Southland climate change impact assessment

Prepared for Environment Southland, Invercargill City Council, Southland District Council and Gore District Council

August 2018

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NIWA CLIENT REPORT No: 2018120CH
Report date: August 2018
NIWA Project: ENS18504

Quality Assurance Statement		
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Executive summary

The global climate system is changing and with it New Zealand's climate and environment. These changes will have implications not only for New Zealand's climate and weather systems but also for freshwater availability for downstream users and for hazard exposure (inland and coastal). Due to the nature of climate change, trends will vary across the country, over the course of the century, and among scenarios of climate change. Building on the assessment of future changes in New Zealand's climate (based on six model projections), this report addresses potential impacts of climate change on a range of components of climate, hydrology and coastal processes across Southland using downscaled Global Climate Model (GCM) outputs from 1971-2099 under different global warming scenarios. The combination of six GCMs and four warming scenarios allows us to consider a plausible range of future trajectories of greenhouse gas emissions and climatic responses.

It is impossible at this stage to attribute the modelled differences between two time periods (in this report, mid-century and end of century) solely to climate change, as natural climate variability is also present and may add to, or subtract from, the climate change effect. The resulting potential impacts of climate change are presented through averaging of the six model projections, which does reduce the underlying natural variability to some extent. With these caveats in mind, the potential effects of changing climate over this century are summarised as follows:

1. The projected Southland temperature changes increase with time and emission scenario. Future annual average warming spans a wide range: 0.5-1°C by 2040, and 0.7-3°C by 2090, largely dependent on scenario. Seasonally, autumn is the season where most of the warming occurs across all time periods and scenarios. Diurnal range (i.e., difference between minimum and maximum temperature during the day) is expected to increase with time and emission scenarios.

2. Changes in extreme temperatures reflect the changes in the average annual signal. The average number of hot days is expected to increase with time and scenario spanning from 0-10 days by 2040 to 5-55 days by 2090. Consequently, the number of heatwave days (i.e., number of consecutive days where the temperature is higher than 25°C) is projected to increase (largest increase with elevation). As expected, the number of frost days is expected to decrease by 0-5 days by mid-century, and by 10-20 frost days by the end of the century.

3. Projected changes in rainfall show a marked seasonality and variability across the Southland region. Annual rainfall is expected to slightly increase by mid-century (0-5%), while the increase spans 5-20% (with a larger increase in the northern part of the region) at the end of the century. Seasonally the largest increases are projected during winter, while summer precipitation is expected to decrease in the Waiau catchment (by up to 10% at the end of the century).

4. By mid-century, the number of wet days is expected to decrease by up to 10 days across most of the region. However, wet days are expected to increase by the end of the century for most of the region, except the Waiau where 10-20 fewer wet days are expected.

5. The number of heavy rain days (i.e., days where the total precipitation exceeds 50mm) is projected to increase throughout the Southland region at all time slices and RCPs,

except for a small area in the eastern Waiau catchment where a small decrease in the number of heavy rain days is projected for mid-century.

6. By mid-century, decreases in annual maximum 5-day rainfall are projected for the centre of the Southland region (up to 15 mm) and increases are projected for the rest of the region, with Fiordland facing the largest increases of 15-30 mm in some parts. At the end of the century, almost the whole Southland region (except the eastern Waiau under mid-range emission scenario) is projected to experience increases in annual maximum 5-day rainfall of up to 15-30 mm.

7. By mid-century the number of dry days are expected in increase up to 10 more days for much of the region except the central part of the region and northern and western Fiordland, for which up to 10 fewer dry days are expected. By the end of century, a decrease in dry days (up to 10-20 days) is projected for most of the region except for the Waiau catchment (increase up to 10-20 days), eastern Fiordland, and Stewart Island/Rakiura.

8. Changes in meteorological drought (assessed using Potential Evaporation Deficit or PED) indicate that the central-northern part of the Southland region is projected to experience the largest increases in PED in the future across both time slices and all emission scenarios. By mid-century, PED is expected to increase by 40-80mm per year for most of the regions, rising to over 100 m per year for the highest emission scenario by 2090.

9. Changes in sea level-rise are expected to be between 0.2-0.3 m by 2040 and increasing to 0.4-0.9 m by 2090. Using a present 1% annual exceedance probability (AEP) coastal flood event (i.e., a 100-year event presently), such an event will become much more frequent as seas continue to rise, with such large events occurring on average on a yearly basis once sea-level rise reaches 0.45 m (expected between 2055-2060 and 2100 (depending on global emission reductions and polar ice-sheet response to warming). Further, moderate and "nuisance" coastal flooding events will become even more common, occurring several times a year for that same sea-level rise. Note: 0.45 m sea-level rise is just an arbitrary value for when a 1% AEP event becomes an annual occurrence (e.g., in Wellington it is only a 0.3 m rise as the tide range is low) – however the adaptation threshold for low-lying parts of Southland may well occur at considerably lower rises in sea level, due to the increasingly regular damage from flooding events (direct or via groundwater) in low-lying pockets, Considering tides only, putting aside storm events, the rising sea level will result in an increasing percentage of normal high tides exceeding given present-day design for coastal infrastructure and roads.

10. Provisional results from a national coastal risk exposure study (Deep South Science Challenge) demonstrate the crucial benefit of having available accurate LiDAR surveys of the topography. The replacement costs of buildings exposed in the LiDAR areas where such surveys are already available (mainly low-lying parts of Invercargill City) is considerable at ~$0.6–1.2B (2011 NZ$) for a range from present exposure to 1% AEP coastal floods up to a 1.2 m sea-level rise (not counting other infrastructure such as roads, 3-waters, rail, airport etc).

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

    - Annual average discharge is expected to remain stable or slightly decrease by mid-century (except North Fiordland). By the end of the century and with increased emissions, average annual flows are expected to increase across the region (up to 50% in Ōreti and Matāura catchments). From a seasonal aspect, spring flows are expected to be slightly higher, summer flows are expected to slightly decrease, while autumn and winter flows are expected to increase.
    - Low flow (expressed as Q95% flow) changes are expected to be variable across the Southland region. Low flows in Fiordland and the headwaters of the Waiau catchment are expected to increase with time and emission scenario. Low flows for the remainder of the region are expected to decrease, except for the coastal areas of the Ōreti and Matāura catchments.
    - Floods (characterised by the Mean Annual Flood) are expected to become larger everywhere.
    - Change in water supply reliability are characterised by little appreciable change across Southland by mid-century, with most parts of the region exhibiting slight increases and some with slight decreases. Late-century, however, the decreases become slightly more accentuated, particularly under a high emissions scenario.

Table 1-1 summarises the key findings of this report for each administrative region by the end of the century.

Table 1-1: Main features of change projections per administrative region by the end of century.

Region Authority	Summary of change
Waiau	Average temperatures are expected to increase above 3.00°C in Northern Waiau while minimum temperatures are expected to increase by more that 1.75°C for most of the Waiau. Hot days are expected to increase by up to 30 days, while cold nights are expected to decrease by around 25-30 nights per year Heatwave days are expected to increase largely for the Northern Waiau valley. Annual precipitation, annual maximum daily and maximum 5-day rainfall are expected to increase by 5 to 20% across the catchment with summer precipitation in coastal Waiau expected to decrease by up to 10%. Number of wet days is expected to decrease for most of the catchment, while number of dry days is expected to increase for most of the catchment except an area north of the Aparima catchment where the number of dry days is expected to decrease. Headwater of the Waiau are expected to experience increase in mean annual low flow (MALF), resulting in increased water supply reliability for this part of the Waiau.

Aparima	Average temperatures are expected to increase up to 2.50°C in Northern Aparima and minimum temperatures are expected to increase by up to 1.7°C. Hot days are expected to increase by up to 30 days, while cold nights are expected to decrease by around 20-25 nights per year. Heatwave days are expected to increase largely for most of the Aparima with orography. Annual precipitation, annual maximum daily and maximum 5-day rainfall are expected to increase by up to 10%, with summer precipitation expected not to change. Number of wet days is expected to increase except on the Northern Aparima while number of dry days is expected to increase by up to 10 days across the catchment. MALF is expected to decrease across the Aparima.
Ōreti	Average temperatures are expected to increase by up to 3.00°C in Northern Ōreti with minimum temperatures are expected to increase by up to 1.75°C . Hot days are expected to increase by up to 30 days per year, while cold nights are expected to decrease around 20-25 nights per year (note strong orographic effect). Heatwave days are expected to increase largely for most of the Ōreti with orography. Annual precipitation, annual maximum daily and maximum 5-day rainfall are expected to increase by 10-15% (mainly in winter) while summer precipitation is not expected to change. Number of wet days is expected to increase except on the Northern Ōreti, while number of dry days are expected to increase by up to 10 days Large increase in mean annual flow, while summer flows are variable across the catchment. However, mean annual low flows are expected to decrease across the Ōreti.
Matāura	Average temperatures are expected to increase above to 3.00°C in northern Matāura with minimum temperatures are expected to increase by up to 1.75°C. Hot days are expected to increase by up to 55 days per year in Northern Matāura. Cold nights are expected to decrease in an average of 20-25 night per year, with a strong orographic gradient between the coast and the Northern Matāura. Heatwave days are expected to increase largely for most of the Matāura with orography. Annual precipitation, annual maximum daily and maximum 5-day rainfall are expected to increase up to 15 % (mainly in winter) with summer precipitation is not expected to change, Number of wet days per year is expected to increase for most of the catchment as per the number of dry days (up to 10 days). Large increase in mean annual flows, while summer flows are variable across the catchment. However, mean annual low flows are expected to decrease across the Matāura catchment.
Fiordland	Average temperatures are expected to increase above 3.00°C in Northern Fiordland. With minimum temperatures are expected to increase by more than 1.75°C for Northern Fiordland. Hot days are expected to increase by 10 days per year except for the northern part where the increase is expected to be around 20 days/year. Number of cold nights are expected to decrease by up to 25 nights per year in Northern Fiordland. Heatwave days are expected to increase largely in northern Fiordland.

	Precipitation, annual maximum daily and maximum 5-day rainfall are expected to increase above 15% (northern Fiordland precipitation increasing by 30%). Largest increase in precipitation in winter (above 40%) with summer precipitation (mainly in winter). Heavy rain days is expecting to increase for most of Fiordland. Number of dry days is expected to increase for most of Fiordland except orthern and western Fiordland. Mean annual low flows and water supply reliability are expected to increase

At this time, it is uncertain as to which of the four climate change scenarios New Zealand and the world is heading for. Current global and New Zealand temperatures are within the ranges of uncertainty for all scenarios. The future trajectory of climate change will depend on geopolitical decisions in terms of reducing greenhouse gas emissions.

Based on a review of existing literature, the potential implications of the projected climate change impacts are briefly discussed for the following industry sectors pertinent for the Southland region: council infrastructure, agriculture, fishing and aquaculture, forestry, tourism, and also to understand potential changes in coastal erosion processes.

1 Introduction

The climate is changing and it is accepted internationally that further changes will result from increasing amounts of greenhouse gases in the atmosphere. In addition, climate will also vary from year to year and decade to decade due to natural processes such as El Niño. Climate change effects over the next decades are predictable with some level of certainty, and will vary from place to place throughout New Zealand (Ministry for the Environment, MfE 2016).

Environment Southland, in collaboration with Invercargill City Council, Southland District Council and Gore District Council (the Councils), commissioned NIWA to produce a regional assessment of the impacts of climate change for Southland. This assessment aims to provide regional information on the impacts of climate change which can be used to support strategic planning and adaptation by the Councils and their communities.

Based on the climate change information generated as part of the *Climate Change Projections for New Zealand* (MfE 2016), and the recent coastal guidance for local government (MfE 2017), NIWA has developed a technical climate change report (including a climate change data output library) based on downscaled global climate change projections for the Councils to support detailed regional, district and community planning. The base report first provides a background on modern climate variability and change to enable meaningful interpretations of the future climate change simulation results across the region (Figure 1-1). As part of the report, changes in different precipitation thresholds are reported at specific locations to reflect potential change in rain risk profiles at those locations (see Figure 1-1).

Analyses are provided through summary maps describing the differences between the historical period 1986-2005 and two future periods: mid-century (2031-2050) and late-century (2081-2100), as per MfE (2016). Using a combination of six downscaled Global Climate Model (GCM) outputs from 1971-2099 under four global warming scenarios (referred hereafter as Representative Concentration Pathways or RCPs) allows consideration of a plausible range of future trajectories of greenhouse gas emissions and climatic responses.

Those changes were estimated for all RCPs, and are provided as netcdf gridded information to Environment Southland. For the sake of clarity only two emissions scenarios are presented in the analysis (RCPs 4.5 and 8.5) in regards to change in climate characteristics and hydrology.

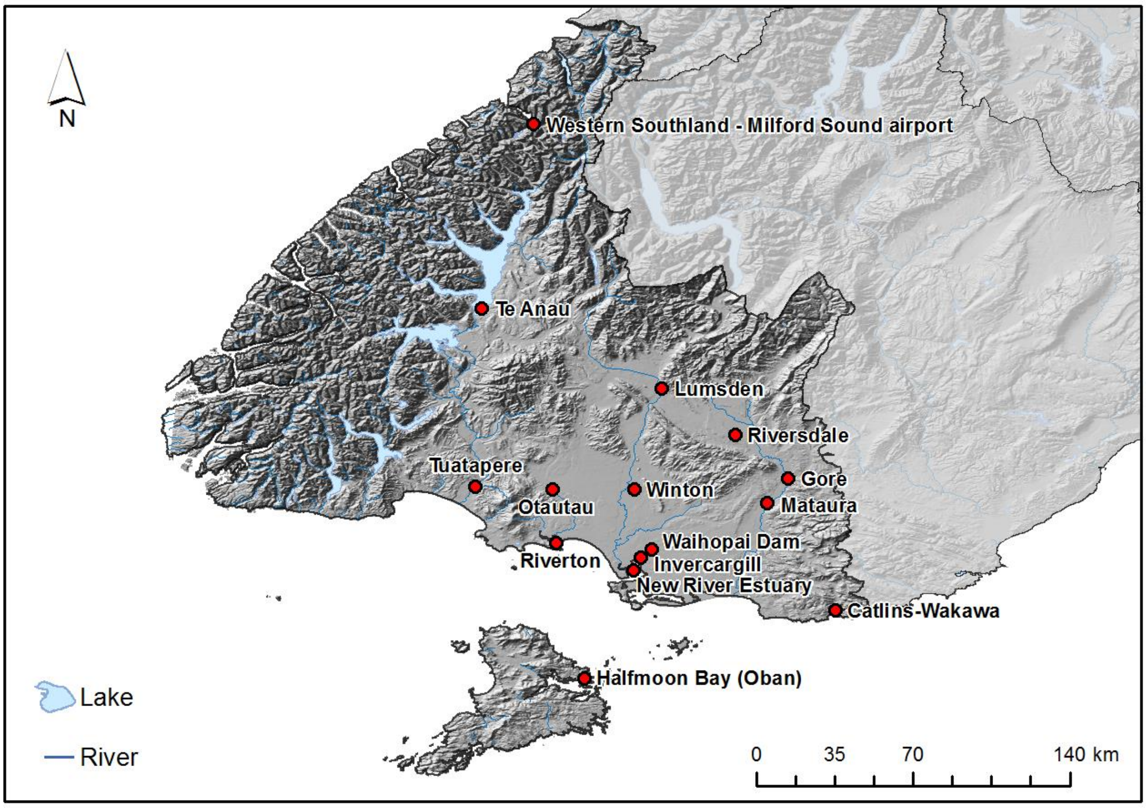

Figure 1-1: Map of the Southland region. Red dots indicate location specific projections presented in this report.

To reflect a precautionary approach, and considering a range of available climate change scenarios, the report considers four RCPs: 2.6 (peak and decline GHG concentration scenario), 4.5 and 6.0 (GHG stabilization scenarios) and RCP 8.5 (representing very high GHG emissions).[1] These four RCP scenarios are considered "standard content" for broadly outlining future climate change effects (see Figure 1-2).

[1] Representative Concentration Pathways represent different climate mitigation scenarios from very low greenhouse gas concentrations to very high.

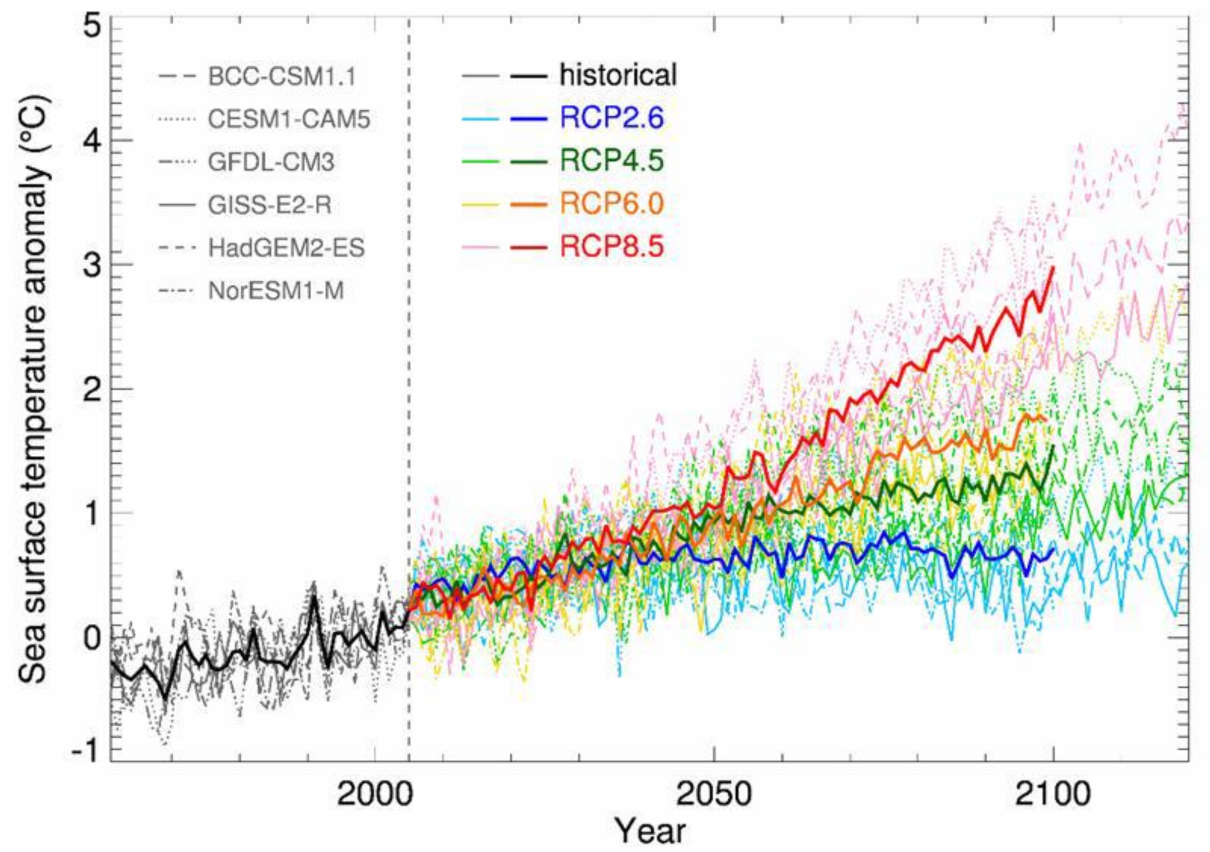

Figure 1-2: Bias-adjusted SSTs, averaged over the RCM domain, for 6 CMIP5[2] global climate models over the historical period (1960-2005), and the future period (2006-2120). Individual models are shown by thin dotted or dashed or solid lines (as described in the inset legend), and the 6-model ensemble-average by thicker solid lines, all of which are coloured according to the RCP pathway.

[2] CMIP5: Coupled Model Intercomparison Project version 5 is a standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models (AOGCMs). CMIP provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. Analysis of CMIP5 dataset provides much of the new material underlying the Intergovernmental Panel on Climate Change version 5 (IPCC5)

2 Introduction to climate change and natural variability

This section describes the present-day climate and climate changes which may occur over the coming century in the Southland region. Consideration about future change incorporates knowledge of both natural variations in the climate and changes that may result from increasing global concentrations of greenhouse gases that are contributed to by human activities. Climatic variables discussed in this section include temperature (mean, mean minimum, hot days, frosts, and heatwave days), rainfall (total rainfall, wet days (> 1 mm), heavy rain days (> 50 mm), annual maximum 1-day rainfall, annual maximum 5-day rainfall, dry days (< 1 mm) and potential evapotranspiration deficit (annual PED accumulation, probability of annual PED > 200 mm).

Future climate change projections for Southland are based on scenarios for New Zealand that were generated by NIWA from downscaling of global climate model simulations from the latest assessments by the Intergovernmental Panel on Climate Change (IPCC, 2013b, IPCC, 2014b, IPCC, 2014c). The climate change information presented in this report is consistent with recently-updated national-scale climate change guidance produced for MfE (Mullan et al. 2016), but this report contains additional analysis that was not included in the MfE report – such as analysis of heatwaves and annual maximum 5-day rainfall.

The remainder of this chapter includes a brief introduction of global climate change, based on the IPCC Fifth Assessment Report. It also includes an introduction to the climate change scenarios used in this report. The methodology that explains the modelling approach for the climate change projections is presented in Appendix A. Climate drivers, such as the El Niño-Southern Oscillation, are also considered as they provide context on year-to-year climate variability experienced in Southland.

2.1 Global climate change: The physical science basis.

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

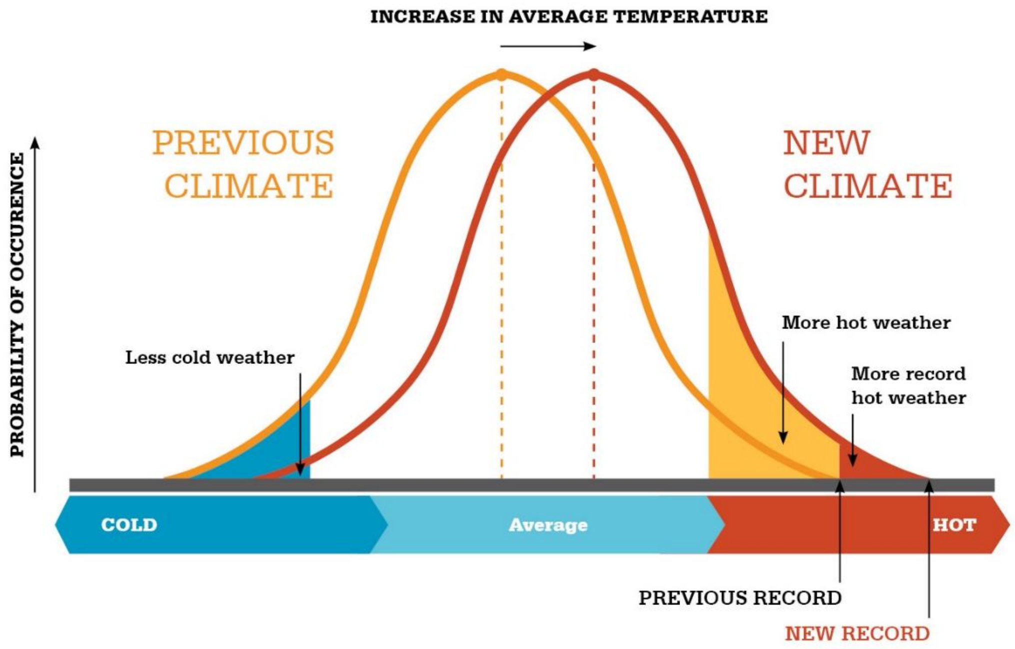

Figure 2-1: Schematic showing how small shifts in average temperature result in large changes in extreme temperatures. From www.climatecommission.gov.au.

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

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

2.1.1 Representative Concentration Pathways

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

This range of uncertainty has been dealt with by the IPCC through consideration of 'scenarios' that describe the radiative forcing and are associated with indicative concentrations of greenhouse gases in the atmosphere. The wide range of scenarios are associated with possible economic, political, and social developments during the 21st century, and beyond. In the 2013 IPCC Fifth Assessment Report, the atmospheric greenhouse gas concentration components of these scenarios are called RCPs.

These are abbreviated as RCP2.6, RCP4.5, RCP6.0, and RCP8.5, in order of increasing radiative forcing[3] by greenhouse gases (i.e., the change in energy in the atmosphere due to greenhouse gas emissions). RCP2.6 leads to very low anthropogenic greenhouse gas concentrations (requiring removal of CO_2 from the atmosphere, also called the 'mitigation' scenario), RCP4.5 and RCP6.0 are two 'stabilisation' scenarios (where greenhouse gas emissions and therefore radiative forcing stabilises by 2100) and RCP8.5 has very high greenhouse gas concentrations (the 'business as usual' scenario with no effective mitigation). Therefore, the RCPs represent a range of 21st century climate policies.

The full range of projected globally-averaged temperature increases for all scenarios for 2081-2100 (relative to 1986-2005), which takes into account the range of projections from about 40 different climate models, is 0.3 to 4.8°C (Figure 2-2). Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform. 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 heatwaves will occur with a higher frequency and duration. Furthermore, the contrast in rainfall between wet and dry regions and wet and dry seasons will increase. Along with increases in global mean temperature, mid-latitude and wet tropical regions will experience more intense and more frequent extreme rainfall events by the end of the 21st century. The global ocean will continue to warm during the 21st century, influencing ocean circulation and sea ice extent.

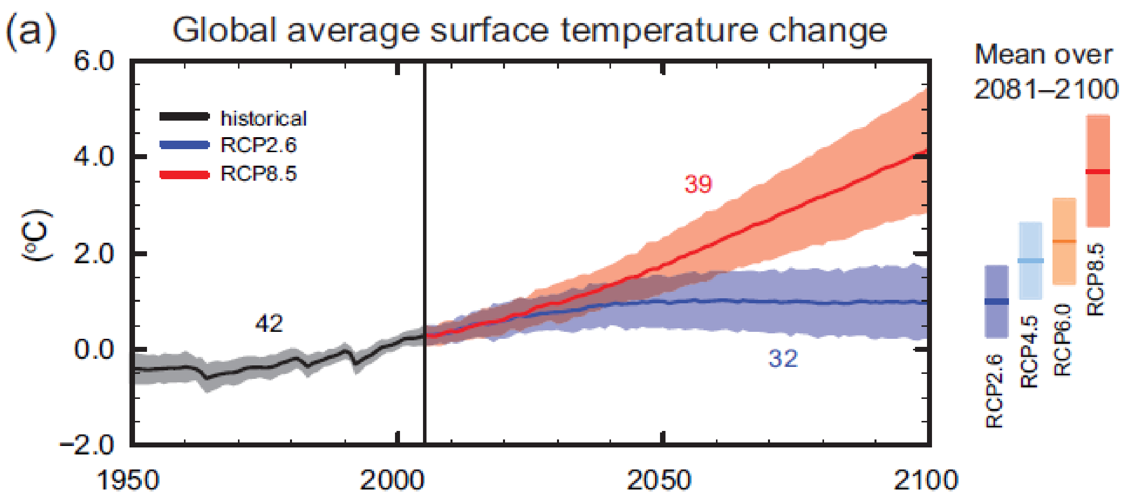

Figure 2-2: CMIP5 multi-model simulated time series from 1950-2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled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

[3] A measure of the energy absorbed and retained in the lower atmosphere. More technically, radiative forcing is the change in the net (downward minus upward) irradiance (expressed in W/m^2, and including both short-wave energy from the sun, and long-wave energy from greenhouse gases) at the tropopause, due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the sun.

