline–kelp assemblages. *J. Mar Exp Biol. Ecol.,* 454**,** 1-8.

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

THRESHER, R. E., GUINOTTE J.M., MATEAR R.J.; ET AL. 2015. Options for managing impacts of climate change on a deep-sea community. *Nature Climate Change* 5**,** 635-639.

TITTENSOR, D. P., BACO, A. R. & HALL-SPENCER, J. M., ET AL. 2010. Seamounts as refugia from ocean acidification for cold-water stony corals. *Marine Ecology- An Evolutionary Perspective* 31**,** 212-225.

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

WONG, P. P., LOSADA, I. J., GATTUSO, J.-P., HINKEL, J., KHATTABI, A., MCINNES, K. L., SAITO, Y. & SALLENGER, A. 2014. Coastal systems and low-lying areas. *In:* BARROS, V. R., FIELD, C. B., DOKKEN, D. J., MASTRANDREA, M. D., MACH, K. J., BILIR, T. E., CHATTERJEE, M., EBI, K. L., ESTRADA, Y. O., GENOVA, R. C., GIRMA, B., KISSEL, E. S., LEVY, A. N., MACCRACKEN, S., MASTRANDREA, P. R. & WHITE, L. L. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, NY, USA: Cambridge University Press.

WRATT, D., MULLAN, A. B., TAIT, A., WOODS, R., BAISDEN, T., GILTRAP, D., HENDY, J. & STROOMBERGEN, A. 2008. Costs and benefits of climate change and adaptation to climate change in New Zealand agriculture: What do we know so far? *Contract report by EcoClimate Consortium: Integrated research on the economics of climate change impacts, adaptation and mitigation.* Ministry of Agriculture and Forestry, 112p.