Global MSL will continue to rise during the 21st century. All scenarios project that the rate of sea-level rise will very likely exceed that observed during 1971-2010 due to increased ocean warming and higher loss of mass from glaciers and continental ice sheets. For all four RCP scenarios, the range of projected global-mean sea-level rise by 2100 (relative to 1986-2005) is 0.28-0.98 m (Church et al. 2013), with a 33% chance that SLR could still lie outside this range. The IPCC Assessment also added a caveat that if the polar ice sheet instabilities eventuated, then there is medium confidence that the additional increase in SLR would not exceed several tenths of a metre by 2100 (Church et al. 2013). It is virtually certain that global mean sea-level rise will continue beyond 2100, with sea-level rise due to thermal expansion and polar ice-sheet melt expected to continue for many centuries. However, while the rise will continue beyond this century, the future magnitude and rate of SLR is strongly tied to the degree to which global carbon emissions can be reduced in the next several decades (MfE 2017).

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

At this time, it is uncertain as to which of the four climate change scenarios New Zealand and the world is heading towards, as current global and New Zealand temperatures are within the ranges of uncertainty for all scenarios. The future trajectory of climate change will depend on geopolitical decisions in terms of reducing greenhouse gas emissions. The Paris climate change agreement[4] aims to limit global warming to less than 2°C above pre-industrial global mean temperature by 2100, and ideally less than 1.5°C above pre-industrial levels. This level of warming is approximately equivalent to the RCP4.5 scenario.

In this report, global climate model outputs based on two RCPs (RCP4.5 and RCP8.5) have been downscaled to produce future projections of climate for Southland. The rationale for choosing these two scenarios was to present a 'business-as-usual' scenario if greenhouse gas emissions continue unabated (RCP8.5) and a scenario which could be realistic if global action is taken towards mitigating climate change (RCP4.5). GIS files for all four RCPs, for all climate variables considered in this report, have been provided to Environment Southland.

2.2 Impacts, adaptation and vulnerability (IPCC Working Group II)

The IPCC AR5 Working Group II Summary for Policymakers (IPCC, 2014b) concluded 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 the distribution and migration patterns of 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

[4] http://www.mfe.govt.nz/climate-change/why-climate-change-matters/global-response/paris-agreement

increased warming of around 1°C, the number of such systems at risk of severe consequences is higher, and many species with limited adaptive capacity (e.g., coral reefs and species reliant on 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 heatwaves, extreme precipitation, and coastal flooding, are already moderate/high with 1°C additional warming. Risks associated with some types of extreme events (e.g., heatwaves) increase further with higher temperatures.

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

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

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

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

In many regions, climate change adaptation experience is accumulating across the public and private sector and within communities. Adaptation is becoming embedded in governmental planning and development processes, but at this stage there has been only limited implementation of responses to climate change. Engineered and technological options are commonly implemented adaptive responses, often integrated within existing programs such as disaster risk management and water management. There is increasing recognition of the value of social, institutional, and ecosystem-based measures and of the extent of constraints to adaptation. Adaptation options adopted to date continue to emphasise incremental adjustments and co-benefits and are starting to emphasise flexibility and learning. Most assessments of adaptation have been restricted to impacts, vulnerability and adaptation planning, with very few assessing the processes of implementation or the effects of adaptation actions.

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

2.3 Mitigation of climate change (IPCC Working Group III)

The IPCC AR5 Working Group III Summary for Policymakers (IPCC, 2014c) noted 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 4.8°C (IPCC, 2014a).

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

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

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

2.4 New Zealand climate change

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

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

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

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

2.5 Natural factors causing fluctuation in climate patterns over New Zealand

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

2.5.1 The effect of El Niño and La Niña

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

During El Niño, easterly trade winds weaken and warm water 'spills' eastward across the equatorial Pacific, accompanied by higher rainfall than normal in the central-east Pacific. La Niña produces opposite effects and is typified by an intensification of easterly trade winds, and retention of warm ocean waters over the western Pacific. ENSO events occur on average 3 to 7 years apart, typically becoming established in April or May and persisting for about a year thereafter (Figure 2-3). The longer Interdecadal Pacific Oscillation (IPO, Section 2.5.2) is associated with different phases of ENSO, with more El Niño events occurring in positive IPO phases (e.g. 1978-1998) and more La Niña events occurring in negative IPO phases (e.g. 1950-1977).

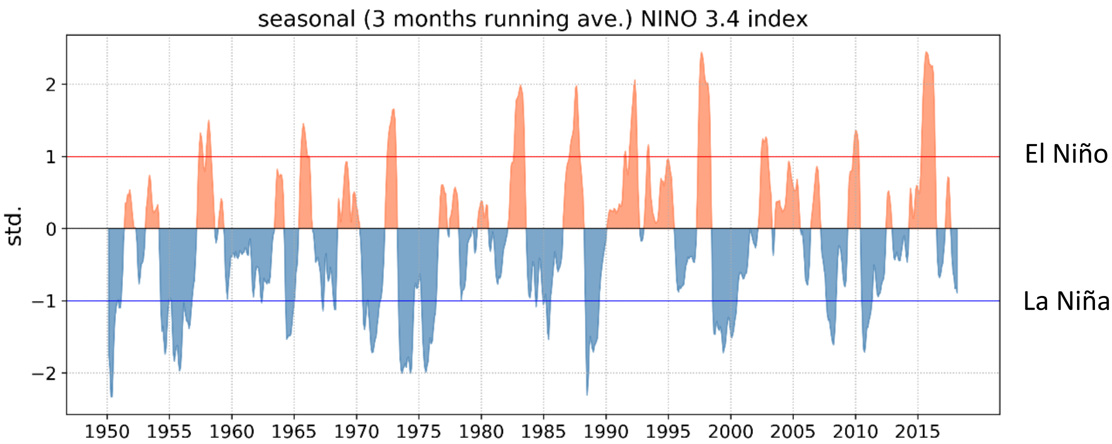

Figure 2-3: Time series of NINO3.4 sea surface temperature from 1950-2017. Values >1 correspond with El Niño and values <1 correspond with La Niña. Data source: http://www.cpc.ncep.noaa.gov/data/indices/ersst5.nino.mth.81-10.ascii.

During El Niño events, the weakened trade winds cause New Zealand to experience a stronger than normal south-westerly airflow. This generally brings lower seasonal temperatures to the country and drier than normal conditions to the north and east of New Zealand, and wetter than usual conditions for parts of Southland (Salinger and Mullan, 1999) (Figure 2-4). Mean sea level around New Zealand can be several centimetres (up to 12 cm) lower than "normal" during peak El Niño events (Ministry for the Environment 2017). During La Niña conditions, the strengthened trade winds cause New Zealand to experience more north-easterly airflow than normal, higher-than-normal temperatures (especially during summer), and drier conditions for much of the South Island, including Southland (Figure 2-5). Mean sea level is generally higher than normal.

According to IPCC (2013b), ENSO is highly likely to remain the dominant mode of natural climate variability in the 21st century, and rainfall variability relating to ENSO is likely to increase. However, there is uncertainty about future changes (over the next 50 to 100 years period) to the amplitude and spatial pattern of ENSO.

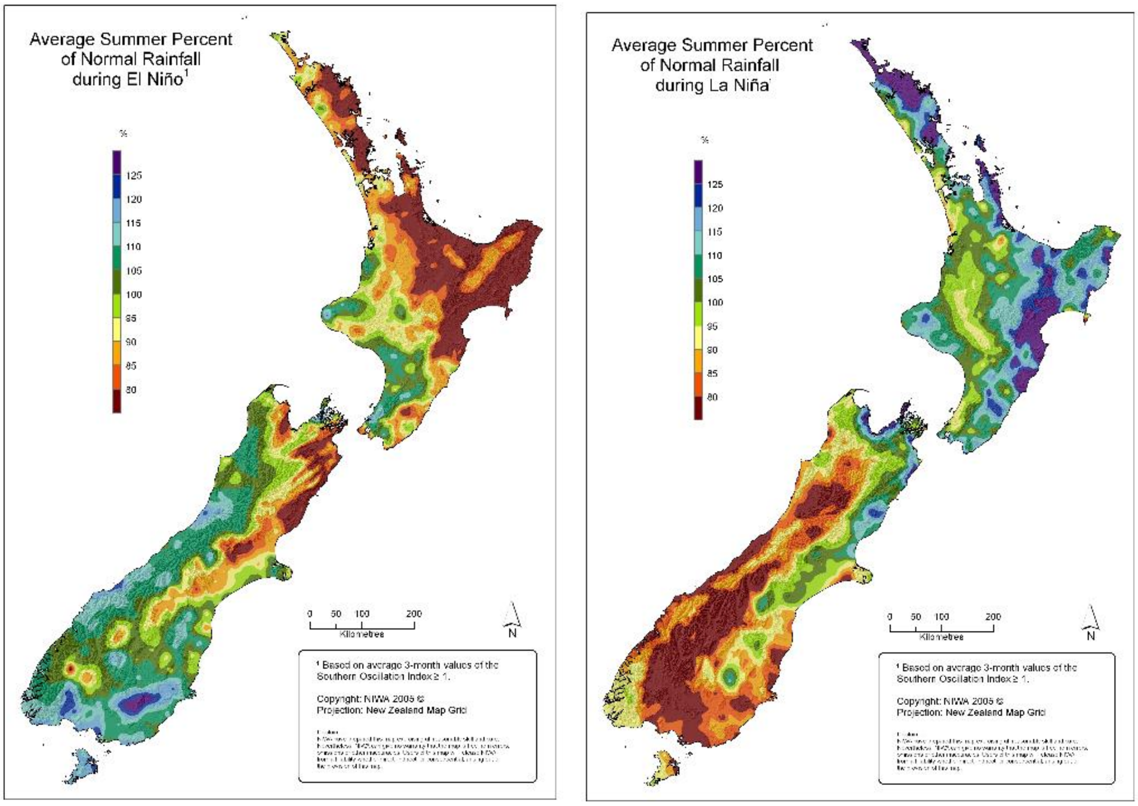

Figure 2-4: Average summer percentage of normal rainfall during El Niño (left) and La Niña (right) in New Zealand. El Niño composite uses the following summers: 1963/64, 1965/66, 1968/69, 1969/70, 1972/73, 1976/77, 1977/78, 1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98, 2002/03. La Niña composite uses the following summers: 1964/65, 1970/71, 1973/74, 1975/76, 1983/84, 1984/85, 1988/89, 1995/96, 1998/99, 1999/2000, 2000/01. This figure was last updated in 2005. © NIWA.

2.5.2 The effect of the Interdecadal Pacific Oscillation

The Interdecadal Pacific Oscillation (IPO) is a large-scale, long-period oscillation that influences climate variability over the Pacific Basin including New Zealand (Salinger et al. 2001). The IPO operates at a multi-decadal scale, with phases lasting around 20 to 30 years. During the positive phase of the IPO, sea surface temperatures around New Zealand tend to be lower, and westerly winds stronger, resulting in wetter conditions for Southland (Figure 2-5). Mean sea level around New Zealand tends to be lower than "normal" or trends in sea-level rise reduced. The opposite occurs in the negative IPO phase (e.g. the Pacific has been in this phase since ~ 1989). The IPO can modify New Zealand's connection to ENSO, and it also positively reinforces (dampens) the impacts of El Niño during IPO+ (-) phases, and of La Niña during the opposite IPO phases.

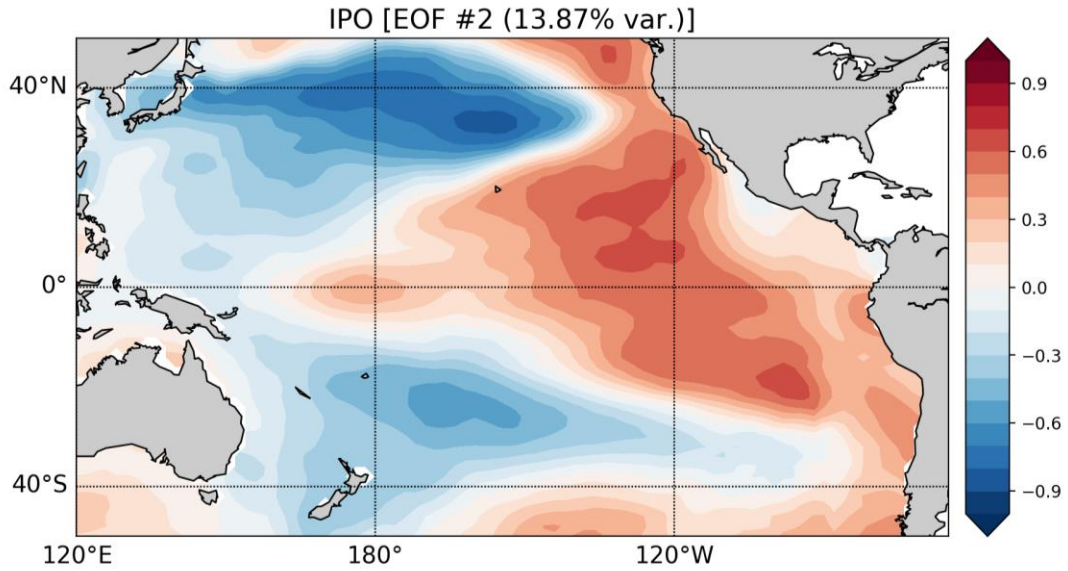

Figure 2-5: SST anomaly spatial pattern (Empirical Orthogonal Function, or EOF) associated with the positive phase of the Interdecadal Pacific Oscillation. The pattern shown, with positive SST anomalies in the eastern tropical Pacific, is IPO+. The IPO- phase has anomalies of opposite sign everywhere. Data source: ERSST version 5 dataset.

2.5.3 The effect of the Southern Annular Mode

The Southern Annular Mode (SAM) represents the variability of circumpolar atmospheric jets that encircle the Southern Hemisphere and extend out to the latitudes of New Zealand. The SAM is often modulated by ENSO, and both phenomena affect New Zealand's climate in terms of westerly wind strength and storm occurrence (Renwick and Thompson, 2006). In its positive phase, the SAM is associated with relatively light winds and more settled weather over New Zealand, with stronger westerly winds further south towards Antarctica (Figure 2-5 and Figure 2-6). In Southland, the positive SAM phase is generally associated with higher than normal daily maximum temperatures and lower than normal rainfall in the west of the region. In contrast, the negative phase of the SAM is associated with unsettled weather and stronger westerly winds over New Zealand, whereas wind and storms decrease towards Antarctica. In Southland, lower than normal daily maximum temperatures and higher rainfall in the west are commonly observed during the negative phase of the SAM.

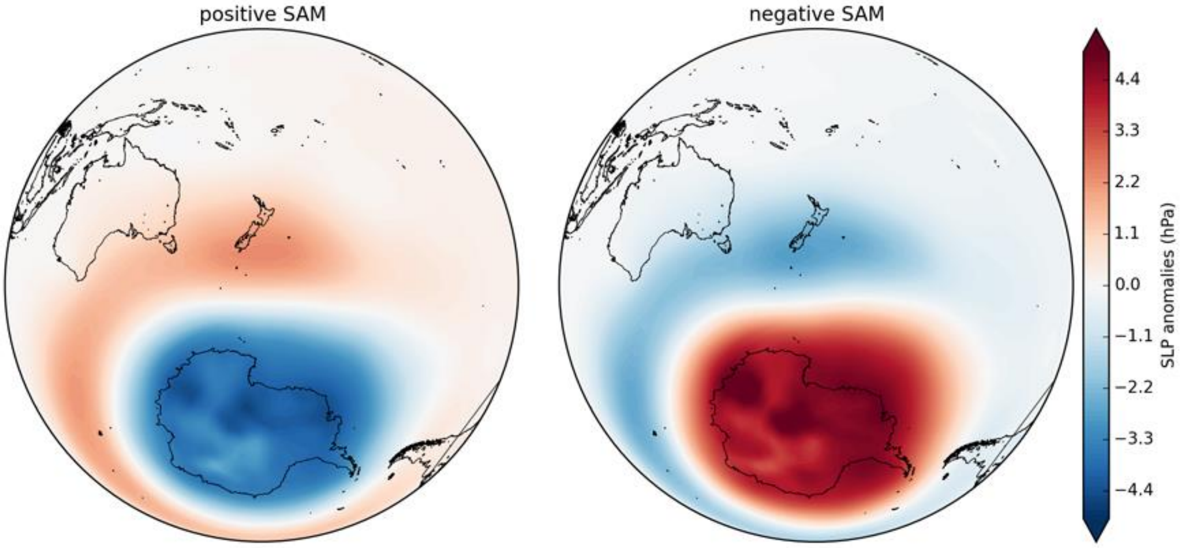

Figure 2-6: Pattern of the pressure variations associated with the positive (left) and negative (right) phases of the SAM. Blue shading indicates below-average pressures and red shading indicates above average pressures. Monthly composites were made using the PC associated with the first EOF of Southern Hemisphere monthly geopotential anomalies at 850 hPa from the NCEP / NCAR reanalysis (Section 2.3.3) using a threshold of +/- 1 std. Data source: **http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html**.

2.5.4 Interactions between natural climate cycles and climate change

El Niño-Southern Oscillation

ENSO is highly likely to remain the dominant mode of natural climate variability in the 21st century, and that rainfall variability relating to ENSO is likely to increase (Huang and Xie, 2015, IPCC, 2013a). However, there is uncertainty about future changes to the amplitude and spatial pattern of ENSO. According to Cai et al. (2014), there may be an increase in 'extreme' El Niño events (like the 1982/83, 1997/98 and 2016/17 El Niño events) with increasing concentrations of greenhouse gases in the atmosphere, due to faster warming over the eastern equatorial Pacific Ocean.

Interdecadal Pacific Oscillation

The IPO influences global mean temperatures through its influence on Pacific sea surface temperatures (Meehl et al. 2013). When the IPO is in its negative phase, Pacific SSTs are cooler than usual, which has led to observed hiatuses in global warming (for example, the shift from the positive to negative IPO in the early 2000s). In contrast, a positive IPO exhibits above normal SSTs in the Pacific, leading to an acceleration in global mean temperatures (e.g. the shift from the negative to positive IPO in the 1970s). The future behaviour of the IPO is uncertain but Meehl et al. (2013) suggests that hiatus periods (associated with negative IPO periods) may become slightly longer.

Southern Annular Mode

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). However, increasing concentration of greenhouse gases 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. 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 (Thompson et al. 2011). 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 westerly wind strength in the mid-high latitudes.

2.6 Natural variability versus anthropogenic impacts

Much of the material in the following Sections 5 and 6 focuses on the projected impact on the climate and oceans of, and surrounding, the Southland region over the coming century of increases in global anthropogenic greenhouse gas concentrations. But natural variations, such as those described in Section 2.5) (associated with for example El Niño, La Niña, the Interdecadal Pacific Oscillation, the Southern Annular Mode, and "climate noise"), will also continue to occur. Those involved in (or planning for) climate-sensitive activities in the Southland 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 2-7. 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 2-7 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 RCP2.6, 41 for RCP8.5).

Over the 1900-2014 historical period, the 7-station curve lies within the 41-model ensemble, in spite of the model temperatures including air temperature over the sea, which is expected to warm somewhat slower than over land (Mullan et al. 2016). For the future 2015-2100 period, the RCP2.6 ensemble shows very little warming trend after about 2050, whereas the RCP8.5 ensemble 'takes off' to be anywhere between +2°C and +5°C by 2100. The *miroc5* model is deliberately chosen to sit in the middle of the ensemble, and illustrates well how interannual variability dominates in individual years: the *miroc5* model under RCP8.5 is the warmest of all models in the year 2036 and the coldest of all models in the year 2059, but nonetheless has a long-term trend that sits approximately in the middle of the ensemble.

Figure 2-7 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.

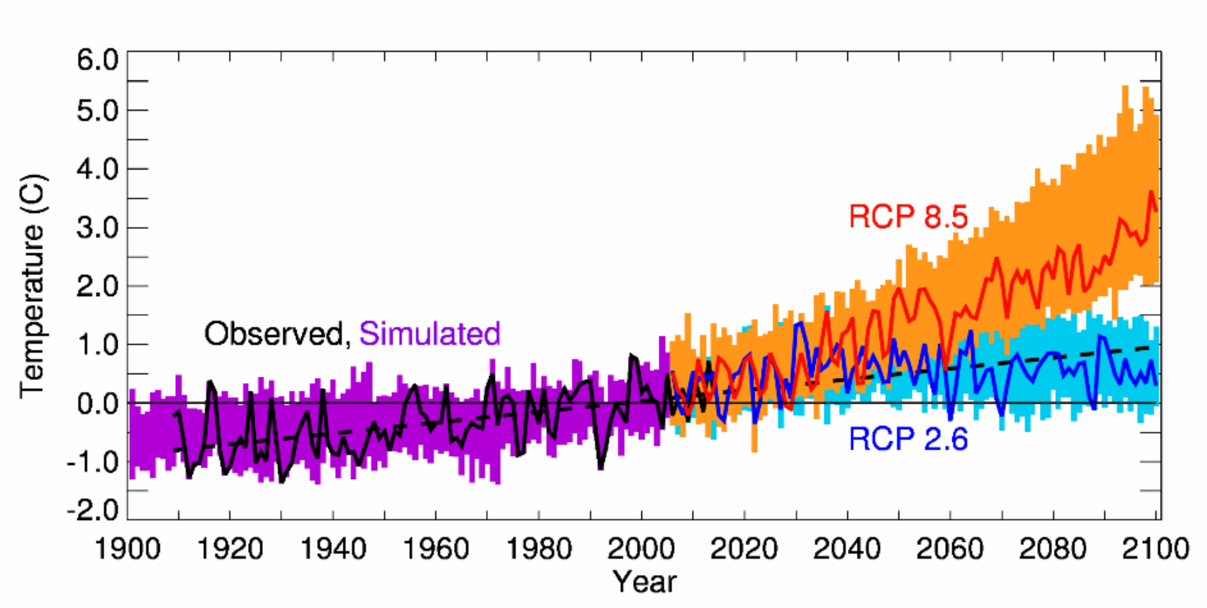

Figure 2-7: New Zealand Temperature - historical record and an illustrative schematic projection illustrating future year-to-year variability. (See text for full explanation). After Mullan et al. (2016).

For rainfall, the fact that we **may** have recently moved into a positive phase of the Interdecadal Pacific Oscillation may depress the impacts of anthropogenic climate change over the next decade or so. Section 2.5.1), showed that periods of positive SOI (e.g., La Niña) may on average experience slightly below normal rainfall in Southland during summer, pushing rainfall in the opposite direction as expected from anthropogenic factors (Section 6.1). A subsequent further reversal of the IPO in 20-30 years' time could have the opposite effect, enhancing part of the anthropogenic (wetting) trend in rainfall for a few decades.

As discussed in Section 2.5), 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 this section is *not* that anthropogenic trends in climate can be ignored because of natural variability. In the projections we have discussed these anthropogenic trends because they become the dominant factor locally as the century progresses. Nevertheless, we need to bear in mind that at some times natural variability will be adding to the human-induced trends, while at others it may be offsetting part of the anthropogenic effect.

3 Methodology

3.1 Atmospheric modelling

NIWA has used climate model simulation data from the IPCC Fifth Assessment (Taylor et al. 2012) to produce updated climate change scenarios for New Zealand (Mullan et al. 2016). Six GCMs were selected by NIWA from the IPCC archive for dynamical downscaling; this involves taking the sea surface temperatures from each model to drive an atmospheric global model, which in turn drives a higher resolution regional climate model (RCM) over New Zealand. The six climate models were selected on the basis of how accurately they represented historical climate in the New Zealand region.

Figure 1-2 shows the bias-corrected sea surface temperatures in the New Zealand region from the six models, for each of the four RCP scenarios. For this report, the climate change projections from each of the six dynamical models are averaged together, creating what is called an ensemble-average, in order to reduce the (independent) natural variability or 'noise' in the model simulations Results are presented at the 5 km x 5 km pixel scale over Southland, to match the resolution of NIWA's observational VCSN (virtual climate station network) data.

3.2 Hydrological modelling

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

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

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

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

- Catchment topography based on a nationally available 30 m Digital Elevation Model (DEM).
- Physiographical data based on the Land Cover Database version two and Land Resource Inventory (Newsome et al. 2000).
- Soil data based on the Fundamental Soil Layer information (Newsome et al. 2000).
- Hydrological properties (based on the River Environment Classification version one (REC1) (Snelder and Biggs 2002)[5].

The method for deriving TopNet's parameters based on GIS data sources in New Zealand is given in Table 1 of Clark et al. (2008). Due to the paucity of some spatial information at national/regional scales, some soil parameters (namely catchment scale hydraulic conductivity at the surface, catchment scale Green and Ampt wetting front suction and catchment scale Clapp-Hornberger c exponent) are set uniformly across New Zealand.

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

Hydrological simulations are based on the REC 1 network aggregated up to Strahler[6] catchment order three (approximate average catchment area of 7 km^2) used within previous national and regional scale assessments (Pearce et al. 2017a, b); residual coastal catchments of smaller stream orders remain included. The simulation results will comprise hourly time-series of various hydrological variables for each computational sub-catchment, and for each of the six GCMs and four RCPs considered. To manage the volume of output data, only river flows information was preserved; all the other state variables and fluxes can be regenerated on demand.

Because of TopNet assumptions, soil and land use characteristics within each computational sub-catchment are homogenised. Essentially this means that the soil characteristics and physical properties of different land uses, such as pasture and forest, will be spatially averaged, and the hydrological model outputs will be an approximation of conditions across land uses.

3.3 Sea-level rise, change in extreme storm-tide and coastal risk exposure

Environment Southland have asked for projected sea-level rise and variation across the Southland region, for a range of RCP scenarios. NIWA will assess the relevant local variations to apply to the three New Zealand-wide sea-level rise (SLR) scenarios to 2120 that NIWA developed for the MfE Coastal Hazards and Climate Change Guidance (MfE 2017). Note these scenarios don't include

[5] Due to time constraints associated with this project, it is not possible to assess the potential impact of climate change on the Digital River Network 3 available for the Southland region.

[6] Strahler order describes river size based on tributary hierarchy. Headwater streams with no tributaries are order 1; 2nd order streams develop at the confluence of two 1st order tributaries; stream order increases by 1 where two tributaries of the same order converge.

RCP6.0, as the SLR by the end of this century under that scenario is very similar to RCP4.5. The assessment of local variations includes an appraisal of vertical land movement (based on available continuous GPS data and publications) and an updated check on the sea-level trend from the Bluff tide-gauge record (the most recent study by Hannah and Bell (2012) indicated a trend of 1.8 mm/yr, which is very close to the New Zealand-wide average). Any significant local variations in sea-level trends would be provided as a local adjustment to the national projections. Note: sea-level change at decadal scales is quite similar across New Zealand, so no large variations are expected.

Three tide-gauge records from Port of Bluff, Dog Island and Stead Street Bridge (Invercargill) were used in this report to variously summarise mean sea level (MSL) trends, seasonal cycles and extreme storm-tide levels (Figure 3-1). Monthly and annual MSL from the Port of Bluff for 1999 onwards were used to ascertain the seasonal cycle in MSL and update the trend in annual MSL up to the end of 2017. The record from the nearby NIWA gauge at Dog Island, which has been operating since February 1997, was analysed for tidal characteristics and recent MSL to compare with Bluff.

Extreme storm-tide level results for New River Estuary are available from a project completed recently by NIWA for Invercargill City Council on a storm-tide analysis of the Stead Street gauge in Invercargill (Gorman et al. 2018). These updated storm-tide levels for various annual exceedance probabilities (AEP) are critical for improving design levels for coastal stopbanks, roads, stormwater and drainage systems and assessing coastal flood risks in the New River Estuary. Further work will be needed (and probably longer records) to establish storm-tide levels for the open coast around Southland – with the open-coast Dog Island gauge registering lower storm-tide levels (excluding wave setup and runup) than the estuary gauge at Stead Street Bridge. Storm-tide and wave overtopping events will become much more prevalent in low-lying areas with only a modest rise in sea level. This aspect is covered in more detail in Section 8.

Figure 3-1: Locations of the three tide gauges used in this report. Stead St is operated by Environment Southland, Bluff by South Port and Dog Island by NIWA.

A high-tide exceedance curve for present-day will be produced from the Bluff record, which can be used to quantify the distribution of all high tides from tide predictions over many decades (excluding weather and climate effects) and then assess the change in frequency of high-tide markers being exceeded by high tides with two example values of SLR (0.4 and 0.8 m).

Environment Southland also requested some commentary on impacts on coastal erosion processes (e.g., Colac Bay/Ōraka, Riverton/Aparima, Bluff, New River Estuary). Unfortunately, erosion processes are complex and highly localised, so even an assessment of the erosion dynamics up to present would be a significant piece of work that cannot be completed for the present report. However, some material around likely generic impacts of SLR on coastal erosion and flooding is provided – particularly for coastal flooding, where specific sea-level rises can be provided for Southland when the present 1% AEP storm-tide level becomes an event that occurs on average once every year.

NIWA is also currently undertaking a national coastal risk exposure study (funded by the Deep South Science Challenge) to update the work NIWA did for the Parliamentary Commissioner for the Environment (PCE 2015; Bell et al. 2015). The NIWA study for the PCE didn't fully describe the risk exposure for Southland as no LiDAR survey data were available; instead for Southland Bell et al. (2015) used the coarser national topographic digital elevation model (DEM), which we now know underestimates the risk exposure by around half. Invercargill City Council and Environment

Southland have recently provided NIWA with the LiDAR data for the City and Waituna Lagoon catchment to include in the update project currently in progress with funding from the Deep South Science Challenge. Provisional aggregated results for buildings and replacement costs in the LiDAR survey areas from this study are provided in this report in summary form. For the rest of Southland, the existing national DEM results are summarised from Bell et al. (2015) for key assets (buildings, roads, jetties and the airport) and population (2013 Census) exposed in the coastal margin up to 3 m above MHWS across the coastal margin of the Southland region and in each of the two coastal territorial authorities.

3.4 Climate change impact assessment

A brief description of each variable to be reported on is provided hereafter, as well as current limitations associated with the analysis. All "changes" refer to differences between the historical period 1986-2005 and two future periods: mid-century (2031-2050) and late-century (2081-2100), as per MfE (2016).

- Precipitation:
  - Average precipitation: change in the annual-average and seasonal-average precipitation for each time slice.
  - Maximum daily: change in the annual-average maximum daily precipitation for each time slice[7].
  - Maximum 5 days: change in the annual-average maximum 5 days precipitation for each time slice.
  - Dry day projections, characterised by the change in annual average number of days where total daily precipitation is less than 1 mm/day.
  - Wet day projections, characterised by the change in annual average number of days where total daily precipitation is equal to or larger than 1 mm/day.
  - Heavy rain day projections, characterised by the change in annual average number of days where total precipitation is equal to or larger than 50 mm/day).
- Sub-catchments: Analysis of change in precipitation will be reported graphically on each Freshwater Management Unit (FMU) from Environment Southland (i.e., Matāura, Aparima, Ōreti, Waiau and Fiordland).
- Temperature:
  - Number of hot days: change in the annual number of days where temperature is 25 °C or above.

[7] Changes in maximum daily precipitation at annual time scales are similar to changes in the annual average 99th percentile daily rain

- Heatwave: change in 'heatwave days'. The estimation of the distribution of heatwave will be carried out over the year July to June in order not to break up any heatwaves that cross the December-January period.
- Frost days: change in annual number of days where average daily temperature is 0 °C or below.
- Overnight minimum: represented by change in minimum daily temperature.

- Projected sea-level rise:
  - Projected change in average annual sea level around Southland based on national scale assessment (Coastal Hazards and Climate Change Guidance, MfE 2017) as sea-level change at decade scales is quite similar across New Zealand, so no large variations are expected.
  - Local variation of sea-level rise: Due to existing data limitations, these changes will be limited to an appraisal of vertical land movement (based on available continuous GPS data and publications) and an updated check on the sea-level trend from the Bluff tide-gauge record.
- Hydrology: change in annual and seasonal characteristics:
  - High flows: change in the Mean Annual Flood (representing the change in the mean largest peak flow for each year). This typically represents flows that are exceeded less than one percent of the time and have a return period between two and three years[8]. This statistic cannot be interpreted as robustly describing the effect climate change will have on rare flood event[9]s.
  - Average flows: change in river flow averaged over the period of analysis.
  - Low flows: change in the Q95% metric, which represents river flows exceeded ninety-five percent of the time.
  - Water supply reliability: change in the fraction of time that the flow is equal to or above the minimum flow threshold stated in the proposed National Environmental Standard for Ecological Flows (MfE 2008) without any water takes. Water supply reliability varies between 0 and 100 percent and is often between 90% and 100% for New Zealand rivers. Reliability of supply of X% indicates that water is not available for agricultural uses (as surface water takes) for (100-X) percent of the time over the period considered.
- Weather events[10]:
  - Drought change in frequency: Following discussion with Environment Southland (Gavin McCullagh, 22 March 2018), change in drought frequency

[8] MAF corresponds to a magnitude of flood that is of a similar magnitude to the flow necessary to fill a river up to the top of its banks, which is rarely a nuisance or a hazard but can be used as a reference for the size of floods that could occur.
[9] Change in flood risk and flood hazard would need to address the more extreme floods, in terms of both size and frequency, and both discharge and inundation extent. Translating the hazard into a risk would require the further consideration of social, cultural, economic, and environmental vulnerability of flood-prone areas.
[10] Flood return period and frequency: due to the time to complete the analysis and current methodology development (within the Deep South National Science Challenge), no analysis of flood return period and frequency will be provided as part of this report

will be reported as change in frequency above a specific threshold of potential evapotranspiration deficit (PED) (to be agreed with Environment Southland at the start of the project). However please note that large uncertainties exist in the derivation of the downscaled driven climate variables (solar radiation, relative humidity, wind) so results are likely to have a large uncertainty.

– Change in precipitation events[11] (see subsection on change in rainfall events) in tabular format for the following locations:

Gore, Matāura, Waikawa and Riversdale townships (Matāura catchment).

Otautau and Riverton/Aparima township (Aparima catchment).

Tuatapere township (Waiau catchment).

Te Anau and Milford Sound Airport (Fiordland catchment).

Winton and Lumsden (Ōreti catchment).

Waihõpai Dam (Waihõpai River).

New River Estuary.

Oban (Stewart Island/Rakiura).

The change in all variables between the baseline and projection periods is represented in either percentage or absolute terms depending on the variable in question. The results for the six GCMs are combined into either a multi-model average (for climate variables) or a multi-model median (for hydrological variables), and the results of the RCPs are kept separate. This approach will provide annual and seasonal maps for each statistic, representing average/median changes in that statistic between baseline and mid-century and baseline and late-century. Changes in hydrological statistics will be reported for the lower end of river reaches while changes in climate statistics will be reported on the Virtual Climate Station Network grid (0.05°C) across Southland.

[11] As per communication with Environment Southland (Gavin McCullagh, 22 March 2018), change of precipitation intensity is to be provided for specific locations only.

4 Present-day and future climate of Southland

Southland is both the most southern and western part of New Zealand and generally is the first to be influenced by weather systems moving onto the country from the west or south. It is well exposed to these systems, although western parts of Fiordland are sheltered from the south and the area east of the western ranges is partially sheltered from the north or northwest. The region is in the latitudes of prevailing westerlies, and areas around Foveaux Strait frequently experience strong winds, but the winds are lighter inland. Winter is typically the least windy time of the year, as well as for many but not all areas, the driest. The western ranges, with annual rainfall exceeding 6000 mm in some parts, are among the rainiest places on Earth. The drier eastern lowlands and hills form a complete contrast, with annual rainfall predominantly between 500 mm and 1000 mm. Dry spells of more than two weeks are not uncommon. Temperatures are on average lower than over the rest of the country with frosts and snowfalls occurring relatively frequently each year. On average, Southland receives less sunshine than the remainder of New Zealand. For more information about Southland's present-day climate other than the information presented in this report, the reader is directed to Macara (2013).

The future climate of Southland will be influenced by a combination of the effects of anthropogenic climate change (increasing global concentrations of greenhouse gases) plus the natural year-to-year and decade-to-decade variability (also referred to as "climate noise") resulting from activity from phenomena such as El Niño-Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO), and the Southern Annular Mode (SAM) as discussed in Section 2.5). The following sections outline the present-day climate of Southland and projected changes due to anthropogenic climate change.

5 Temperature

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

5.1 Mean temperature

5.1.1 Present

The map for 'present-day' annual and seasonal mean temperature in Southland is presented in Figure 5-1. This map shows a 20-year average of mean temperature over 1986-2005. Note that this map presents modelled present-day climate, i.e., six global climate models are run in hindcast mode and this map is the average of the six models.

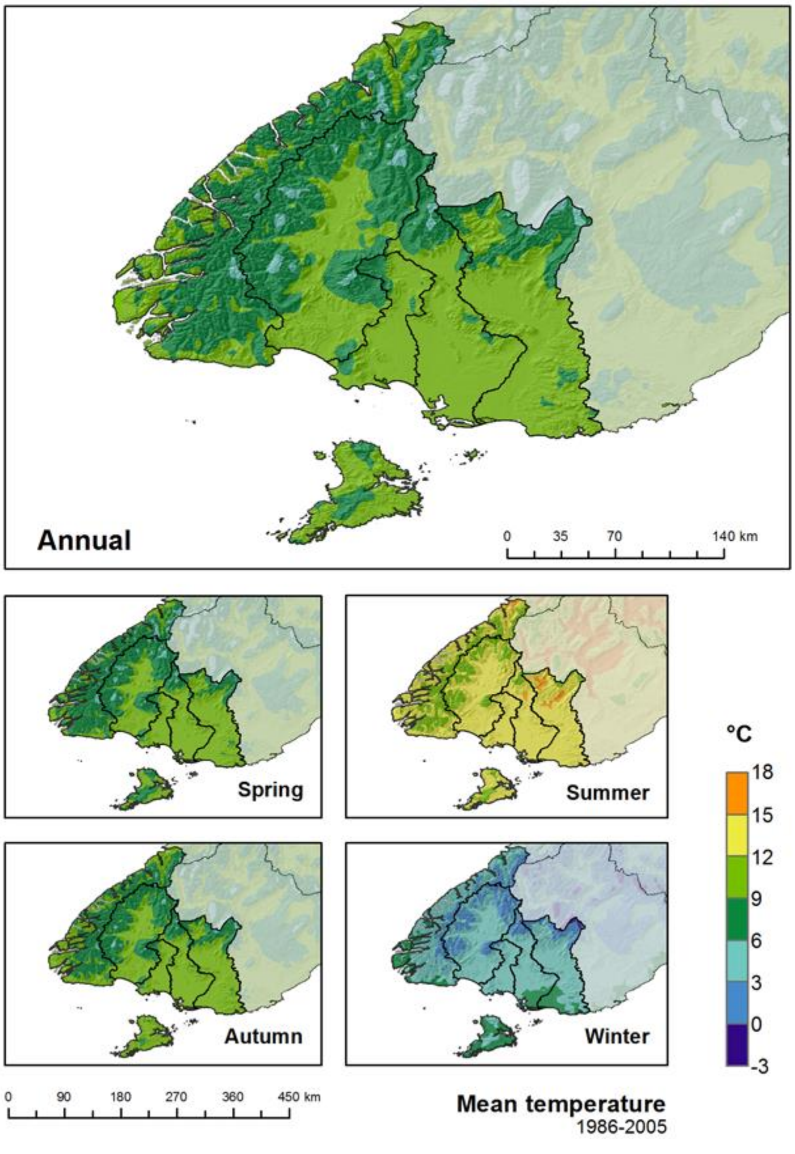

Figure 5-1: Modelled annual and seasonal mean temperature for Southland (1986-2005). Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

The lowest mean annual temperatures are recorded at the highest elevations in the Southland region (3-6°C), and the warmest temperatures are recorded in the lowlands (9-12°C). In summer, mean temperatures reach 15-18°C in some parts of the Matāura catchment, but most of the region has a summer mean temperature of 12-15°C. In winter, most of the region experiences a mean temperature of 3-6°C with cooler temperatures at higher elevations.

5.1.2 Future

Projected changes in annual and seasonal mean temperatures are presented in this section, for RCP4.5 and RCP8.5. Mean temperature is documented for all seasons and two future periods (2040 and 2090) in Figure 5-2 to Figure 5-5.

Changes in mean temperature are positive under both time slices and RCPs, with larger increases with time and emissions scenario. For annual mean temperature, RCP4.5 projections show increases of 0.50-0.75°C across most of the Southland region by 2040, and 0.75-1.00°C in northern areas (Figure 5-2). By 2090, most of the region projections increases in annual mean temperature of 1.00-1.25°C, with for the northern areas projection to increase by 1.25-1.50°C (Figure 5-3). For RCP8.5 at 2040, increases of 0.50-1.00°C are projected (Figure 5-4). At 2090, a 2.00-2.50°C increase in annual mean temperature is projected for most of Southland, with projections for some northern areas to increase of up to 3.00°C (Figure 5-5).

For seasonal mean temperature, autumn is the season where the most warming is projected to occur, for all time periods and scenarios. The least warming is projected to occur in spring at 2040 under RCP4.5 and RCP8.5, in summer at 2090 under RCP4.5, and winter at 2090 under RCP8.5.

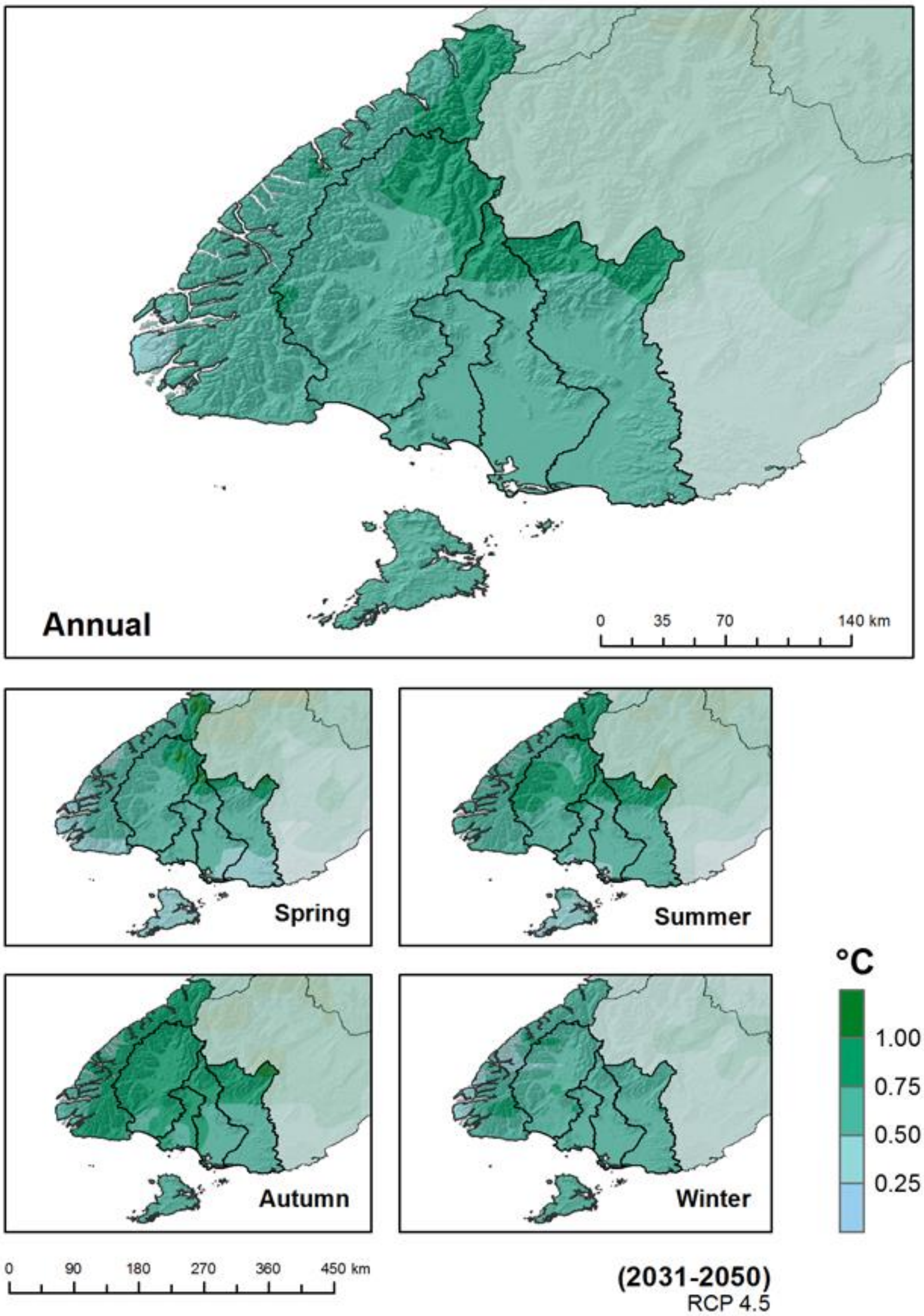

Figure 5-2: Projected annual and seasonal daily mean temperature changes at 2040 (2031-2050 average) for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

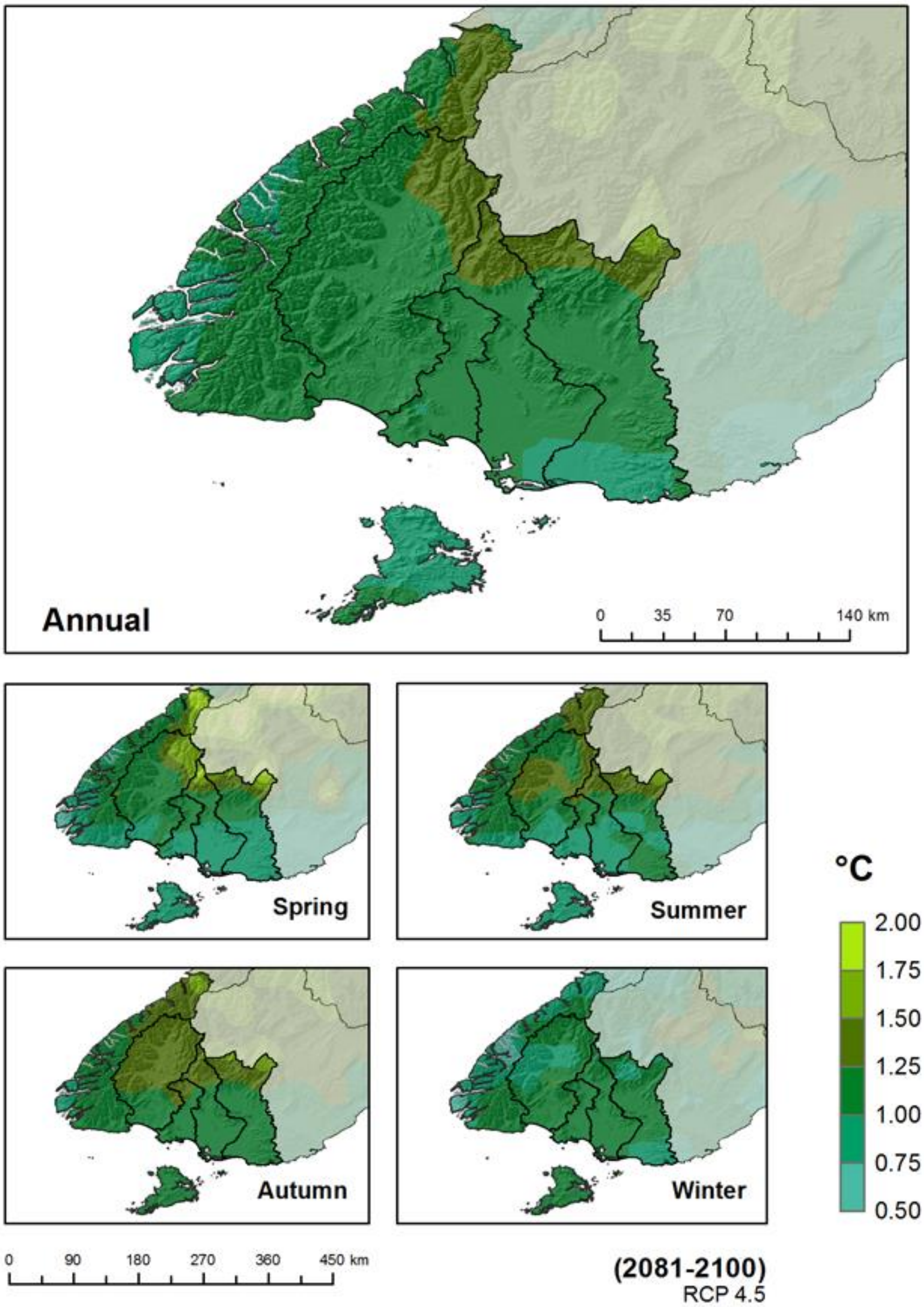

Figure 5-3: Projected annual and seasonal daily mean temperature changes at 2090 (2081-2100 average) for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

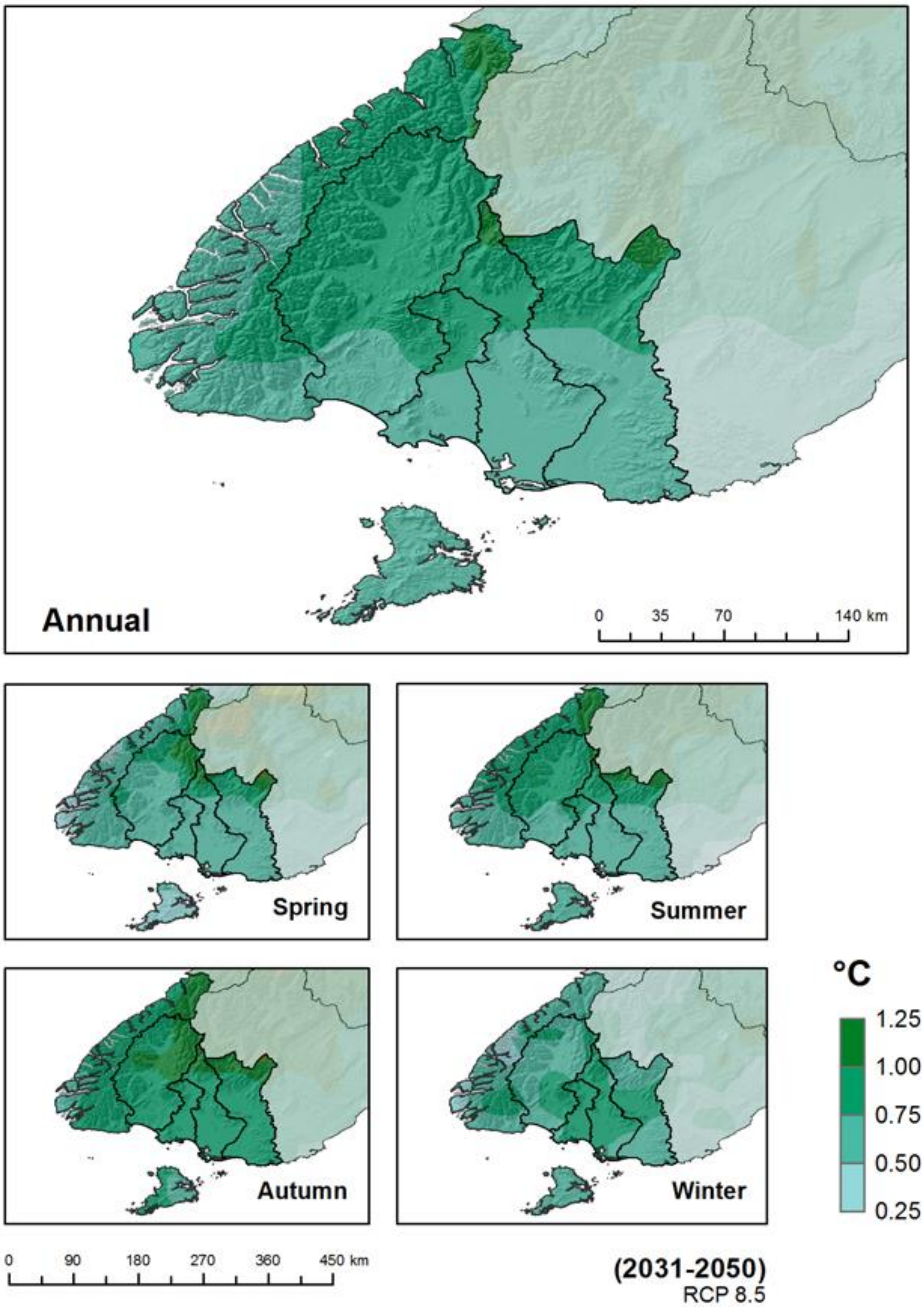

Figure 5-4: Projected annual and seasonal daily mean temperature changes at 2040 (2031-2050 average) for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

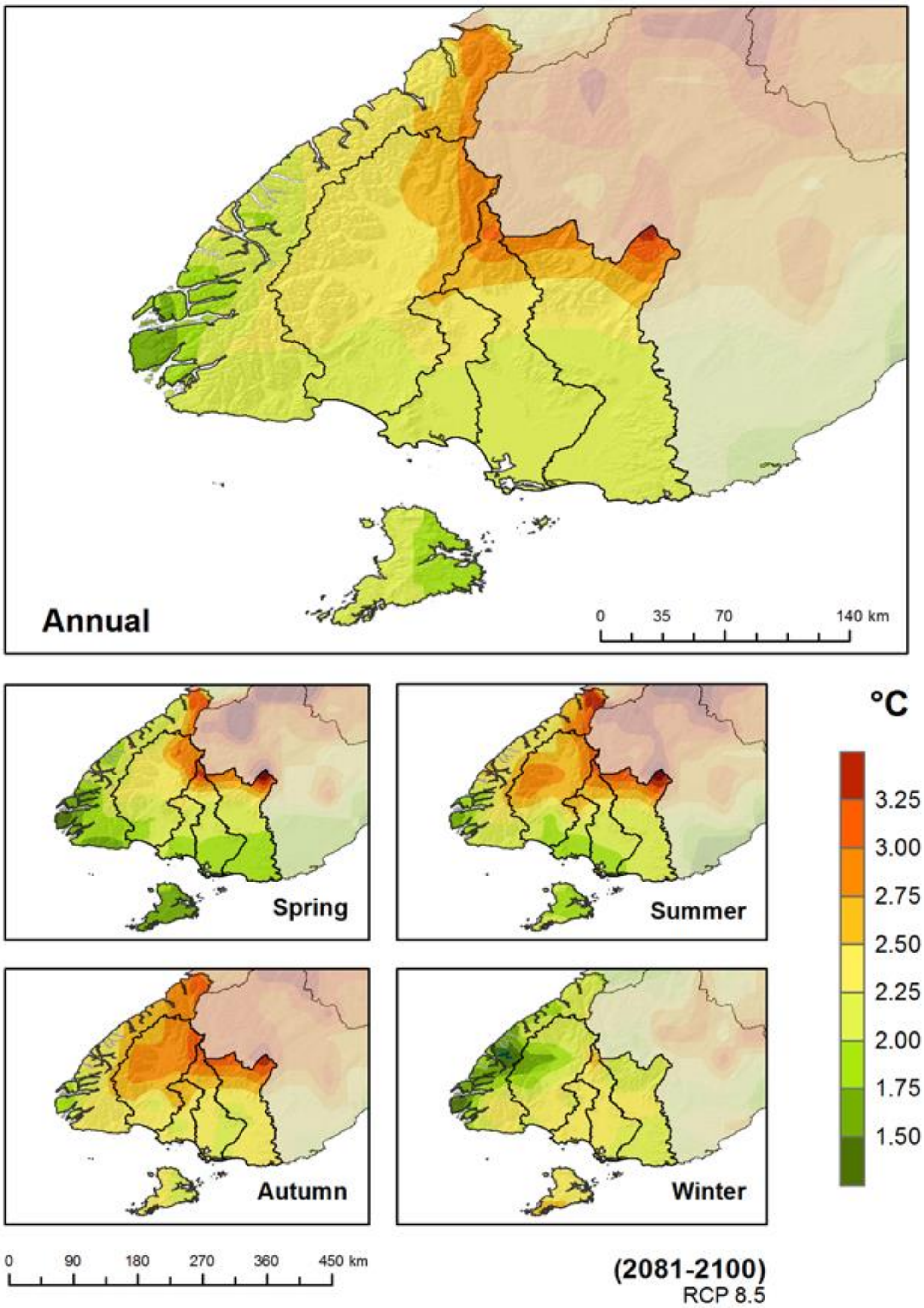

Figure 5-5: Projected annual and seasonal daily mean temperature changes at 2090 (2081-2100 average) for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

5.2 Minimum temperature

Minimum temperatures (T_{min}) are generally recorded in the early hours of the morning, and therefore are also known as night time temperatures.

5.2.1 Present

The map for 'present-day' annual and seasonal mean minimum temperature in Southland is presented in Figure 5-6. This map shows a 20-year average of mean minimum temperature over 1986-2005. Note that this map presents modelled present-day climate, i.e., six global climate models are run in hindcast mode and this map is the average of the six models.

The lowest annual mean minimum temperatures are recorded at the highest elevations in the Southland region (0-2°C), and the warmest mean minimum temperatures are recorded along the coastal margins (6-8°C). In summer, mean minimum temperatures reach 6-8°C in most parts of the Southland region, but higher elevations experience lower summer mean minimum temperatures of 2-6°C. In winter, most of the region experiences a mean minimum temperature of 0-2°C with cooler temperatures at higher elevations.

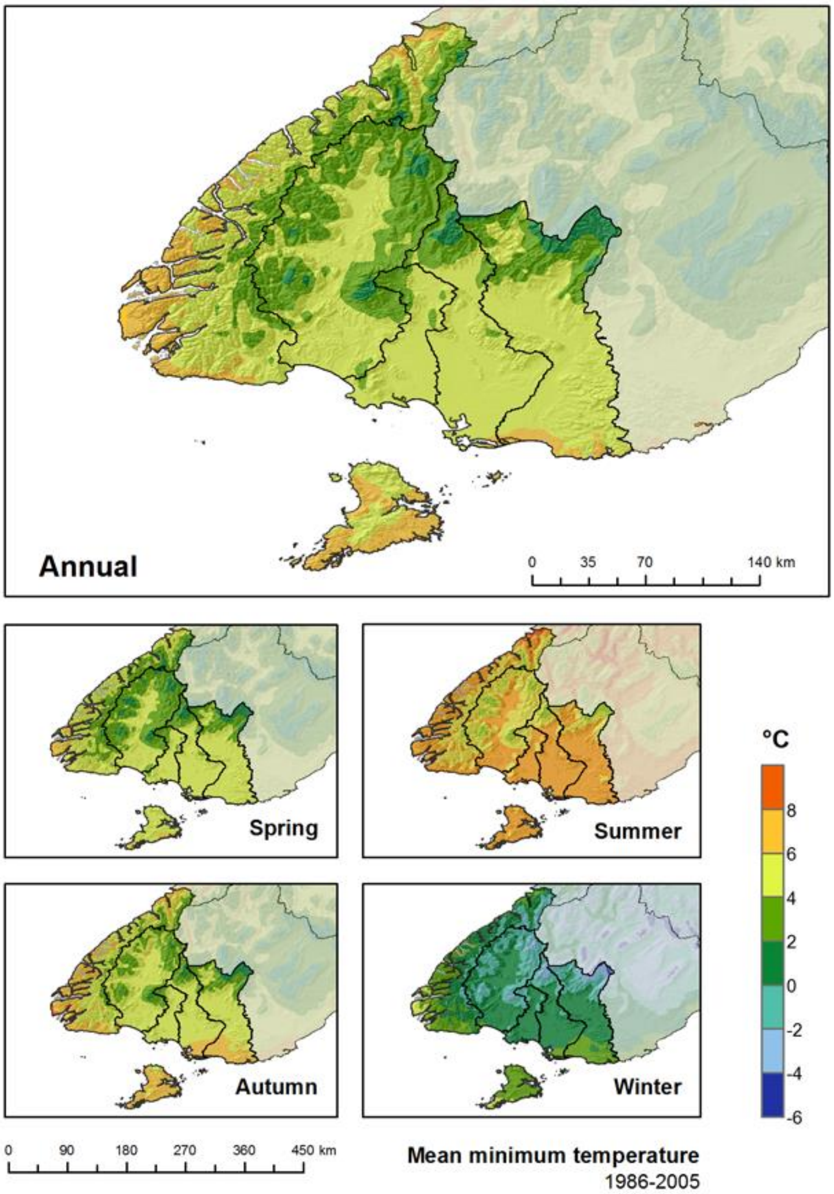

Figure 5-6: Modelled annual and seasonal mean minimum temperature for Southland (1986-2005). Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

5.2.2 Future

Projected changes in minimum temperatures (T_{min}) are presented in this section, for RCP4.5 and RCP8.5. T_{min} is documented for all seasons and two future periods (2040 and 2090) in Figure 5-7 to Figure 5-10.

Changes in T_{min} are positive under both time slices and RCPs, with larger increases with time and emissions scenario. For annual T_{min}, RCP4.5 projections show increases of 0.25-0.50°C across most of the region by 2040 (Figure 5-7). By 2090 under RCP4.5, the increases in annual T_{min} of 0.50-1.00°C are projected (Figure 5-8). For RCP8.5 at 2040, increases in annual T_{min} of 0.25-0.75°C are projected (Figure 5-9). At 2090, a 1.25-2.00°C increase in annual T_{min} is projected for Southland (Figure 5-10). For seasonal changes in T_{min}, autumn is when the most warming occurs for each RCP and time period, and the least warming generally occurs in spring or summer.

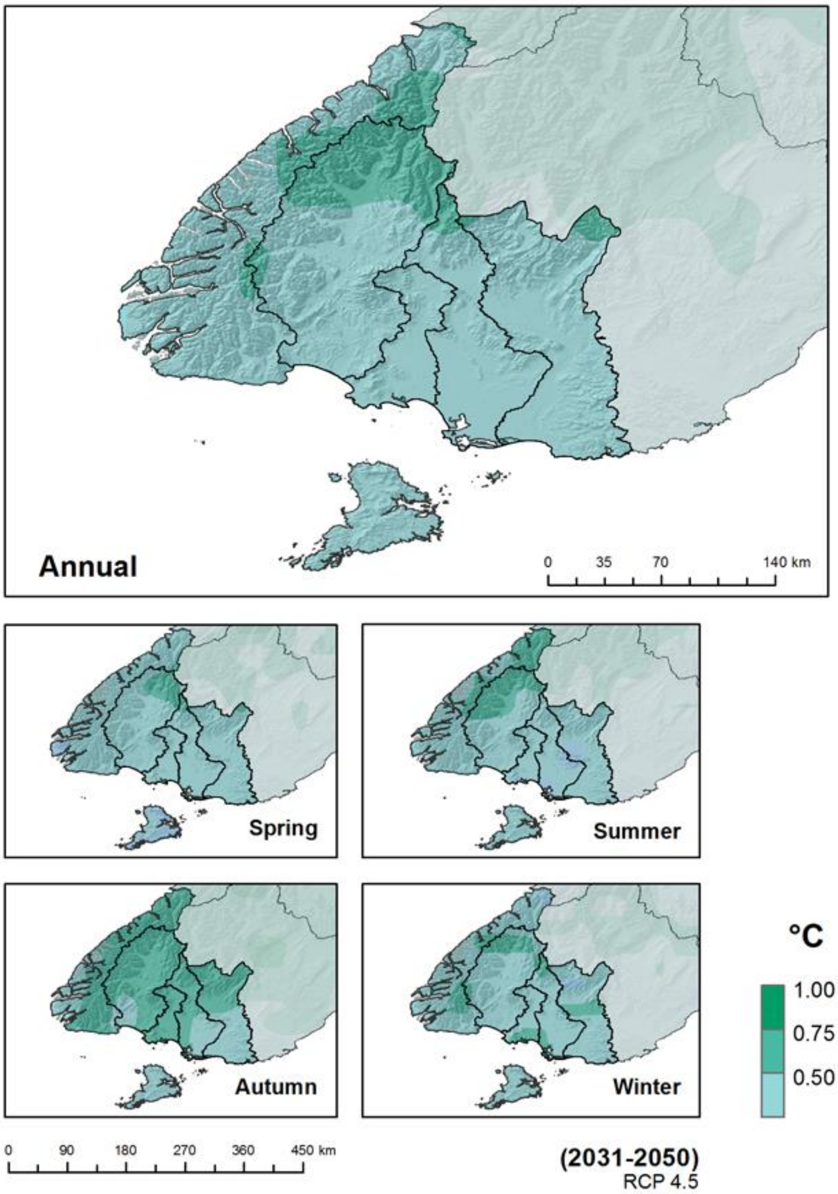

Figure 5-7: Projected annual and seasonal mean minimum temperature changes at 2040 (2031-2050 average) for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

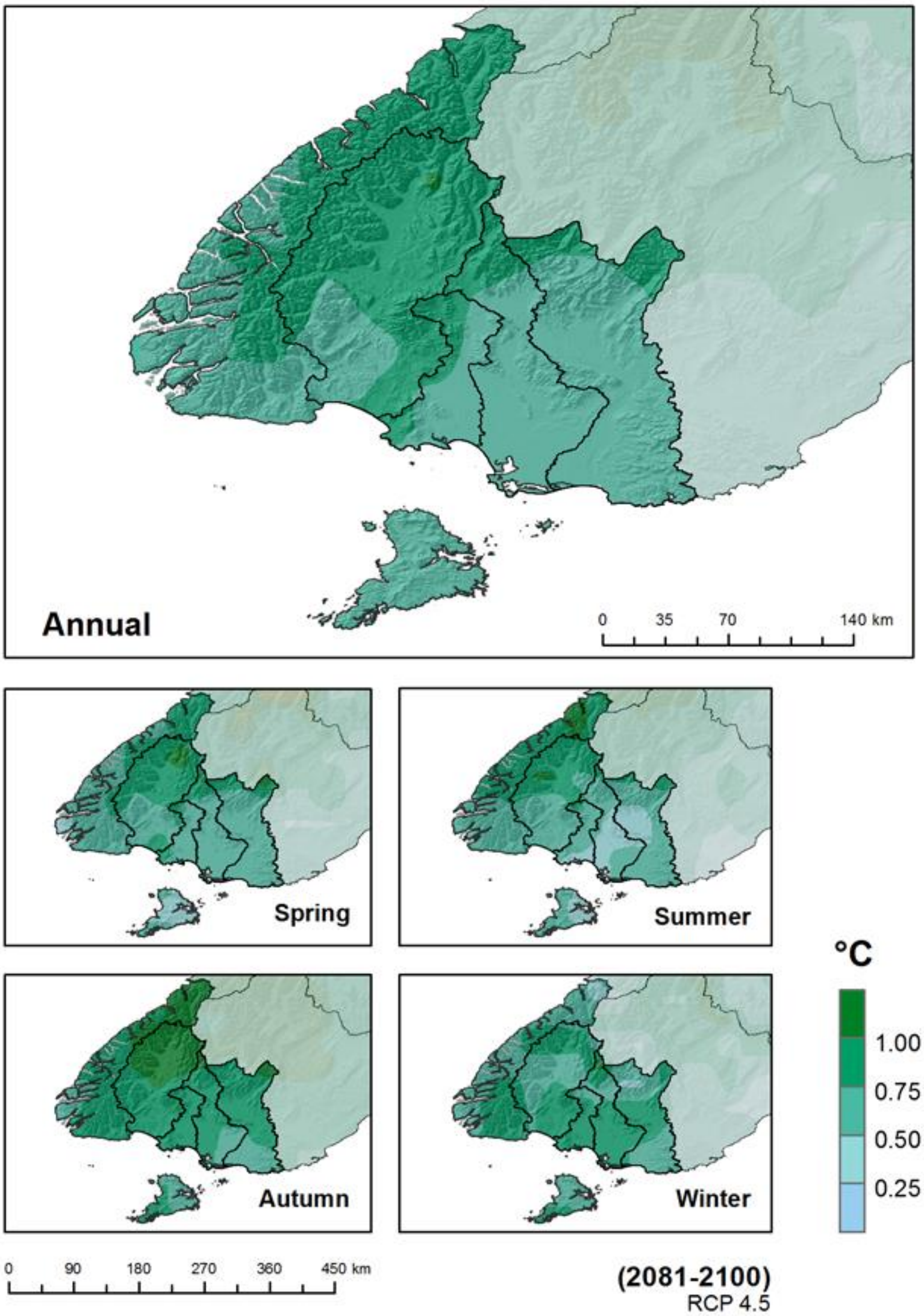

Figure 5-8: Projected annual and seasonal mean minimum temperature changes at 2090 (2081-2100 average) for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

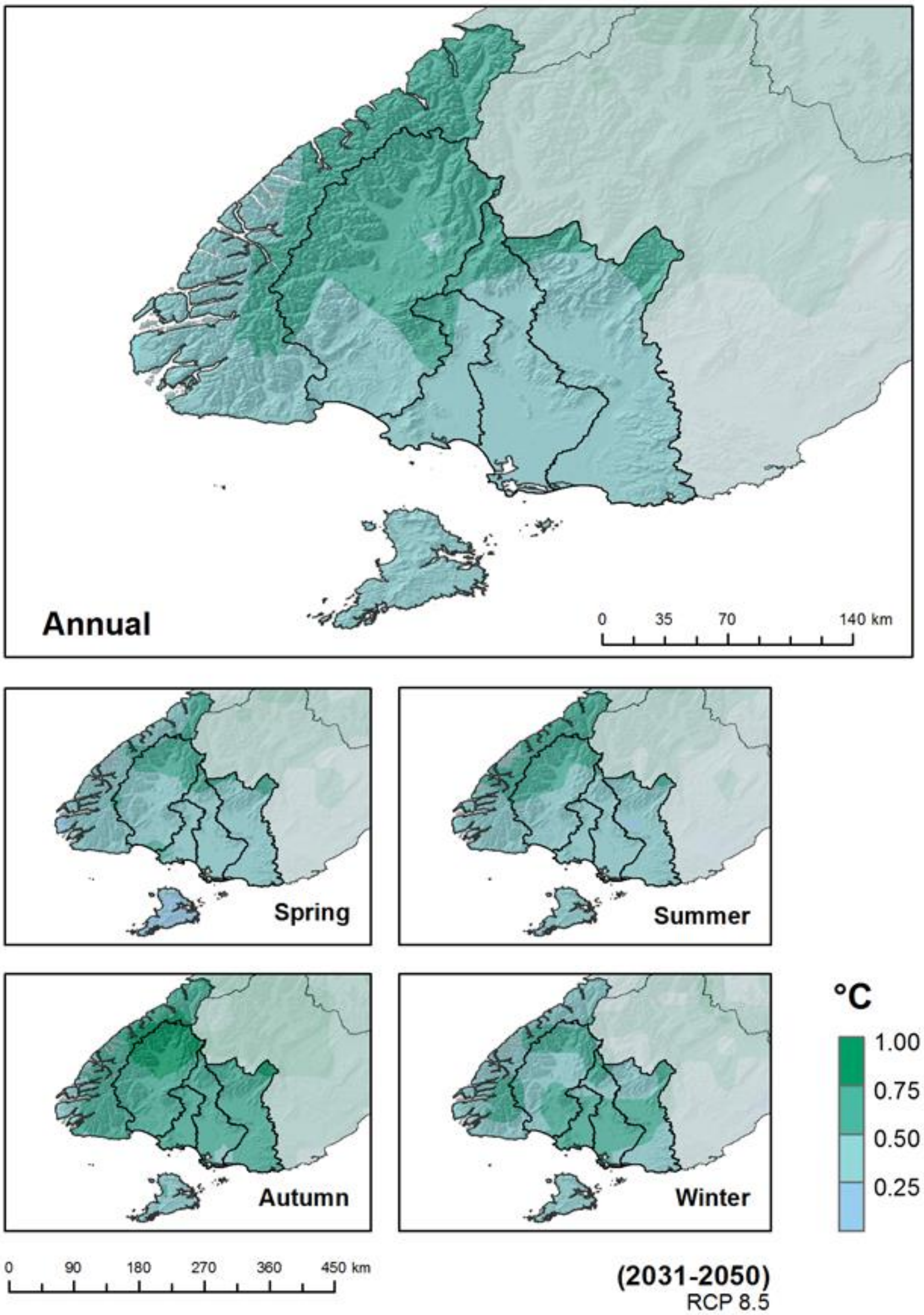

Figure 5-9: Projected annual and seasonal mean minimum temperature changes at 2040 (2031-2050 average) for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

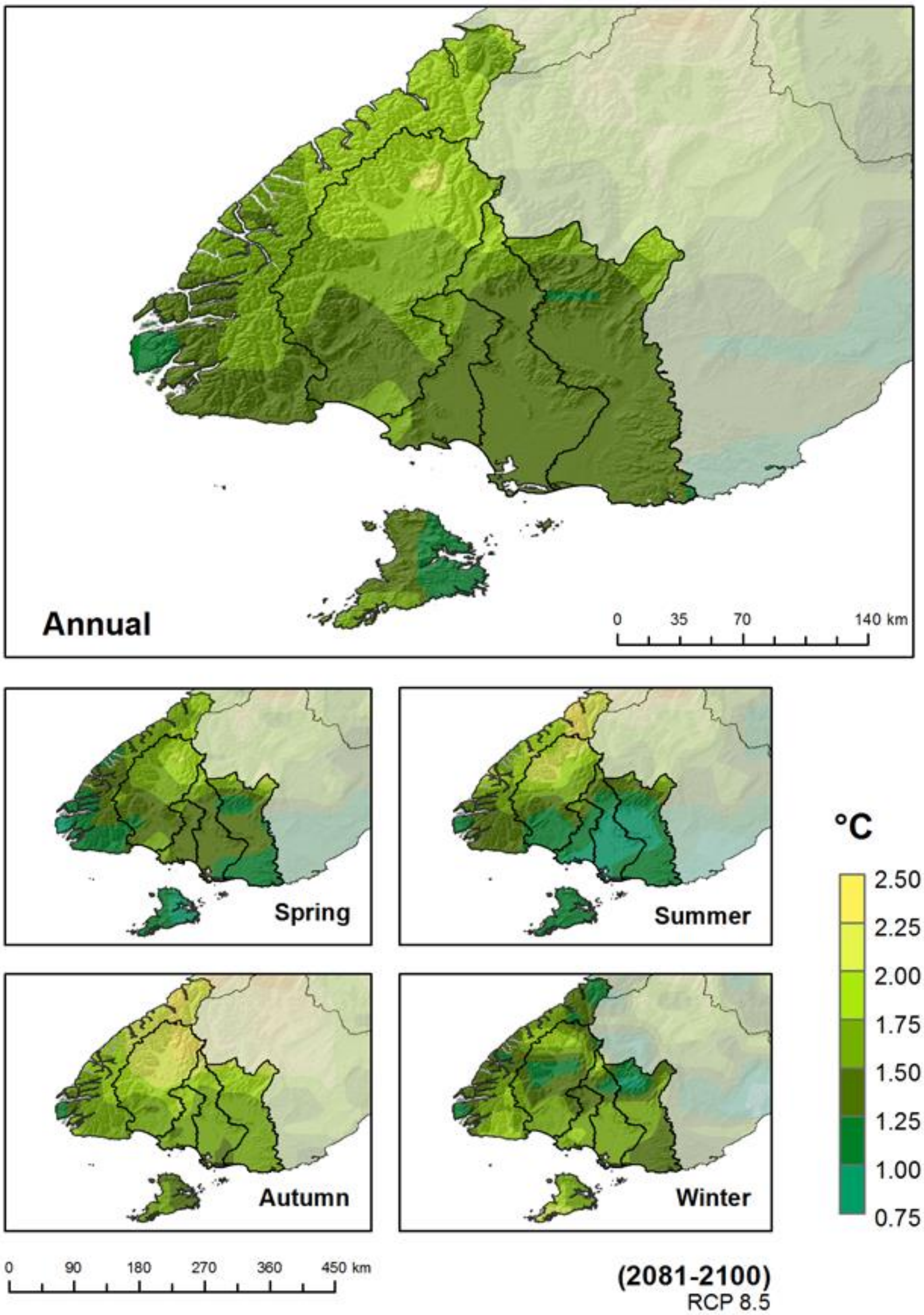

Figure 5-10: Projected annual and seasonal mean minimum temperature changes at 2090 (2081-2100 average) for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

5.3 Hot days and frosts

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

5.3.1 Present

The map for 'present-day' annual number of hot days (days with maximum temperature > 25°C) in Southland is presented in Figure 5-11, and for cold nights/frosts (days with minimum temperature < 0°C) in Figure 5-12. These maps show a 20-year average of hot days and frosts over 1986-2005. Note that these maps present modelled present-day climate, i.e., six global climate models are run in hindcast mode and these maps are the average of the six models.

The current annual average number of hot days varies throughout the Southland region, with the highest number observed in the northern Matāura catchment - over 30 hot days per year in isolated areas - and 15-20 hot days per year in larger parts of the northern Matāura and Ōreti catchments (Figure 5-11). Much of the lowland part of Southland as well as northern Fiordland experiences 5-10 hot days per year, and the remainder of the region experiences less than five hot days per year.

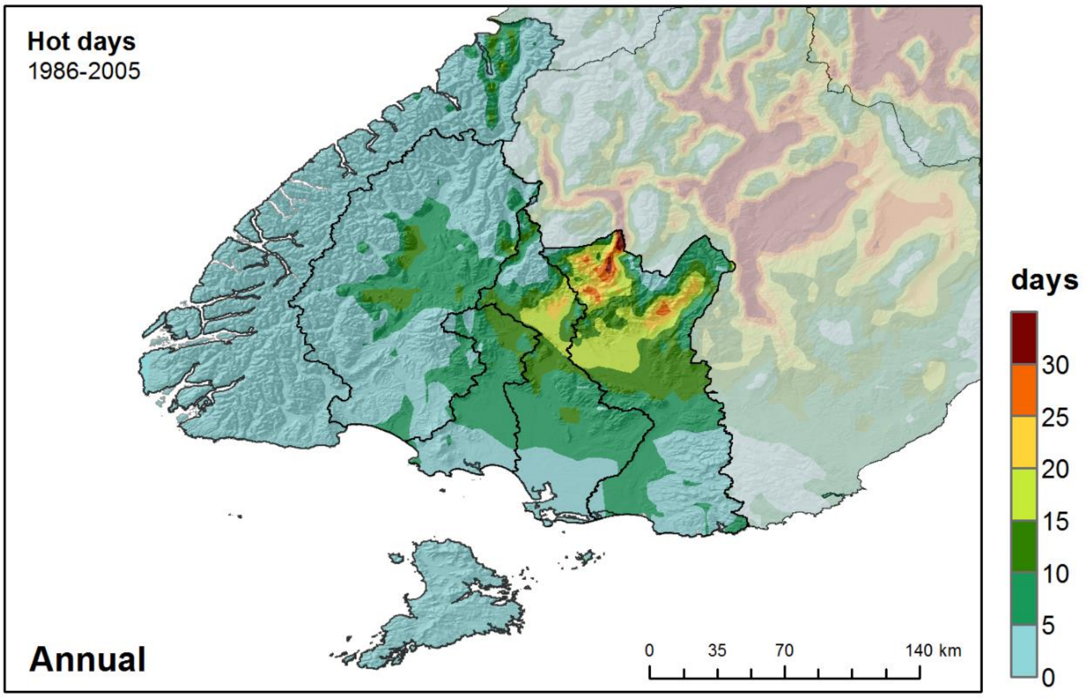

Figure 5-11: Modelled average annual number of hot days in Southland (Tmax >25°C), 1986-2005. Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

In terms of cold nights or frosts, most are currently observed in the high elevation alpine areas in the northwest of the region (> 150 cold nights per year) (Figure 5-12). Many of the remaining high elevation areas experience 100-150 cold nights per year. The lower elevation areas inland from the coast currently observe 25-50 cold nights per year, and the coastal margins generally experience 0-25 cold nights per year. Note that this map is at a 5 km resolution so a larger number of local scale frosts may occur, for example on valley floors and mountain tops.

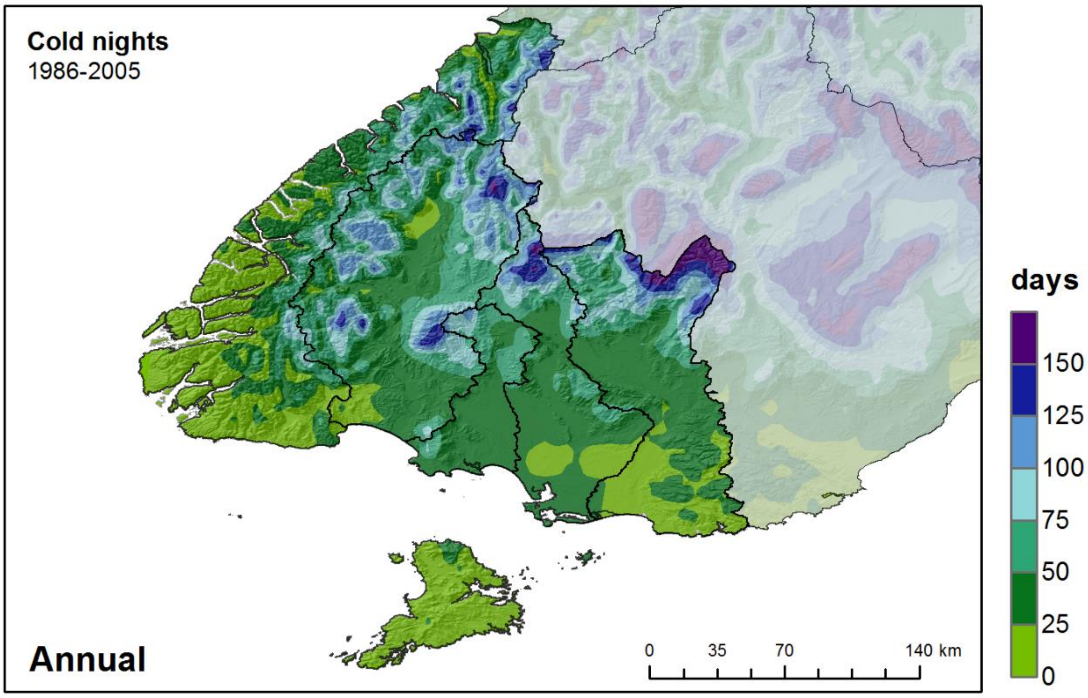

Figure 5-12: Modelled average annual number of cold nights (frosts) in Southland (Tmin <0°C), 1986-2005. Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

5.3.2 Future

As the seasonal mean temperature increases over time, we also expect to see changes in temperature extremes. In general, an increase in high temperature extremes, and a decrease in low temperature extremes is expected. The projected increase in the number of hot days per year at 2040 and 2090 relative to 1995, for RCP4.5 and RCP8.5 is shown in Figure 5-13.

At 2040 under both scenarios, most of the Southland region is projected to experience 0-10 more hot days per year. A small area in the northern Matāura catchment is projected to experience 10-15 more hot days per year (this area is slightly larger under RCP8.5 than RCP4.5). By 2090 under RCP4.5, most of Fiordland and the western Waiau catchment, as well as Stewart Island/Rakiura, are projected to experience 0-5 more hot days per year, the southern part of the region is projected to experience 5-10 more hot days per year, and the northern-central part of the region as well as northern Fiordland is expected to experience 10-15 more hot days per year. For some parts of the northern MatāuraMatāura catchment, projections indicate 15-20 more hot days per year. At 2090 under RCP8.5, however, the number of projected hot days is significantly higher, with the northern MatāuraMatāura catchment expecting up to 55 more hot days per year. Much of the northern-central part of the region, as well as northern Fiordland, is expecting increases of more than 30 hot days per year.

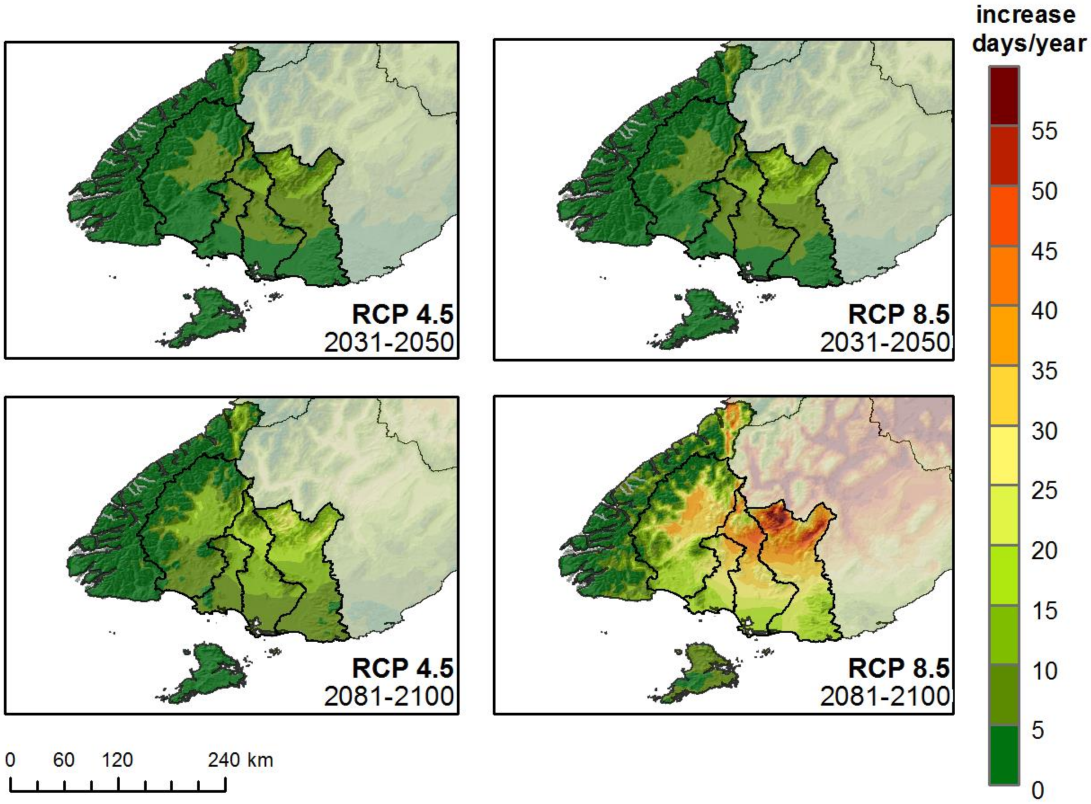

Figure 5-13: Projected increase in number of hot days per year (T_{max} >25°C) at 2040 (2031-2050) and 2090 (2081-2100) for RCP4.5 (left panels) and RCP8.5 (right panels), for Southland. Projected change in hot days is relative to 1986-2005. Results show the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, MatāuraMatāura.

The projected decrease in the number of cold nights (i.e., frosts) per year at 2040 and 2090 relative to 1995, for RCP4.5 and RCP8.5 is shown in Figure 5-14. By 2040 under both RCP4.5 and RCP8.5, the number of frosts is projected to decline by 0-5 frosts per year for most of the region, and by up to 20 frosts per year at high elevations. By 2090 under RCP4.5, lowland areas are expected to experience 10-15 fewer frosts per year, and up to 25 fewer frosts at higher elevations. Under RCP8.5 at 2090, the majority of the region is expected to experience at least 20 fewer frosts per year, with high elevations expecting a decrease of at around 50 fewer frosts.

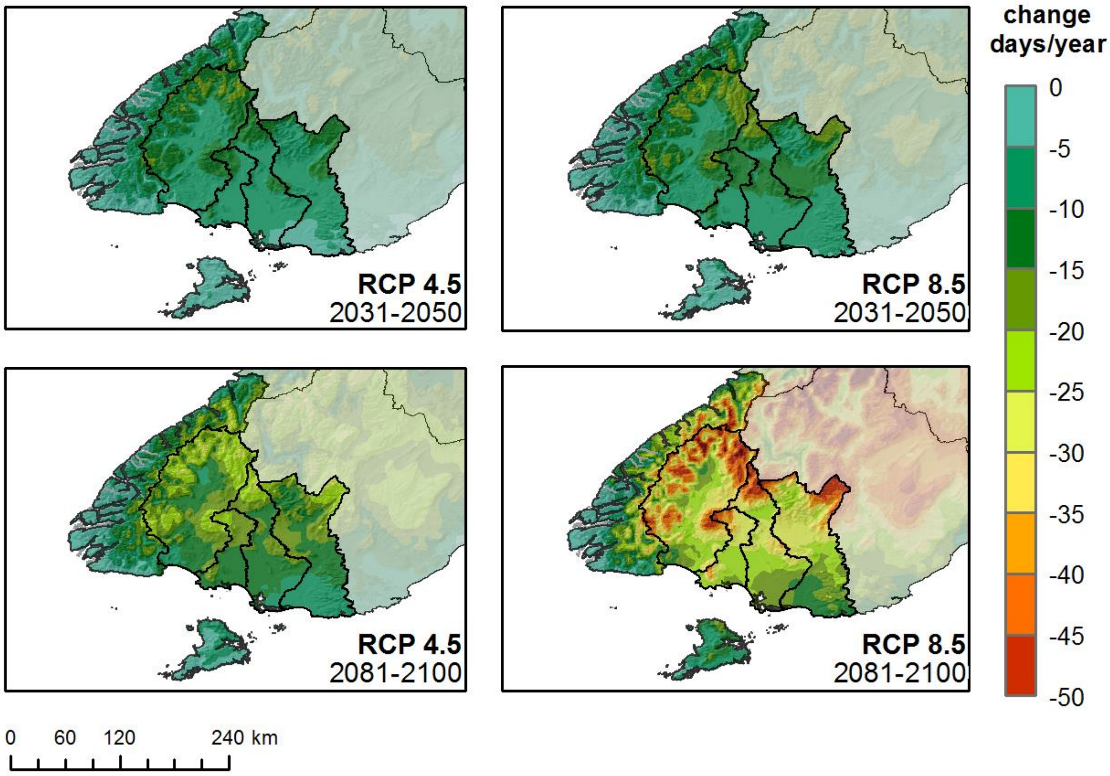

Figure 5-14: Projected decrease in number of cold nights (frosts) per year (Tmin <0°C) at 2040 (2031-2050) and 2090 (2081-2100) for RCP 4.5 (left panels) and RCP8.5 (right panels), for Southland. Projected change in cold nights is relative to 1986-2005. Results show the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, MatāuraMatāura.

5.4 Heatwaves

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

Table 5-1 shows the 20-year average number of heatwave days for the present climate (1986-2005) and for RCPs 4.5 and 8.5 at two future times, for 14 locations within the Southland region. The three sites of Te Anau, Riversdale and Lumsden have the most heatwave days, varying from about 3 days under the present climate up to about 25 days at the end of the century under RCP8.5. Each heatwave event is a whole number of days, with a minimum length of at least 3 days. Counts less than three in Table 5-1 (or Figure 5-15) indicate that a 3-day heatwave, for example, does not occur every year in every model.

Figure 5-15 illustrates how heatwave days, and its changes, have been calculated for Lumsden (selected because it lies within a sub-region of Southland with very high number of current and future number of heatwave days). In the present climate (blue histogram bars), the number of heatwave days for 8-day events at Lumsden is 0.133; summing over 20 years and six climate models, this converts to 16 days (=0.133*20*6), or two 8-day events in total. Similarly, the number of heatwave days for 6-day events is 0.100, also corresponding to two 6-day events. On the other hand, there were no 7-day events simulated by any of the six models in the 20-year period 1986-2005. The total of all the present-day counts (the blue bars) comes to 2.6 days, as given in Table 5-1. The present-day totals, and the changes, are mapped over the Southland region in the following Figure 5-16 and Figure 5-17.

Table 5-1: Heatwave days for the present climate, and for two future time-slices under RCPs 4.5 and 8.5, shown for 14 locations in the Southland region.

		Heatwave days						
Period	RCP	Gore	Matāura	Riversdale	Winton	Lumsden	Waihōpai	NewRiver
Present		2.1	1.2	3.7	1.3	2.6	0.3	0.4
2031-2050	RCP4.5	4.0	2.9	7.4	3.4	6.2	0.8	0.9
	RCP8.5	4.7	3.3	7.7	4.2	7.1	1.2	1.0
2081-2100	RCP4.5	7.0	5.0	11.5	6.5	10.6	1.8	1.9
	RCP8.5	16.6	13.6	24.6	16.5	25.2	6.3	6.2
		Heatwave days						
Period	RCP	Te Anau	Milford Sound airport	Riverton/ Aparima	Tuatapere	Otautau	Catlins-Waikawa	Halfmoon Bay
Present		3.0	0.6	0.5	1.0	1.0	0.2	0.0
2031-2050	RCP4.5	8.0	1.8	1.1	1.4	2.1	0.9	0.0
	RCP8.5	7.4	1.8	1.3	2.2	2.5	1.2	0.1
2081-2100	RCP4.5	12.0	3.8	2.3	3.3	4.0	2.0	0.3
	RCP8.5	28.2	10.9	8.1	9.2	11.4	6.8	0.8

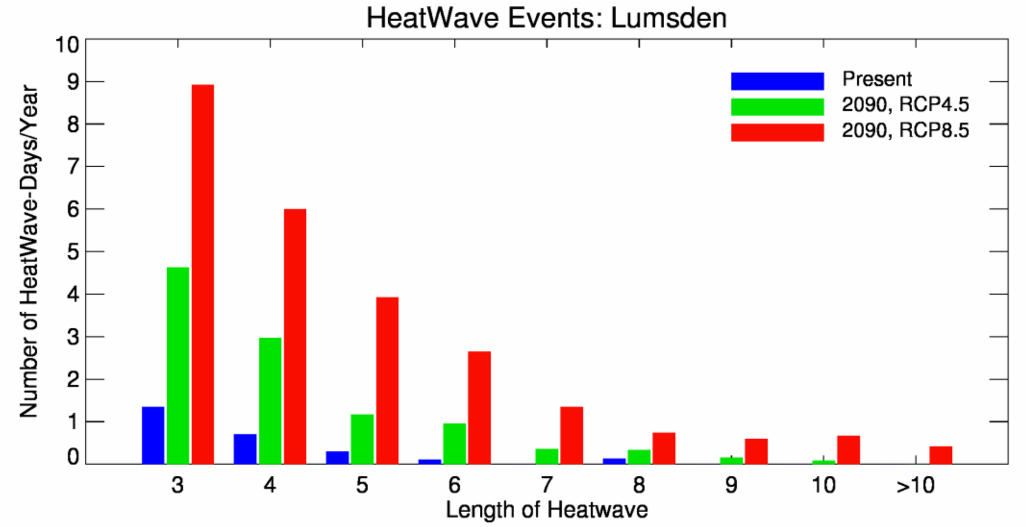

Figure 5-15: Average number of heatwave days per year for Lumsden, plotted as a function of the length of the heatwave in days. Colour bars represent counts under the historical climate (blue) and for 2090 under RCP4.5 (green) and RCP8.5 (red). The last column shows all accumulated heatwave days of 11 days and longer.

5.4.1 Present

The map for 'present-day' annual number of heatwave days (a count of all days during periods with at least three consecutive days with a maximum temperature > 25°C) in Southland is presented in Figure 5-16. These maps show a 20-year average of heatwave days over 1986-2005. Note that these maps present modelled present-day climate, i.e., six global climate models are run in hindcast mode and these maps are the average of the six models.

At present, most of the Southland region experiences no or very few heatwave days (less than five per year) (Figure 5-16). The only part of the region to experience a larger number of heatwave days is in the northern Ōreti catchment, which experiences 5-10 heatwave days per year, and the northern Matāura catchment, which experiences up to 20 heatwave days per year.

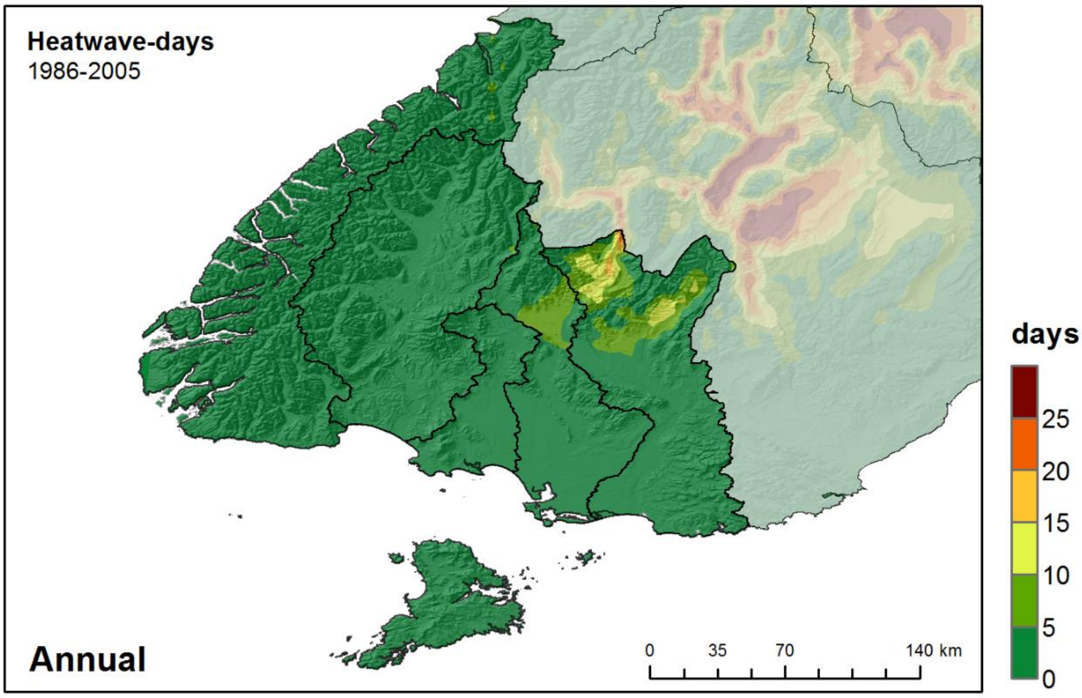

Figure 5-16: Modelled average annual number of heatwave days in Southland (Tmax >25°C), 1986-2005. Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

5.4.2 Future

The future projections for the change in the annual number of heatwave days is presented in Figure 5-17, for 2040 and 2090 under RCP4.5 and RCP8.5. The maps show the ensemble average of the six dynamically downscaled global climate models. At 2040 for both RCPs, most of the region is expected to experience a negligible increase in the number of heatwave days of 0-5 days per year, on average. For northern parts of the Ōreti and Matāura catchments, projections are expected to increase in heatwave days of 5-15 days per year. By 2090 under RCP4.5, a large swath of the inland Southland region is projected to experience 5-10 more heatwave days per year. For parts of the northern Matāura catchment projections are expected to increase by 15-20 heatwave days per year. By 2090 under RCP8.5, most inland parts of the region, except for the Fiordland catchment, are projected to experience at least 10 more heatwave days per year, with projected increases of over 35 heatwave days per year for the northern Matāura catchment.

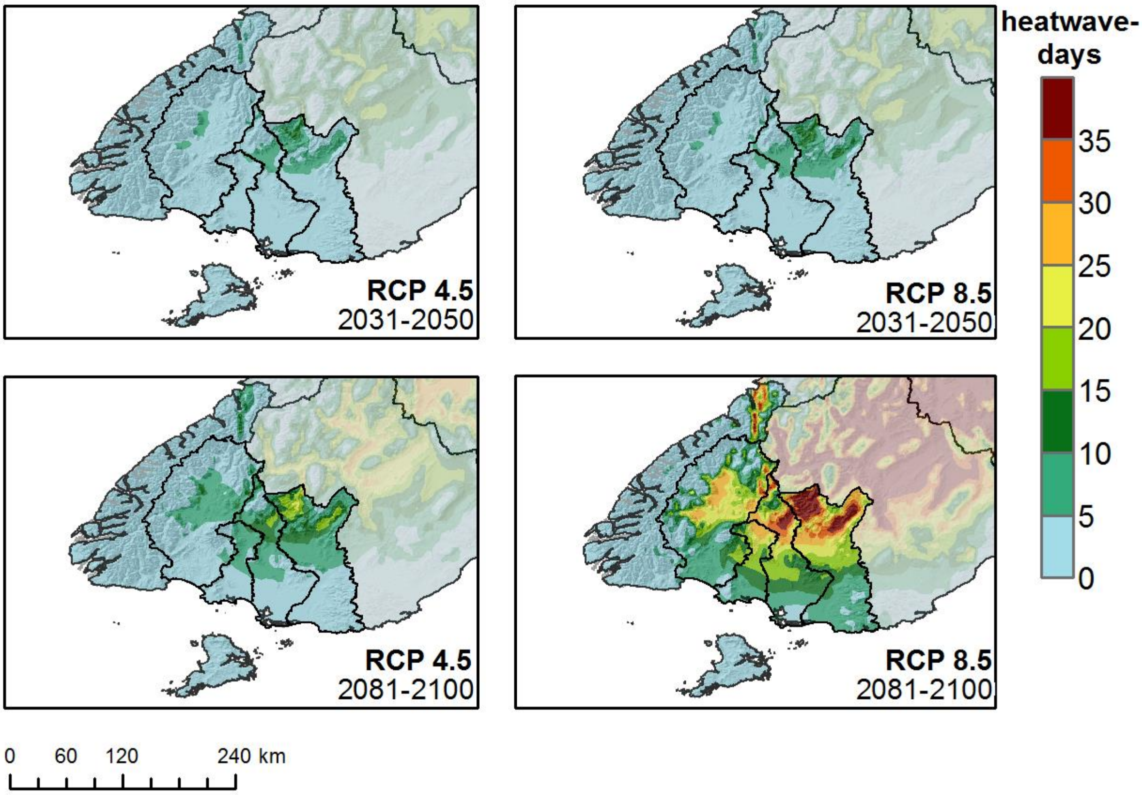

Figure 5-17: Projected increase in average annual heatwave days at 2040 (2031-2050) and 2090 (2081-2100) for RCP4.5 (left panels) and RCP8.5 (right panels), for Southland. Projected change in heatwave days is relative to 1986-2005. Results show the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6 Rainfall

Rainfall variables presented include total rainfall amount, number of wet days (> 1 mm), number of heavy rain days (> 50 mm), maximum 1-day rainfall (Rx1day), maximum 5-day rainfall (Rx5day), dry days (< 1 mm) and potential evapotranspiration deficit. For all variables, present-day conditions are summarised and future projections are presented for RCP4.5 and RCP8.5 at 2040 and 2090.

6.1 Total rainfall

6.1.1 Present

The map for 'present-day' annual and seasonal total rainfall in Southland is presented in Figure 6-1. This map shows a 20-year average of total rainfall over 1986-2005. Note that this map presents modelled present-day climate, i.e., six global climate models are run in hindcast mode and this map is the average of the six models.

The rainfall patterns in Southland clearly show the influence of elevation and exposure to the main rain-bearing airflows from the west. The area that receives the most annual rainfall in Southland is the mountainous area of Fiordland (> 6000 mm per year). This part of the region is among the wettest in New Zealand and the world. The orographic effect caused by the western mountains is reflected in the lower rainfall totals to the east of Fiordland. The driest part of the region is in the centre and east, where 500-1000 mm is recorded per year. There is a strong gradient in the western Waiau catchment where the amount of annual rainfall increases from 1000-2000 mm to > 6000 mm with increasing elevation. Spring is the wettest season and winter is the driest, on average.

6.1.2 Future

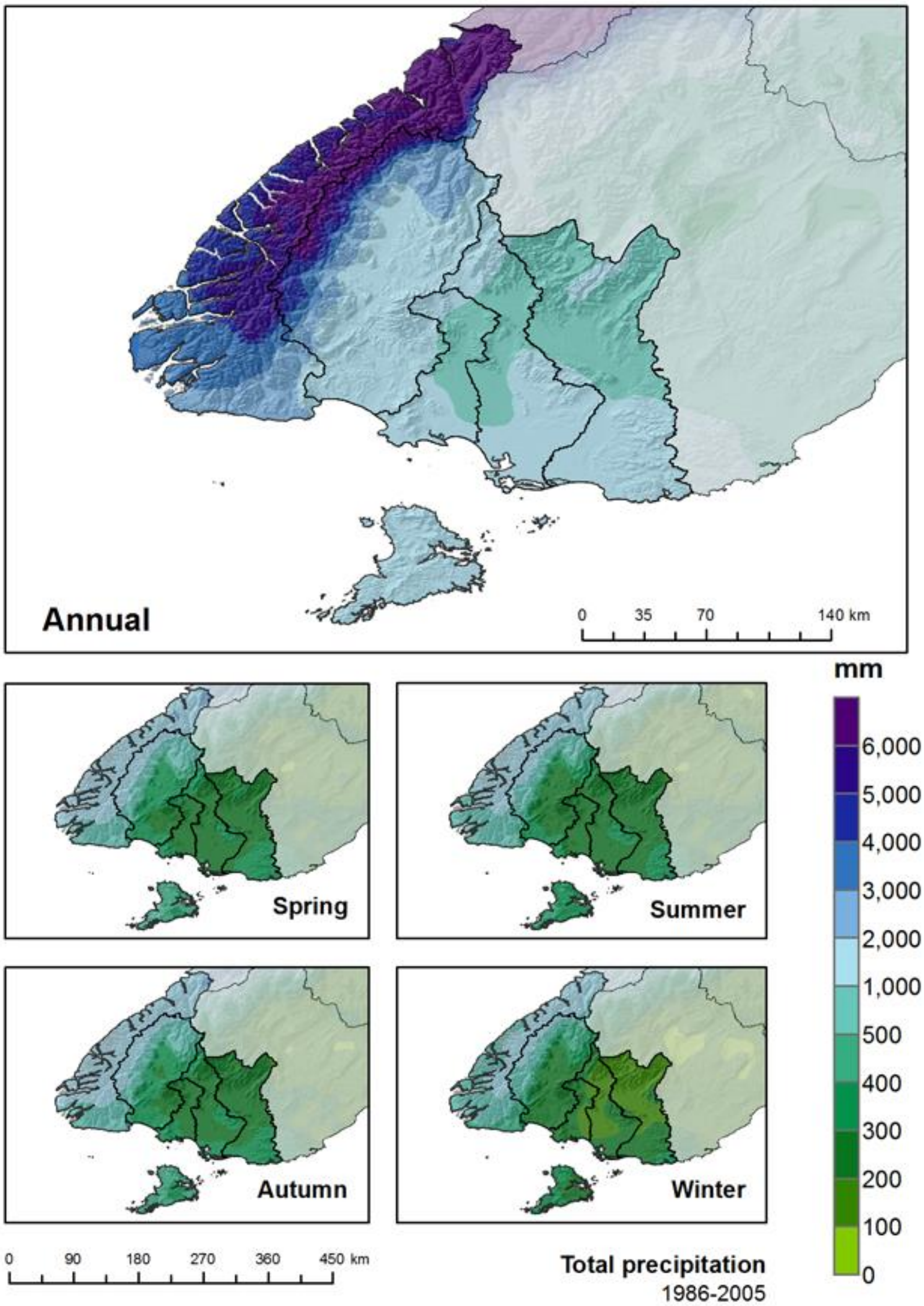

Figure 6-1: Modelled mean annual and seasonal total rainfall for Southland (1986-2005). Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

The ensemble averages for dynamically downscaled projections of total rainfall, using NIWA's Regional Climate Model, are presented in this section. Figure 6-2 to Figure 6-5 show the projected seasonal and annual patterns of rainfall change over Southland at 2040 and 2090 for RCP4.5 and RCP8.5.

By 2040, for most of the Southland region, annual rainfall is projected to increase by 0-5% under both RCP4.5 (Figure 6-2) and RCP8.5 (Figure 6-4). There are areas which project annual rainfall increases of 5-10% under RCP8.5, particularly in the north of the region. Under RCP4.5 at 2090, most of the region is projected to experience increases in annual rainfall of 5-10% (Figure 6-3), with some areas in northern Fiordland expected to experience increases of 10-15%. At 2090 under RCP8.5 (Figure 6-5), much larger increases are projected for annual rainfall. The area around Milford Sound is projected to experience 30-40% more annual rainfall, while most of the rest of Fiordland is expected to experience increases of 20-30%. Most of the remainder of the region is projected to experience 10-20% more annual rainfall.

In terms of seasonal rainfall changes, the largest increases in rainfall are projected for winter. The amount of rainfall increases with time period and RCP, with the largest increases projected for RCP8.5 at 2090 – increases of over 40% in winter rainfall are projected for Fiordland and other northern parts of the region during that time period. Decreases in seasonal rainfall are projected in summer in the central and lower Waiau catchment under both scenarios and future time periods. The largest decreases are projected for summer at 2090 under RCP8.5, when up to 10% less rainfall is projected.

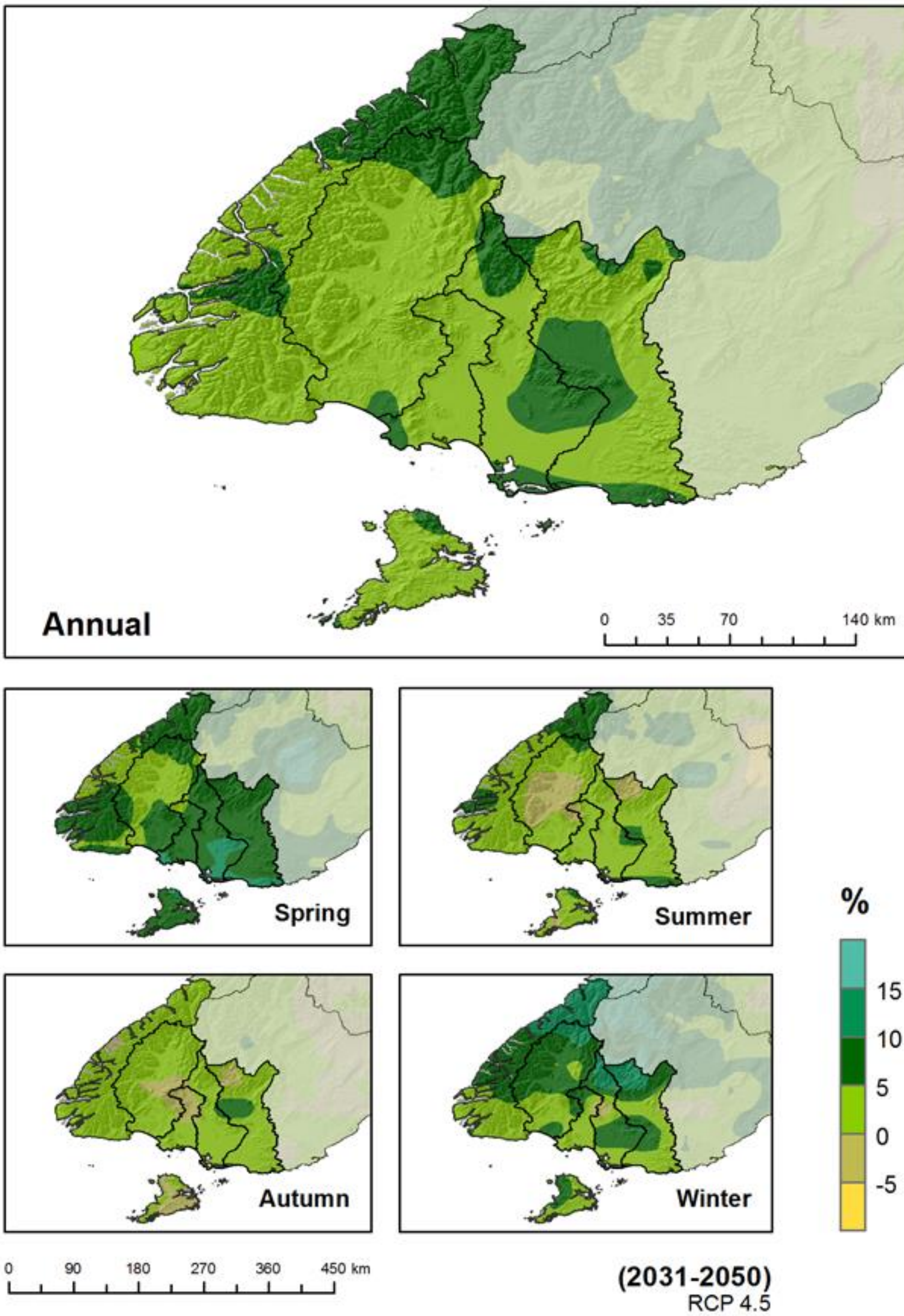

Figure 6-2: Projected annual and seasonal rainfall changes (in %) at 2040 (2031-2050 average) for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

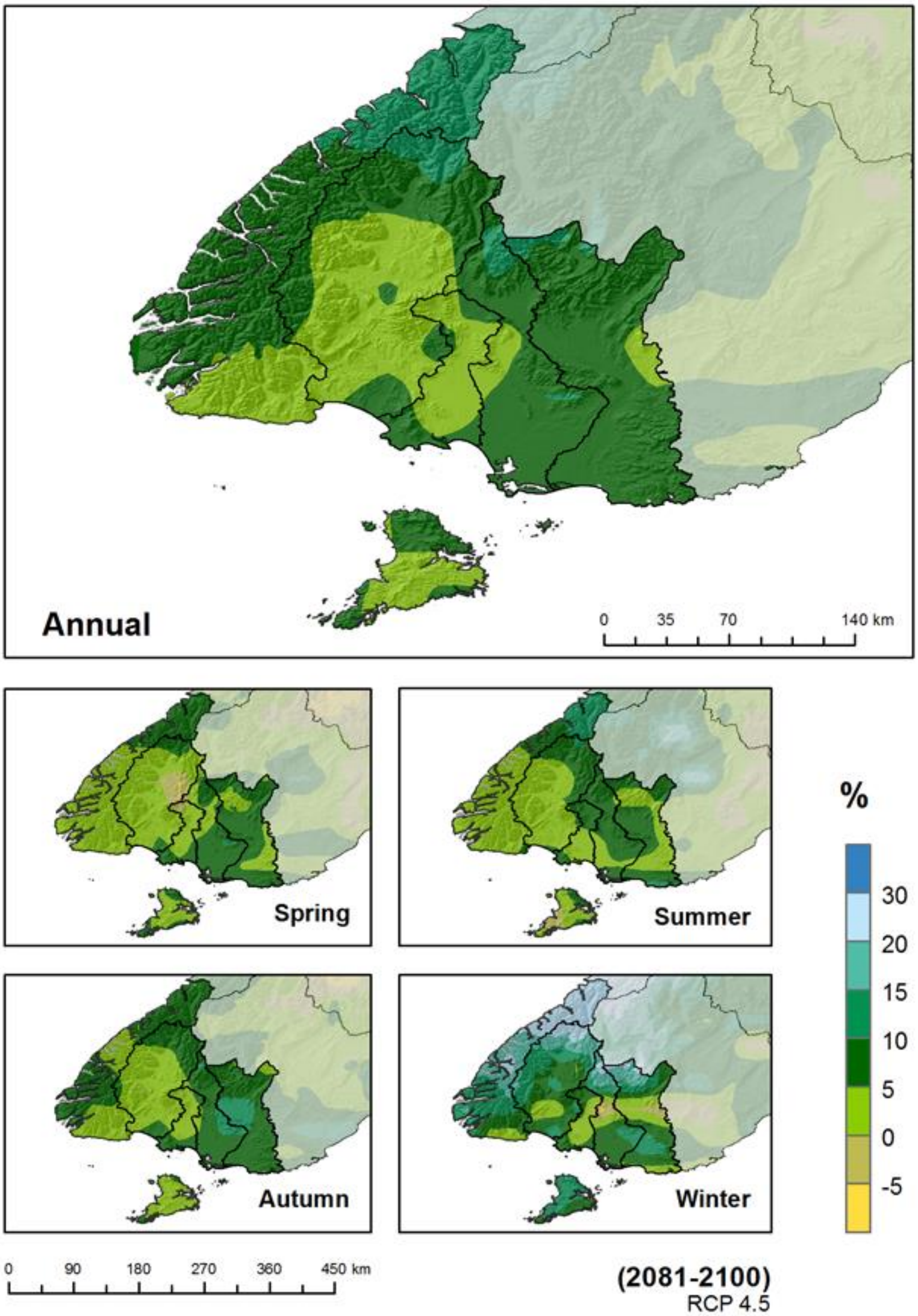

Figure 6-3: Projected annual and seasonal rainfall changes (in %) at 2090 (2081-2100 average) for RCP4.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

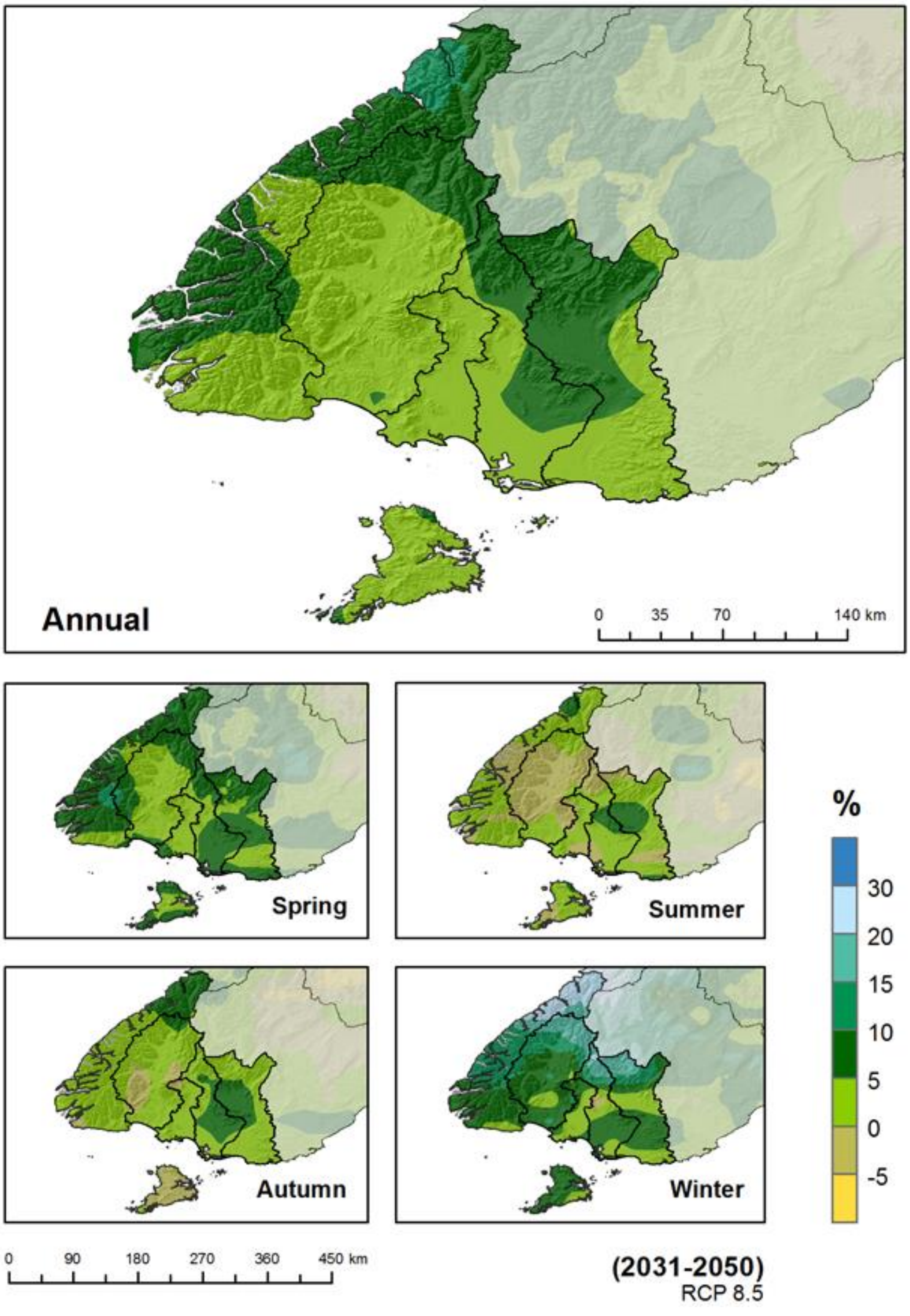

Figure 6-4: Projected annual and seasonal rainfall changes (in %) at 2040 (2031-2050 average) for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

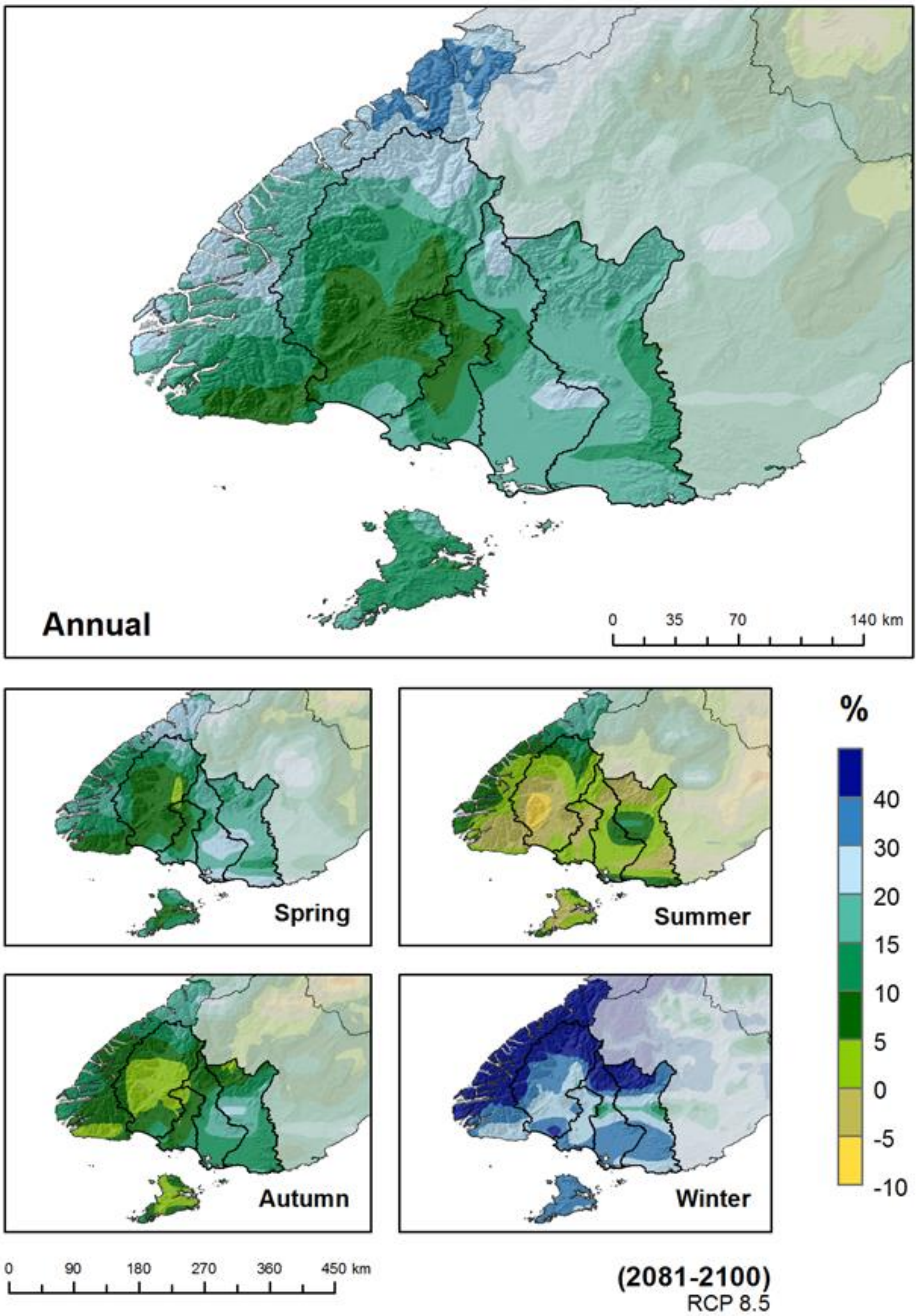

Figure 6-5: Projected annual and seasonal rainfall changes (in %) at 2090 (2081-2100 average) for RCP8.5. Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.2 Wet days (>1 mm)

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

6.2.1 Present

The map for 'present-day' annual number of wet days (> 1 mm) in Southland is presented in Figure 6-6. This map shows a 20-year average of wet days over 1986-2005. Note that this map presents modelled present-day climate, i.e., six global climate models are run in hindcast mode and this map is the average of the six models.

At present, the highest amount of wet days per year is recorded in Fiordland, where 200-250 wet days per year are experienced on average (Figure 6-6). There is a small area in southern Fiordland which experiences 250-300 wet days per year. Most of the region experiences 150-200 wet days per year, with some parts of the northern Matāura catchment experiencing 100-150 wet days per year.

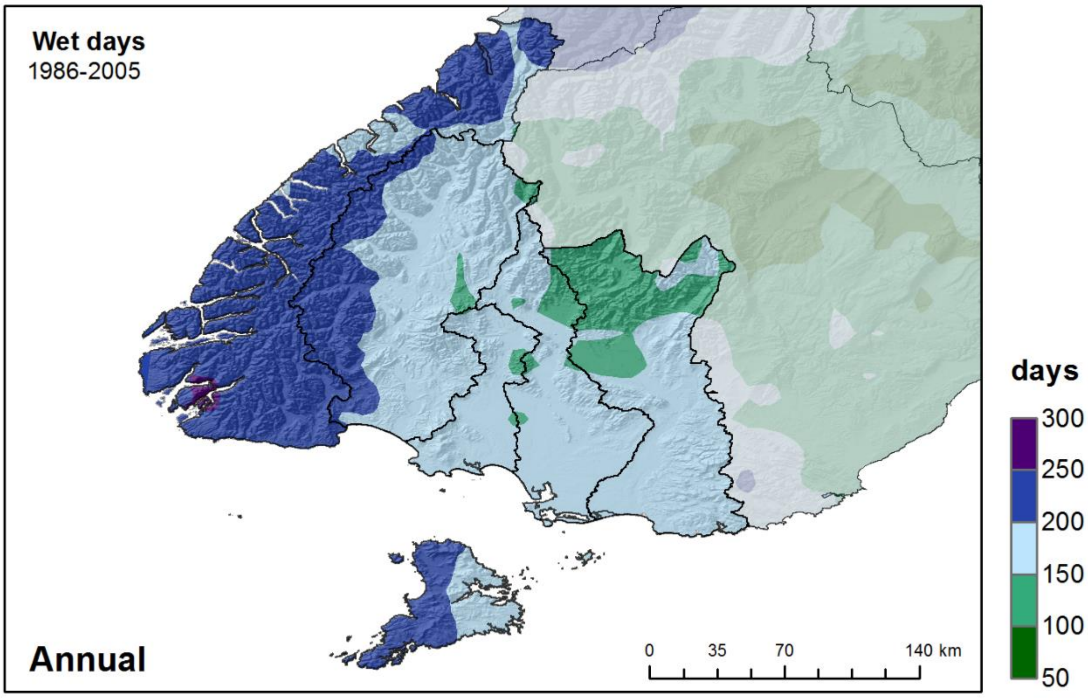

Figure 6-6: Modelled mean annual number of wet days (days with > 1 mm rain) for Southland (1986-2005). Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.2.2 Future

Projections of changes to annual wet days (where daily rain >1 mm) are presented for 2040 and 2090, compared to 1995 under RCP4.5 and RCP8.5 in Figure 6-7.

The projections for RCP4.5 and RCP8.5 at 2040 are similar, with 0-10 fewer wet days per year expected for much of the Fiordland and Waiau catchments, as well as the southern Matāura and Ōreti catchments and Stewart Island/Rakiura. Up to 10 more wet days per year are expected for the central part of the region and northern and western Fiordland. At 2090 under RCP4.5, an increase in wet days is projected for most of the region outside the Waiau catchment and Stewart Island/Rakiura. An increase of 10-20 wet days per year is projected for northern Fiordland. Under RCP8.5 at 2090, increases in the number of wet days are projected for most of the region, with the largest increases in western and northern Fiordland. The largest decreases are projected for the eastern Waiau catchment, where 10-20 fewer wet days per year are expected.

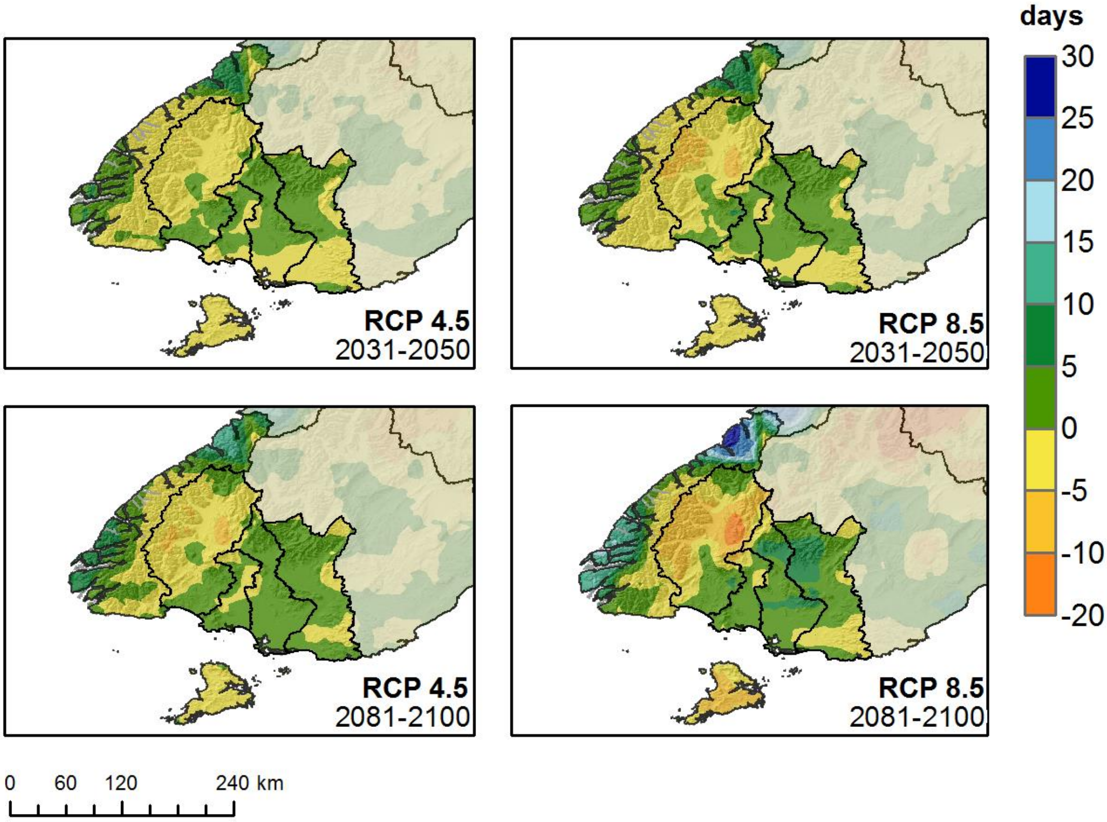

Figure 6-7: Projected annual wet day changes (days where rain > 1 mm; in number of days), for RCP4.5 (left panels) and RCP8.5 (right panels), at 2040 (2031-2050) and 2090 (2081-2100). Relative to 1986-2005 average, based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.3 Heavy rain days (> 50 mm)

Numerous measures can be used to describe heavy rainfall. The threshold used in this section is 50 mm of rain per day, following consultation with Environment Southland. Following sections use different measures of heavy and extreme rainfall to consider different ways rainfall changes over time in Southland.

6.3.1 Present

The map for 'present-day' annual number of heavy rain days (> 50 mm) in Southland is presented in Figure 6-8. This map shows a 20-year average of heavy rain days over 1986-2005. Note that this map presents modelled present-day climate, i.e., six global climate models are run in hindcast mode and this map is the average of the six models.

The annual average number of heavy rain days varies significantly across the Southland region (Figure 6-8). Most of the northern half of Fiordland experiences 30-50 heavy rain days per year, whereas much of the southern half of Fiordland observes less than 20 heavy rain days per year. Most heavy rain events come from the west and therefore fall on the mountains in Fiordland, which shelter the lower elevations to the east. Most of the Southland region east of Fiordland experiences less than one heavy rain day per year, on average. There is a strong gradient in the western Waiau catchment where the number of heavy rain days increases from 1-10 days to 40-50 days with increasing elevation.

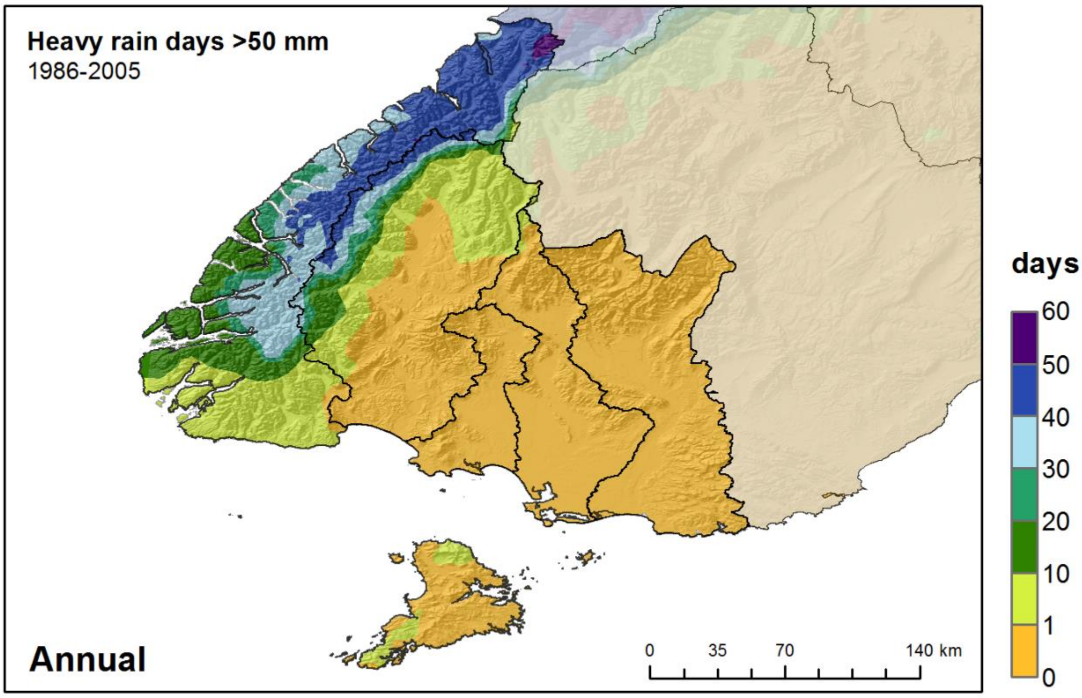

Figure 6-8: Mean annual number of heavy rain days (days with > 50 mm rain) for Southland (1986-2005). Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.3.2 Future

Projections of heavy rain days are presented for 2040 and 2090 under RCP4.5 and RCP8.5 in Figure 6-9, derived from the ensemble average of six dynamically downscaled models.

The number of heavy rain days is projected to increase throughout the Southland region at both time slices and RCPs, except for a small area in the eastern Waiau catchment which projects a small decrease in the number of heavy rain days at 2040. At 2040 under RCP4.5 and RCP8.5, and at 2090 under RCP4.5, most of the region outside the Fiordland catchment is expected to experience an increase in the number of heavy rain days by 0-2 days per year. Fiordland is expected to experience an increase of 2-6 days per year during these times and RCPs. At 2090 under RCP8.5, most of the region outside of the Fiordland catchment still is expected to experience an increase of 0-2 heavy rain days per year, but the northern Fiordland catchment is expected to experience 12-14 more heavy rain days per year and most of the rest of the catchment is expected to experience 6-10 more heavy rain days per year.

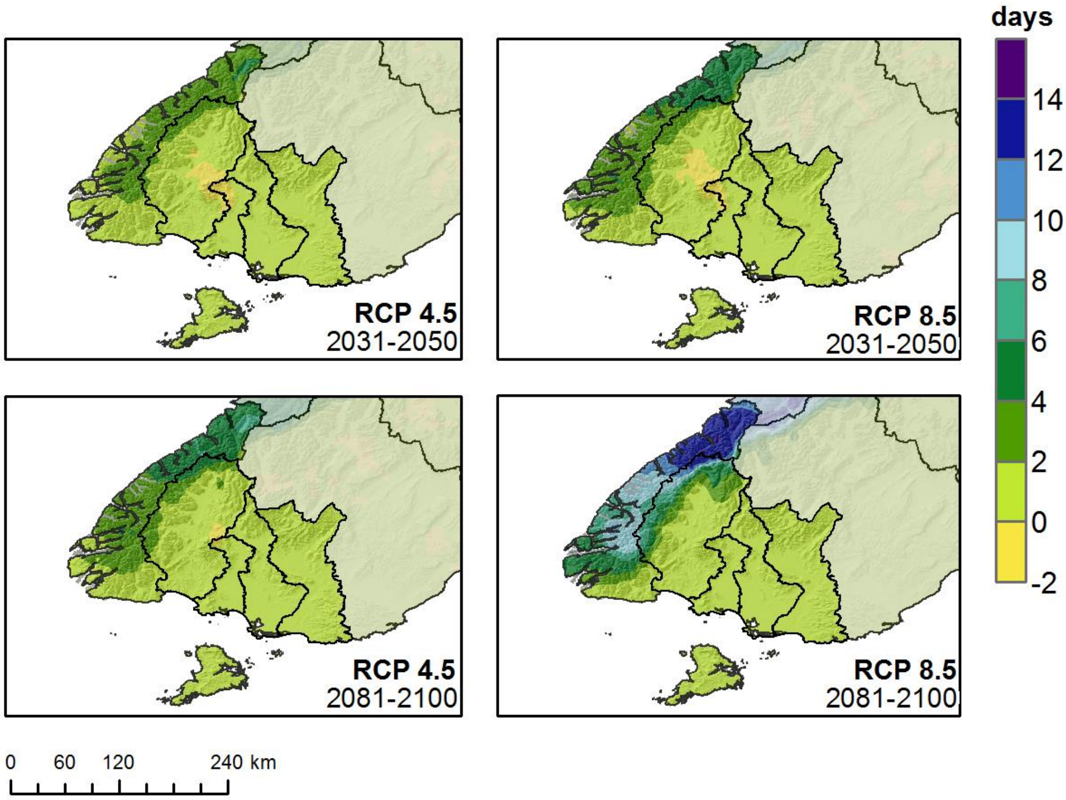

Figure 6-9: Projected changes in the number of annual heavy rain days (daily rain > 50 mm) for Southland, for RCP4.5 (left panels) and RCP8.5 (right panels), at 2040 (2031-2050) and 2090 (2081-2100). Projected change in heavy rain days is relative to 1986-2005. Results show the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.4 Maximum 1-day rainfall (Rx1day)

The annual maximum 1-day rainfall (otherwise known as Rx1day) is calculated as the wettest day of each year, which is then averaged over the 20-year period (e.g., 1986-2005 for the 'present' and 2031-2050 and 2081-2100 for the future projections). Rx1day would be broadly comparable to a 24-hour duration rainfall event with a return period of approximately one year. Information on rainfall intensity and return periods in Southland is available from Macara (2013) and www.hirds.niwa.co.nz.

6.4.1 Present

The map for 'present-day' annual maximum 1-day rainfall (Rx1day) for Southland is presented in Figure 6-10. This map shows a 20-year average of Rx1day over 1986-2005. Note that this map presents modelled present-day climate, i.e., six global climate models are run in hindcast mode and this map is the average of the six models.

The annual average Rx1day is highest in the northern half of Fiordland, where 1-day rainfall totals of over 200 mm are common (Figure 6-10). Rx1day totals of 100-200 mm are observed in most of the rest of Fiordland. In contrast, most of the region east of the Waiau catchment experiences Rx1day totals of 0-50 mm, with some areas (including Stewart Island/Rakiura) experiencing totals of 50-100 mm. There is a strong gradient in the western Waiau catchment where Rx1day increases from 0-50 mm to 200-250 mm with increasing elevation.

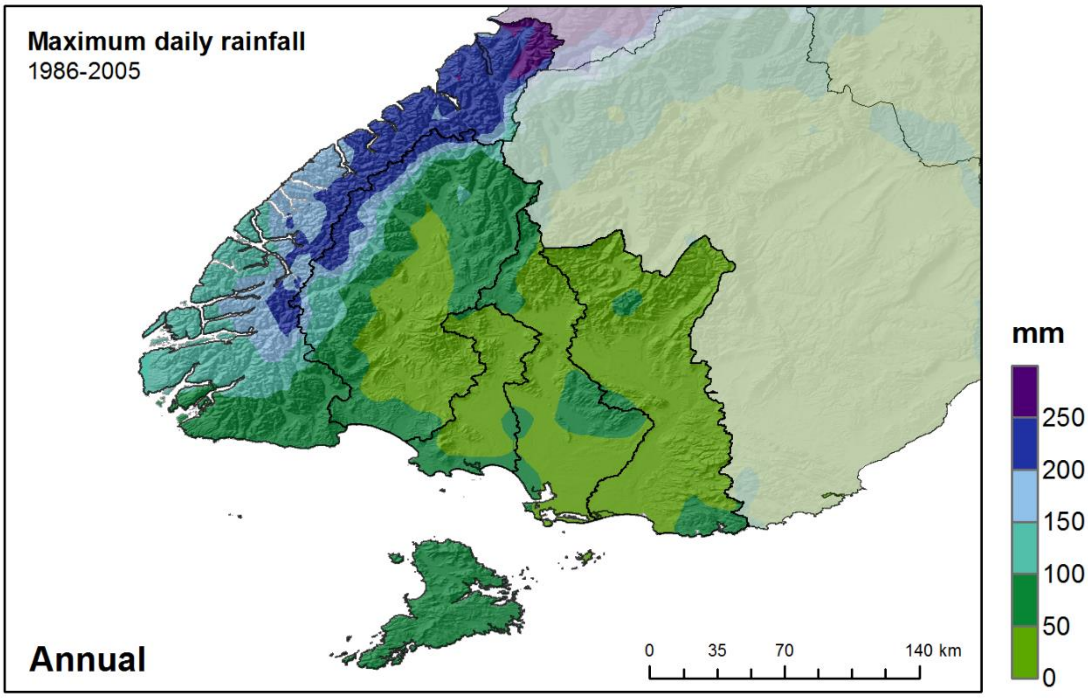

Figure 6-10: Modelled mean annual maximum 1-day rainfall (Rx1day) for Southland (1986-2005). Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.4.2 Future

The projected change in annual maximum daily rainfall (Rx1day) is presented in Figure 6-11 for RCP4.5 and RCP8.5 at 2040 and 2090. The maps show the ensemble average of six dynamically downscaled global models.

At 2040, the projections for RCP4.5 and RCP8.5 are similar. Decreases in Rx1day are projected for the centre of the Southland region (up to 10 mm) and increases are projected for the rest of the region. Most of the region projects increases of 0-10 mm but there are larger increases projected for Fiordland, particularly in the north, where 30-40 mm more rain is projected.

At 2090 under RCP4.5, the whole Southland region is projected to experience increases in Rx1day. Fiordland is projected to experience 10-40 mm more rainfall, and the rest of the region is projected to experience 0-20 mm more rainfall. At 2090 under RCP8.5, Fiordland is projected to experience increases of more than 30 mm, with northern parts projecting increases exceeding 100 mm. Most of the remainder of the region projects increases of 10-30 mm.

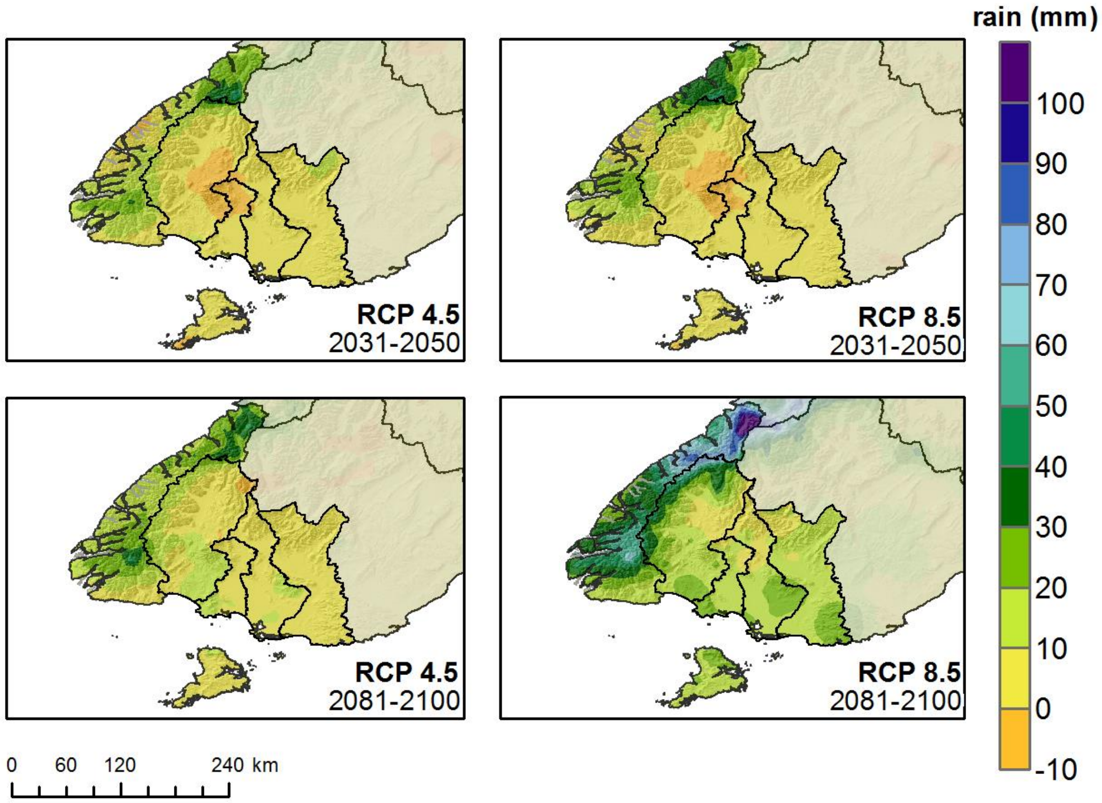

Figure 6-11: Projected changes in the annual maximum daily rainfall (Rx1day, measured in mm) for Southland, for RCP4.5 (left panels) and RCP8.5 (right panels), at 2040 (2031-2050) and 2090 (2081-2100). Projected change in Rx1day is relative to 1986-2005. Results show the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.5 Maximum 5-day rainfall (Rx5day)

The maximum 5-day rainfall (otherwise known as Rx5day) is calculated as the wettest 5-day period of each year, which is then averaged over the 20-year period (e.g., 1986-2005 for the 'present' and 2031-2050 and 2081-2100 for the future projections).

6.5.1 Present

The map for 'present-day' annual maximum 5-day rainfall (Rx5day) for Southland is presented in Figure 6-12. This map shows a 20-year average of Rx5day over 1986-2005. Note that this map presents modelled present-day climate, i.e., six global climate models are run in hindcast mode and this map is the average of the six models.

The annual average Rx5day is highest in the northern half of Fiordland, where 5-day rainfall totals of over 400 mm are common, and exceed 500 mm north of Milford Sound (Figure 6-12). Rx5day totals of 200-400 mm are observed in most of the rest of Fiordland. In contrast, most of the region east of the Waiau catchment experiences Rx5day totals of 50-100 mm. There is a strong gradient in the western Waiau catchment where Rx5day increases from 50-100 mm to 400-500 mm with increasing elevation.

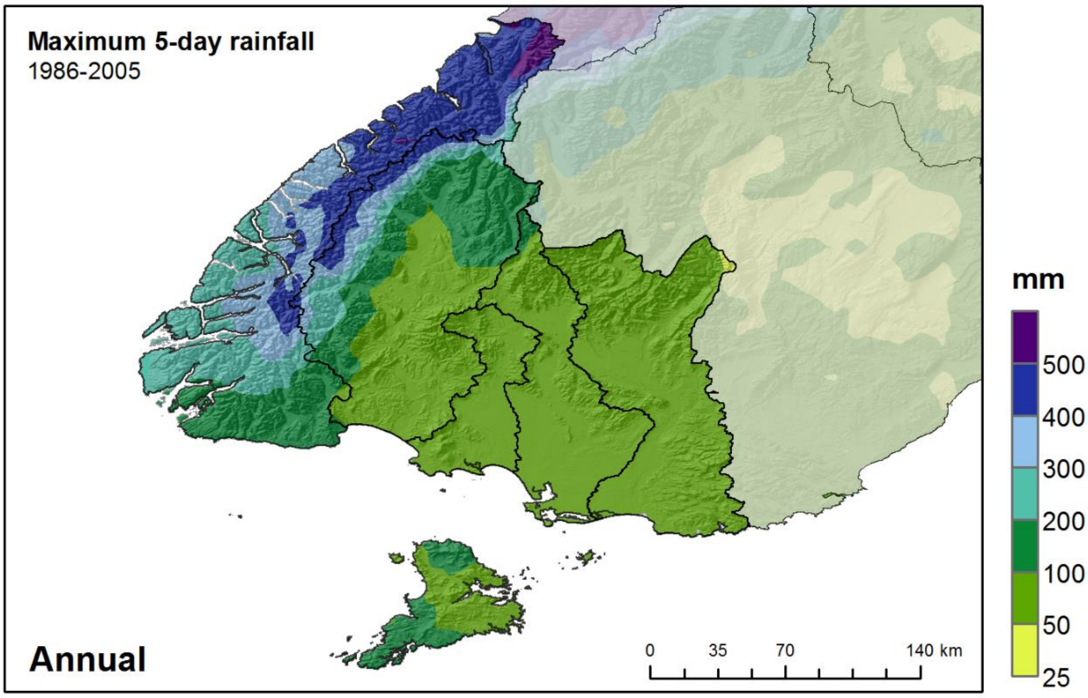

Figure 6-12: Modelled mean annual maximum 5-day rainfall (Rx5day) for Southland (1986-2005). Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.5.2 Future

The projected change in annual maximum 5-day rainfall (Rx5day) is presented in Figure 6-13 for RCP4.5 and RCP8.5 at 2040 and 2090. The maps show the ensemble average of six dynamically downscaled global models.

At 2040, the projections for RCP4.5 and RCP8.5 are similar. Decreases in Rx5day are projected for the centre of the Southland region (up to 15 mm) and increases are projected for the rest of the region, with Fiordland projecting the largest increases of 15-30 mm in some parts.

At 2090 under RCP4.5, almost the whole Southland region is projected to experience increases in Rx5day, except for a small area in the eastern Waiau catchment which projects a small decrease. Fiordland is projected to experience 15-30 mm more rainfall, and the rest of the region is projected to experience 0-15 mm more rainfall. At 2090 under RCP8.5, most of Fiordland is projected to experience increases of more than 45 mm, with northern parts projecting increases exceeding 105 mm. Most of the remainder of the region projects increases of 15-30 mm.

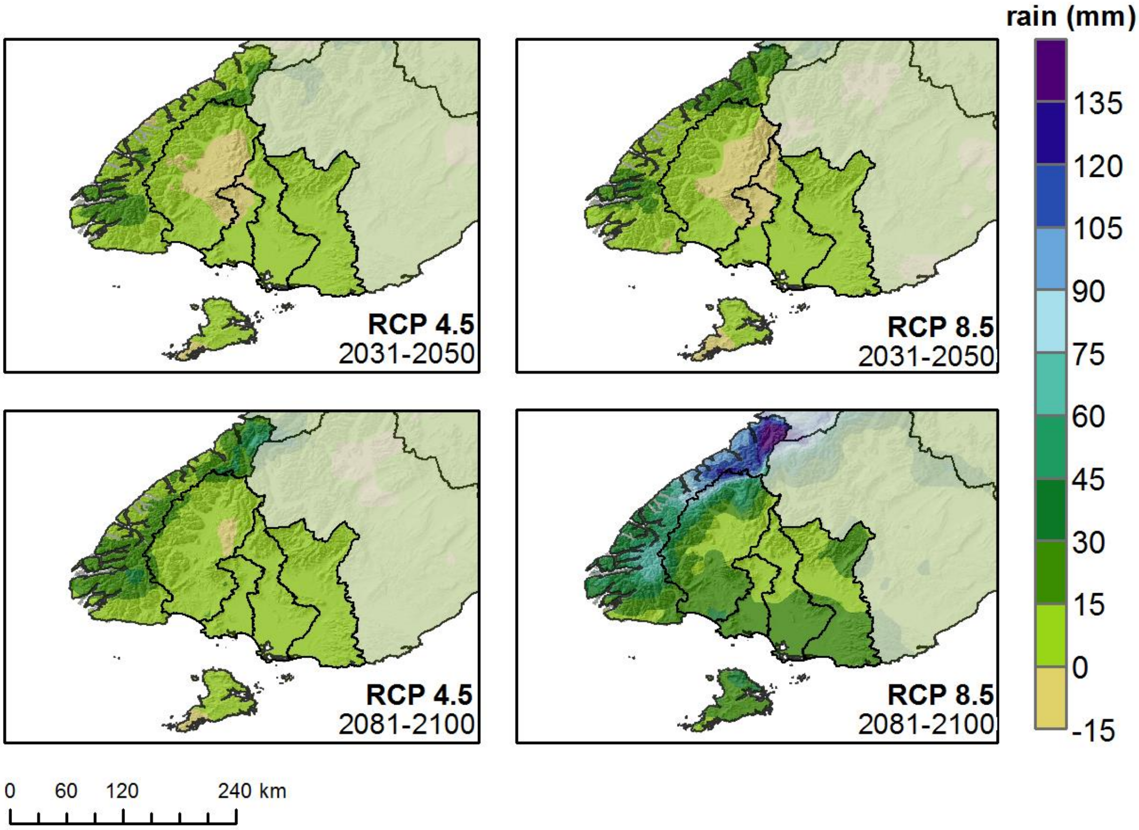

Figure 6-13: Projected changes in the annual maximum 5-day rainfall (Rx5day, measured in mm) for Southland, for RCP4.5 (left panels) and RCP8.5 (right panels), at 2040 (2031-2050) and 2090 (2081-2100). Projected change in Rx5day is relative to 1986-2005. Results show the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.6 Rainfall intensity and wet day thresholds

The tables in this section describe rainfall characteristics for fourteen locations within the Southland region (as selected by Environment Southland) (Figure 6-14). The site-specific changes can also be inferred from the maps in this report.

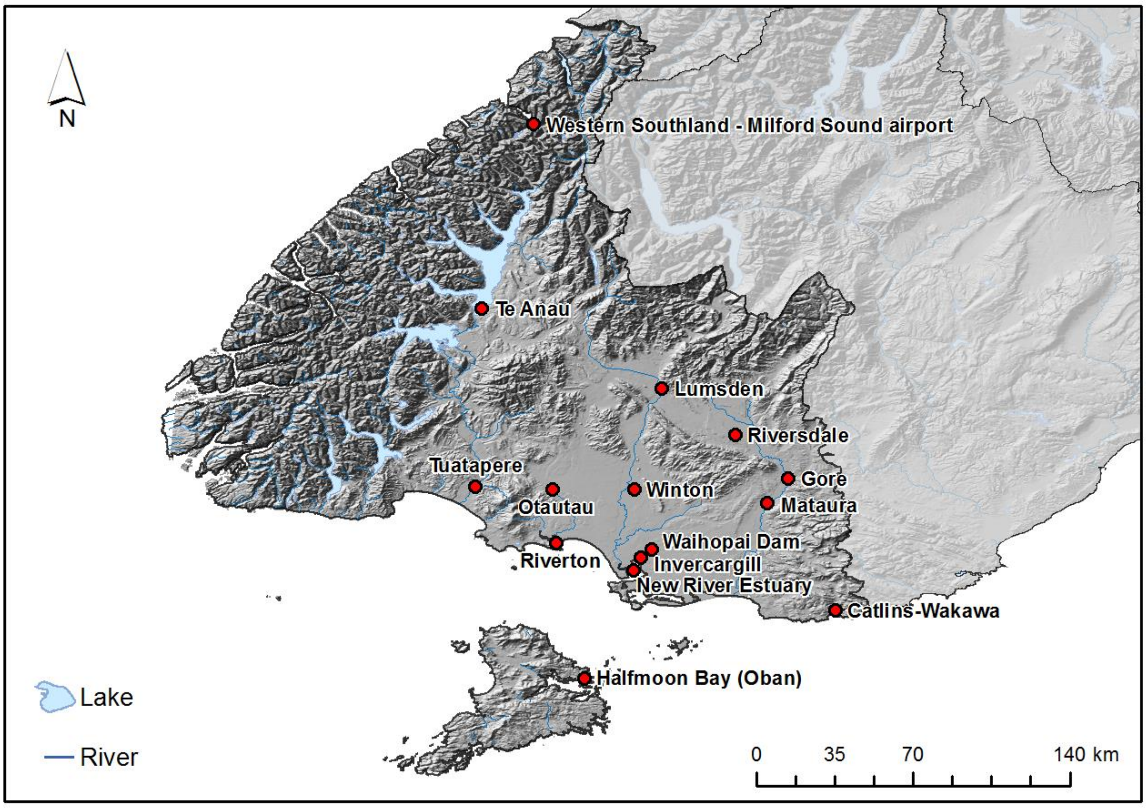

Figure 6-14: Map of the Southland region. Red dots indicate location specific projections presented in this report.

Tables 6-1 to 6-4 show the average number of rain days per year for the 14 Southland locations, for progressively increasing thresholds: 1 mm, 10 mm, 25 mm and 50 mm. The lowest threshold of 1 mm (Table 6-1) corresponds to what is commonly referred to as a "wet day", as discussed in Section 6.2. The converse is a "dry day" (Section 6.7), when rainfall is less than 1 mm. So, for example, for Gore in the present climate (as the models simulate it), there are 162.8 wet days per year on average, and 202.4 dry days (= 365.25 – 162.8). For the 14 selected locations, there are only small future changes in the number of wet days across the scenarios and time-slices. All locations show an increase in the average number of wet days per year by the end of the century, but even then, the maximum increase all sites the exception of Milford Sound Airport (MSA) is only about 5 days, at the sites of Riversdale, Winton and Lumsden. The change at the west coast site of MSA is an extraordinary 22 days for the later period of the extreme RCP8.5 projection.

For the larger 10 mm threshold (Table 6-2), the 13 locations currently experience between 20 days per year (at Gore) and 45 days per year (Halfmoon Bay) whereas MSA experiences 120 days. All locations except MSA show a future increase in the number of days with rainfall exceeding 10 mm, with the changes ranging from about 5 to 9 days more per year and the corresponding changes over MSA are up to about double average over the other sites (14 days).

For the 25 mm threshold (Table 6-3), the frequency across the selected locations ranges from 1 day/year (Gore) to 7 days/year (Halfmoon Bay) and 79 days/year (MSA). A rainfall of 25 mm or more is thus rather uncommon in the Southland region once east of Fiordland. There is a clear signal of an increasing number of days above 25 mm with higher emission scenarios and later in the century. By 2090 under RCP8.5, an additional two to five days per year have rainfall exceeding the threshold; in other words, the frequency of exceedance approximately doubles at most sites. On the other hand, the maximum increase in the number of days at the Fiordland site (MSA) is 14 days; is however the frequency of exceedance increases only up to 18%.

For the highest threshold of 50 mm (Table 6-4, and see Section 6-3), such rainfall amounts are very rare for the selected locations, although they become quite common in Fiordland (Figure 6-8). In the present climate, rainfall exceeding 50 mm occurs on only about 1.5 days/decade at Gore and 7 days/decade at Tuatapere. By 2090 under RCP8.5, this is projected to increase to 6 days/decade at Gore up to 19 days/decade at Catlins-Waikawa. In other words, heavy rainfall is expected to occur 3–4 times as often as under the present climate. At the Fiordland site (MSA) the maximum change is from 42 to 55 days/year corresponding to a 30% increase in annual frequency.

Table 6-1: Average number of wet days per year, for 14 Southland locations. Wet days are defined as days with rainfall greater than 1 mm.

Period	Present	2031-2050				2081-2099			
RCP		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Gore	162.80	164.70	163.10	163.80	165.10	164.20	164.30	166.00	166.60
Matāura	170.10	172.70	170.00	171.10	171.40	171.90	171.50	173.40	173.00
Riversdale	148.00	149.40	149.40	148.70	149.60	149.20	150.30	152.70	152.60
Winton	159.10	162.20	160.30	161.30	161.00	160.90	160.60	163.90	164.60
Lumsden	153.80	155.60	155.00	155.00	155.10	155.80	156.20	157.90	158.90
Waihōpai	169.10	170.70	168.20	168.80	169.00	169.90	170.00	171.90	170.30
New River	175.10	177.10	174.40	175.30	174.80	176.30	176.60	178.80	176.30
Te Anau	167.60	166.90	165.10	166.40	163.70	166.20	163.8	167.60	166.90
Milford Sound Airport	220.10	225.80	225.40	224.40	226.60	224.10	228.8	220.10	225.80
Riverton/Aparima	170.70	171.40	170.10	170.30	170.20	170.10	171.1	170.70	171.40
Tuatapere	164.80	168.30	166.40	166.90	165.40	167.40	168.5	164.80	168.30
Otautau	159.00	160.10	160.10	160.60	160.30	159.90	159	159.00	160.10
Catlins-Waikawa	183.50	185.10	184.00	185.30	183.70	185.20	185.5	183.50	185.10
Halfmoon Bay	192.30	192.70	191.00	191.70	190.20	192.30	190.4	192.30	192.70

Table 6-2: Average number of days per year with rainfall greater than 10 mm, for 14 Southland locations.

Period	Present	2031-2050				2081-2099			
RCP		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Gore	19.60	21.50	22.20	21.30	21.90	20.80	22.00	24.30	24.80
Matāura	27.60	30.40	30.10	29.60	30.60	28.90	30.60	32.90	34.10
Riversdale	18.10	19.90	20.30	20.10	20.10	18.90	20.50	22.30	23.20
Winton	24.00	25.80	25.70	25.50	26.60	24.70	26.50	28.70	30.20
Lumsden	24.10	25.30	25.20	25.50	26.60	24.70	26.20	28.70	29.00
Waihōpai	28.80	30.20	30.50	30.20	30.40	30.20	31.20	33.60	34.90
New River	29.70	31.60	32.20	32.20	31.90	31.10	32.50	35.30	37.20
Te Anau	32.10	33.90	33.60	34.20	34.10	33.20	34.10	36.20	38.10
Milford Sound Airport	120.40	123.60	123.40	123.80	124.10	122.50	126.00	131.20	134.10
Riverton/Aparima	30.10	30.90	31.70	31.20	30.80	30.40	32.10	33.10	35.20
Tuatapere	32.20	33.70	34.00	33.00	34.10	33.40	33.70	36.10	37.00
Otautau	31.30	31.00	31.90	30.90	31.40	30.80	31.50	32.60	33.50
Catlins-Waikawa	43.10	45.60	45.80	45.40	45.50	45.60	47.10	49.50	51.60
Halfmoon Bay	45.30	47.10	47.10	46.00	46.30	46.00	47.50	49.20	51.10

Table 6-3: Average number of days per year with rainfall greater than 25 mm, for 14 Southland locations.

Period	Present	2031-2050				2081-2099			
RCP		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Gore	1.10	1.80	1.50	1.70	1.50	1.50	1.90	2.30	2.90
Matāura	1.80	2.60	2.40	2.50	2.60	2.30	2.90	3.50	4.10
Riversdale	1.50	2.00	2.10	2.30	2.10	1.90	2.30	2.60	3.00
Winton	2.10	2.80	2.90	2.70	2.80	2.70	3.10	3.60	4.30
Lumsden	1.90	2.20	2.30	2.20	2.10	2.10	2.30	2.50	3.20
Waihōpai	2.40	2.80	3.30	2.90	3.20	2.70	3.30	3.70	4.40
New River	3.10	3.50	4.00	3.40	3.90	3.40	4.10	4.80	5.40
Te Anau	3.30	3.60	3.70	3.80	3.90	3.60	4.10	4.40	5.30
Milford Sound Airport	78.50	83.20	81.60	81.90	83.10	81.20	84.30	88.60	92.30
Riverton/Aparima	2.70	3.00	3.40	3.00	3.30	3.00	3.40	3.90	4.30
Tuatapere	4.20	5.20	5.20	5.00	5.10	4.60	5.40	5.90	6.60
Otautau	3.60	4.00	3.90	4.10	3.90	3.60	4.10	4.20	4.40
Catlins-Waikawa	6.60	8.20	8.50	8.00	8.20	7.60	9.00	10.30	11.80
Halfmoon Bay	7.10	8.20	8.20	7.70	8.30	7.70	8.40	9.50	10.10

Table 6-4: Average number of days per year with rainfall greater than 50 mm, for 14 Southland locations.

Period	Present	2031-2050				2081-2099			
RCP		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Gore	0.10	0.30	0.30	0.20	0.30	0.30	0.30	0.40	0.60
Matāura	0.20	0.30	0.40	0.40	0.40	0.40	0.40	0.60	0.70
Riversdale	0.30	0.60	0.50	0.50	0.50	0.50	0.60	0.70	0.90
Winton	0.40	0.60	0.70	0.60	0.60	0.60	0.70	0.80	1.10
Lumsden	0.20	0.40	0.30	0.20	0.30	0.30	0.20	0.30	0.50
Waihōpai	0.30	0.50	0.50	0.50	0.50	0.50	0.70	0.70	1.00
New River	0.40	0.60	0.70	0.60	0.60	0.60	0.70	0.80	1.20
Te Anau	0.30	0.30	0.30	0.30	0.30	0.40	0.40	0.40	0.50
Milford Sound Airport	42.30	45.60	45.10	45.70	46.90	44.40	47.00	50.60	55.20
Riverton/Aparima	0.40	0.60	0.70	0.60	0.60	0.60	0.70	0.80	1.10
Tuatapere	0.70	0.90	0.90	0.70	0.80	0.80	0.90	1.00	1.40
Otautau	0.20	0.40	0.30	0.30	0.40	0.30	0.40	0.40	0.60
Catlins-Waikawa	0.60	1.00	1.00	0.90	0.80	0.80	1.10	1.30	1.90
Halfmoon Bay	0.50	0.60	0.70	0.60	0.60	0.60	0.70	0.90	1.00

Tables 6-5 and 6-6 show the maximum 1-day and 5-day rainfalls for the 14 locations, as described across Southland in Sections 6-4 and 6-5, respectively. For annual 1-day extremes rainfall, Gore's extreme is the smallest (about 35 mm), with Winton, Otautau, Riverton/Aparima, Waihōpai Dam and New River Estuary receiving about 50 mm and Halfmoon Bay and Tuatapere receiving about 60 mm. All future scenarios show increases in these extremes. The largest increase, of about 40% across all locations, occurs at 2090 under RCP8.5. The 5-day extremes (Table 6-6) are 50–60% higher than the 1-day extremes, and these rainfall amounts are projected to increase by about 25% by 2090 under RCP8.5. Gore Lumsden and Riversdale are the driest of the 14 locations, and Halfmoon Bay, Tuatapere and Catlins-Wakawa the wettest outside of Fiordland.

The average rainfall divided by the average number of rain days is known as the rainfall "intensity". Table 6-7 shows the annual values of rainfall intensity for the 14 selected locations, for present and future climates. Under the present climate, rainfall intensity is 5 to 7 mm across the selected 14 locations and show only modest increases with time and emission scenario. Once again, Gore is the driest of the 14 sites, and Halfmoon Bay , Tuatapere and Catlins-Wakawa the wettest outside of Fiordland.

Table 6-5: Average annual maximum 1-day rainfall (Rx1day, measured in mm), for 14 Southland locations.

Period	Present	2031-2050				2081-2099			
RCP		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Gore	35.40	39.60	39.30	38.10	40.00	39.90	41.20	44.60	49.80
Matāura	41.90	46.90	46.70	46.30	47.60	48.10	49.10	52.50	60.70
Riversdale	39.70	44.70	43.00	42.60	44.50	44.20	47.10	48.70	51.60
Winton	48.30	50.90	51.70	51.30	52.10	52.60	56.00	56.80	66.60
Lumsden	37.70	42.30	42.20	39.70	42.10	42.90	42.80	44.30	46.80
Waihōpai	47.10	49.20	52.90	54.10	51.80	54.00	57.30	58.50	66.30
New River	47.50	49.40	53.80	53.80	51.00	52.70	57.10	59.80	66.70
Te Anau	41.00	41.30	41.50	42.20	41.30	43.70	44.80	43.70	49.10
Milford Sound Airport	211.20	236.30	241.90	237.60	246.50	236.60	235.60	252.30	266.50
Riverton/Aparima	52.00	55.80	58.40	54.80	55.60	56.40	61.50	62.30	71.80
Tuatapere	60.10	68.40	69.60	66.30	67.70	67.50	73.70	78.10	87.30
Otautau	45.10	53.00	49.70	46.90	50.70	54.60	54.90	53.60	62.20
Catlins-Waikawa	54.40	54.00	60.20	60.30	57.80	57.80	6.80	64.20	75.40
Halfmoon Bay	57.90	60.20	65.30	62.20	62.50	61.10	67.00	73.80	78.90

Table 6-6: Average annual maximum 5-day rainfall (Rx5day, measured in mm), for 14 Southland locations.

Period	Present	2031-2050				2081-2099			
RCP		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Gore	56.20	60.00	62.00	57.20	59.40	61.20	62.10	65.80	70.20
Matāura	66.80	71.70	74.10	69.30	72.20	73.50	74.50	78.10	85.10
Riversdale	59.60	64.90	63.40	60.80	63.10	63.20	66.50	70.10	70.90
Winton	71.50	75.70	75.50	72.30	75.20	75.40	79.60	80.70	89.20
Lumsden	58.00	63.80	62.70	58.80	62.90	64.90	64.10	67.10	68.70
Waihōpai	73.40	77.90	79.70	80.70	78.20	80.80	84.90	85.50	94.70
New River	76.50	80.50	83.30	82.90	79.00	82.20	87.00	89.30	98.40
Te Anau	74.50	76.40	73.30	77.60	74.80	78.4	78.2	78.2	82.7
Milford Sound Airport	429.50	453.70	438.70	462.00	446.40	463.3	446.4	463.4	529.6
Riverton/Aparima	77.50	81.60	84.10	80.20	80.20	81.4	88.1	89	98
Tuatapere	88.90	97.70	98.90	99.10	94.80	96.2	102.7	105.9	119.8
Otautau	70.20	79.50	75.10	73.50	76.30	78.8	80.2	80.4	87.8
Catlins-Waikawa	96.90	104.20	105.90	101.40	98.80	102.9	108	109.7	120.8
Halfmoon Bay	98.60	104.70	107.90	105.90	102.90	103.7	107	118.1	129.3

Table 6-7: Average rainfall intensity (in mm), for 14 Southland locations. The rainfall intensity is calculated by dividing the annual rainfall total by the number of days with rainfall greater than 1 mm.

Period	Present	2031-2050				2081-2099			
RCP		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Gore	5.40	5.6	5.6	5.6	5.6	5.60	5.70	5.90	6.00
Matāura	6.00	6.3	6.3	6.3	6.3	6.30	6.40	6.60	6.90
Riversdale	5.50	5.8	5.7	5.8	5.7	5.60	5.80	5.90	6.20
Winton	6.00	6.2	6.2	6.2	6.2	6.10	6.30	6.50	6.80
Lumsden	5.80	6	6	6	6	5.90	6.10	6.20	6.40
Waihōpai	6.30	6.5	6.6	6.6	6.6	6.50	6.70	6.80	7.20
New River	6.30	6.5	6.7	6.6	6.6	6.50	6.70	6.90	7.30
Te Anau	6.50	6.90	6.80	7.00	7.00	6.90	7.10	7.20	7.60
Milford Sound Airport	27.40	29.80	29.90	30.00	30.30	29.40	30.50	31.60	33.10
Riverton/Aparima	6.40	6.50	6.70	6.60	6.60	6.50	6.70	6.80	7.20
Tuatapere	7.00	7.10	7.20	7.10	7.20	7.00	7.20	7.50	7.80
Otautau	6.70	7.30	7.30	7.20	7.20	7.20	7.30	7.40	7.50
Catlins-Waikawa	7.80	7.90	8.00	8.00	8.00	7.80	8.10	8.50	9.00
Halfmoon Bay	7.70	7.70	7.80	7.60	7.80	7.50	7.90	8.20	8.50

6.7 Dry days (< 1 mm)

Dry days are defined in this report as days with less than 1 mm of rainfall, i.e., the inverse of wet days presented in Section 6.2.

6.7.1 Present

The map for 'present-day' annual number of dry days in Southland is presented in Figure 6-15. This map shows a 20-year average of dry days over 1986-2005. Note that this map presents modelled present-day climate, i.e., six global climate models are run in hindcast mode and this map is the average of the six models.

The highest amount of dry days per year is experienced in the northern Matāura catchment, where 225-250 dry days per year are observed on average (Figure 6-15). Much of the central part of the Southland region experiences 200-225 dry days per year, and 175-200 dry days per year is common for most of the region east of the western Waiau catchment. Southern Fiordland experiences the fewest dry days per year (100-150 days per year).

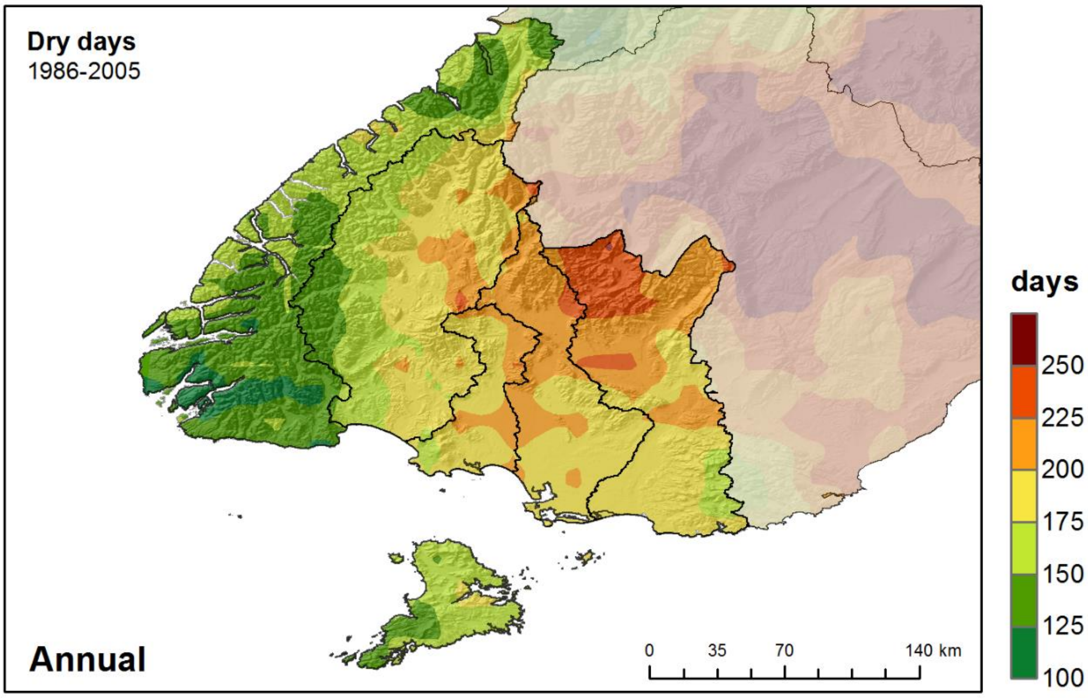

Figure 6-15: Modelled mean annual number of dry days (days with < 1 mm rain) for Southland (1986-2005). Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.7.2 Future

The projected changes in dry days for the Southland region are presented for RCP4.5 and RCP8.5 at 2040 and 2090 in Figure 6-16, derived from the ensemble average of six dynamically downscaled models.

The projections for RCP4.5 and RCP8.5 at 2040 are similar, with up to 10 more dry days per year expected for much of the Fiordland and Waiau catchments, as well as the southern Matāura and Ōreti catchments and Stewart Island/Rakiura. Up to 10 fewer dry days per year are expected for the central part of the region and northern and western Fiordland. At 2090 under RCP4.5, a decrease in dry days is projected for most of the region outside of the Waiau catchment, eastern Fiordland, and Stewart Island/Rakiura. A decrease of 10-20 dry days per year is projected for northern Fiordland. Under RCP8.5 at 2090, decreases in the number of dry days are projected for about half of the region, with the largest decreases in western and northern Fiordland. The largest increases are projected for the eastern Waiau catchment, where 10-20 more dry days per year are expected.

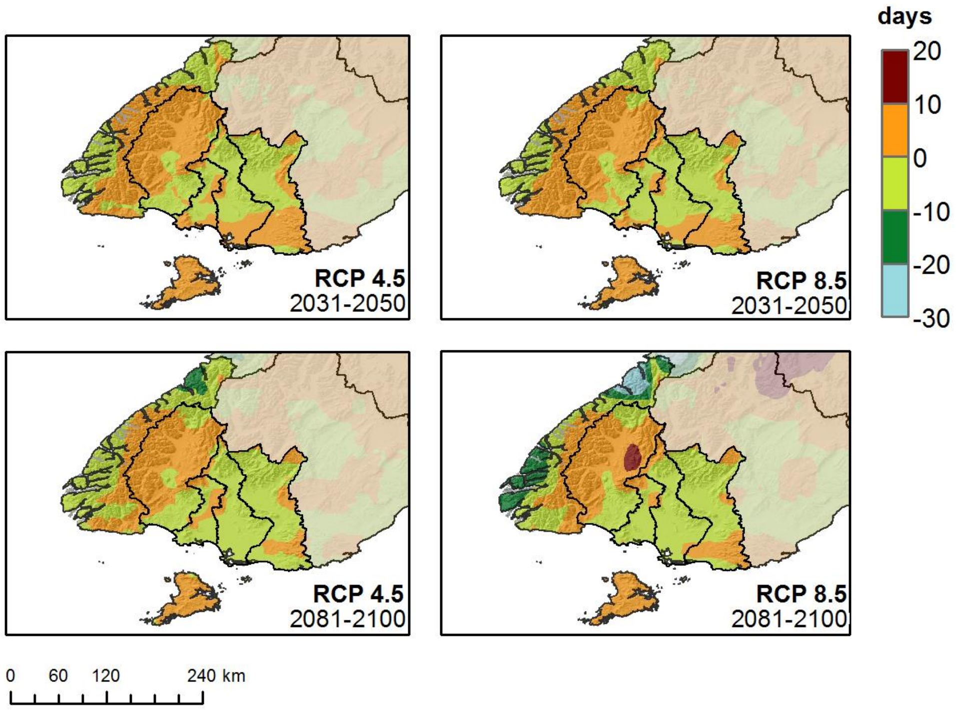

Figure 6-16: Projected annual dry day changes (days where rain <1mm; in number of days) at 2090 (2081-2100 average) for RCP8.5. Projected change is relative to 1986-2005. Results show the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.8 Potential evapotranspiration deficit

Due to the importance of primary production to New Zealand's economy, the occurrence of drought is of major concern. The measure of meteorological drought[12] that is used in this section is 'potential evapotranspiration deficit' (PED). Evapotranspiration is the process where water held in the soil is gradually released to the atmosphere through a combination of direct evaporation and transpiration from plants. As the growing season advances (the growing season starts in July and ends in June), the amount of water lost from the soil through evapotranspiration typically exceeds rainfall, giving rise to an increase in soil moisture deficit. As soil moisture decreases, pasture production becomes moisture-constrained and evapotranspiration can no longer meet atmospheric demand.

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

PED is calculated as the cumulative difference between potential evapotranspiration (PET) and rainfall from 1 July of a calendar year to 30 June of the next year, for days of soil moisture under half

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

of available water capacity (AWC), where an AWC of 150mm for silty-loamy soils is consistent with estimates in previous studies (e.g., Mullan et al. 2005). PED, in units of mm, can be thought of as the amount of missing rainfall needed in order to keep pastures growing at optimum levels. Higher PED totals indicate drier soils. An increase in PED of 30 mm or more corresponds to an extra week of reduced grass growth. Accumulations of PED greater than 200 mm indicate very dry conditions in Southland.

6.8.1 Present

The map for 'present-day' annual PED accumulation in Southland is presented in Figure 6-17, which indicates the driest areas in Southland. This map shows a 20-year average of PED accumulation over 1986-2005. Note that this map presents modelled present-day climate, i.e., six global climate models are run in hindcast mode and the map shows the average of the six models.

The higher the PED accumulation, the drier the soils are, with accumulations of > 200 mm indicating very dry conditions for Southland (although PED exceeding 200 mm is common in drier eastern parts of New Zealand). Present-day annual average PED is highest in the northern Matāura catchment (over 400 mm per year in some places) and also in the northern Ōreti and eastern Waiau catchments (100-200 mm per year) (Figure 6-17). Annual PED accumulation is lowest in southern Fiordland and parts of Stewart Island/Rakiura, where negligible PED is observed. Most of the region outside of these areas experiences between 1 and 25 mm of PED per year, and this low number reflects the high rainfall totals observed in much of Southland.

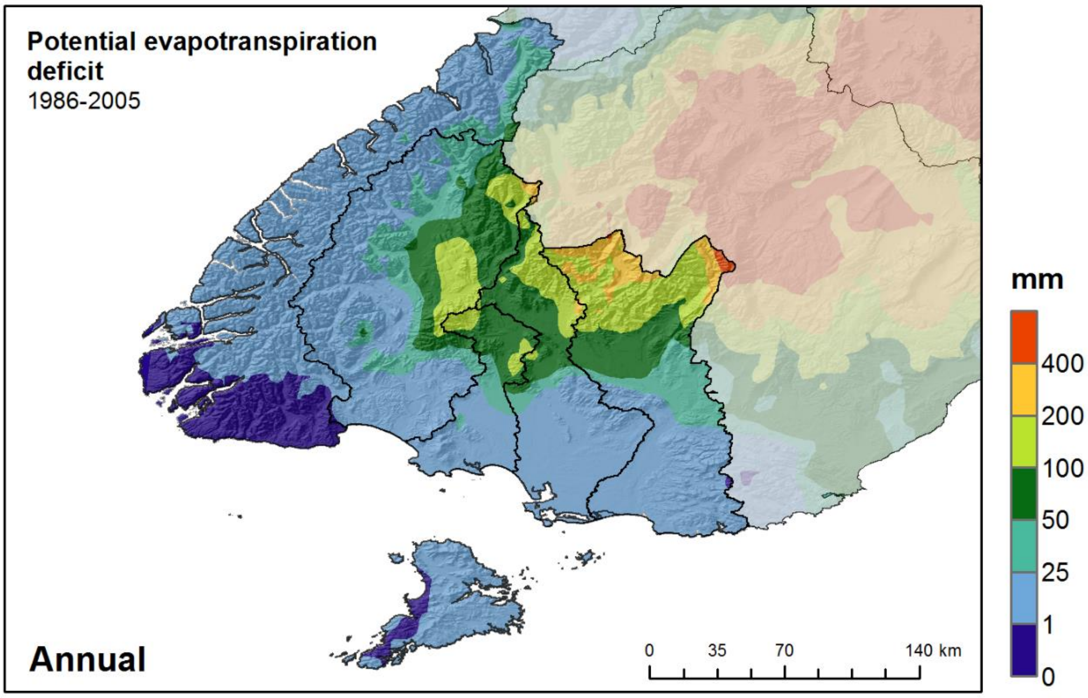

Figure 6-17: Modelled annual average Potential Evapotranspiration Deficit (PED) accumulation (mm) for Southland (1986-2005). Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

PED is presented in an alternative way in Figure 7-18, which shows the annual probability of PED accumulation exceeding 200 mm (i.e., the probability of very dry conditions in any one year in Southland). This map shows a 20-year average of the annual probability of PED exceeding 200 mm over 1986-2005. Note that this map presents modelled present-day climate, i.e., six global climate models are run in hindcast mode and the map shows the average of the six models.

The annual average probability of PED accumulation exceeding 200 mm is displayed in Figure 6-18. The probability is highest in the northern Matāura catchment, where there is over a 75% chance of annual PED exceeding 200 mm. Other parts of the northern Matāura catchment, as well as the northern Ōreti and eastern Waiau catchments have between a 10 and 50% chance of PED exceeding 200 mm per year. Most of the region has almost no chance (0-1%) of experiencing > 200 mm of PED per year.

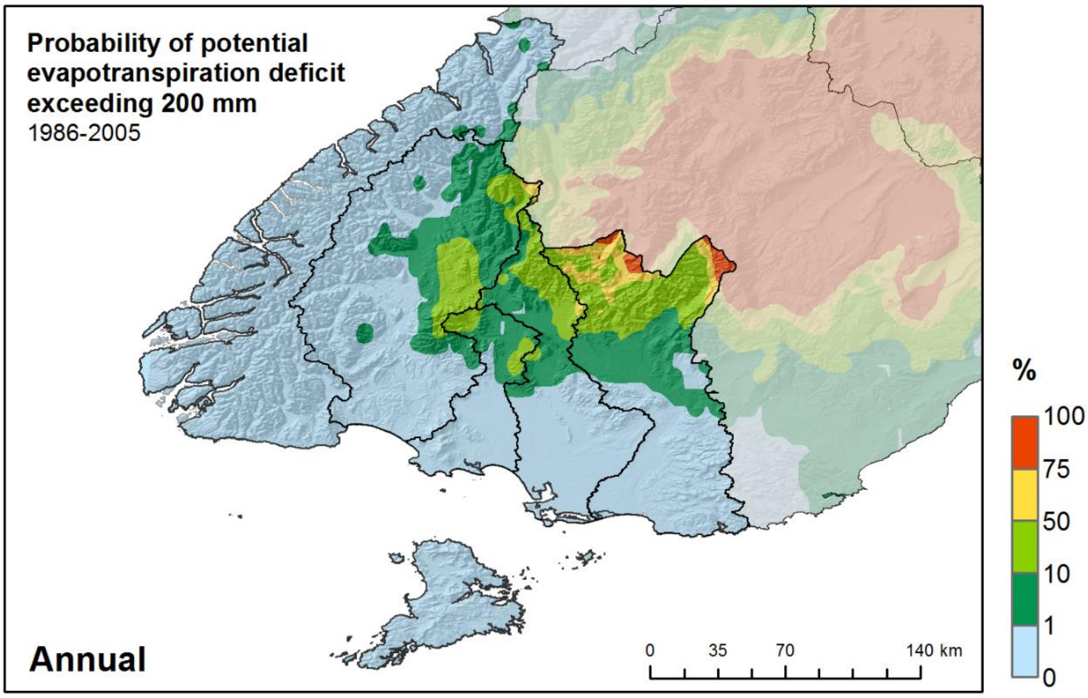

Figure 6-18: Modelled annual average probability of Potential Evapotranspiration Deficit (PED) exceeding 200 mm of accumulation for Southland (1986-2005). Based on the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

6.8.2 Future

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

Maps for projected changes in PED (mm of accumulation) are presented in Figure 6-19 for RCP4.5 and RCP8.5 at 2040 and 2090. The maps are plotted with an annual accumulated PED anomaly with respect to the historical annual average (1986-2005 average). The ensemble average of six dynamically downscaled models is presented. As shown by Figure 6-19, the central-northern part of the Southland region is projected to experience the largest increases in PED (i.e., the largest drying trend) in the future across both time slices for both RCPs. At 2040 under both RCPs and 2090 under RCP4.5, increases in PED of 80-100 mm per year are projected for parts of the Waiau and Matāura catchments, with increases of 40-80 mm of PED projected for much of the region. Fiordland and the southeastern part of Southland project the smallest increases in PED, with 0-20 mm increases projected for those areas. By 2090 under RCP8.5, the central part of the Southland region is projected to experience over 100 mm more PED per year.

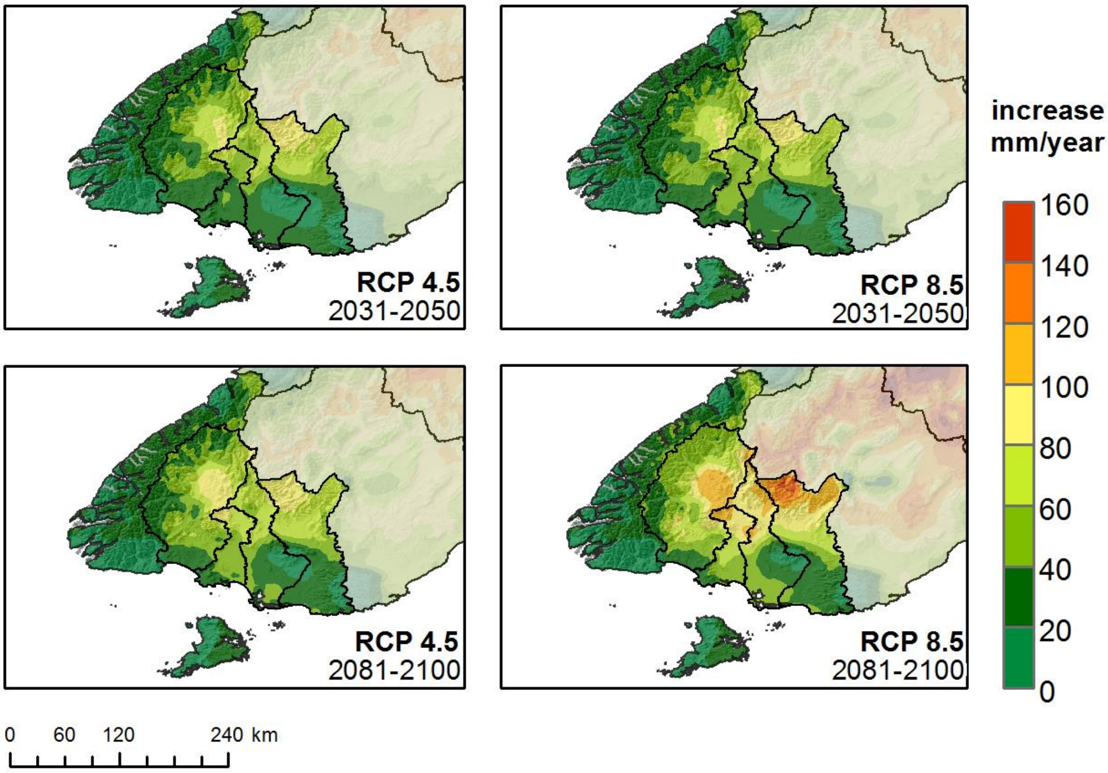

Figure 6-19: Projected changes in Potential Evapotranspiration Deficit (PED, in mm accumulation over the July-June 'hydrologic year') for Southland, for RCP4.5 (left panels) and RCP8.5 (right panels), at 2040 (2031-2050) and 2090 (2081-2100). Projected change in PED is relative to 1986-2005. Results show the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

The change in the probability of annual PED exceeding 200 mm is presented in Figure 6-20, for RCP4.5 and RCP8.5 at 2040 and 2090. The maps are plotted with the probability of annual PED exceeding 200 mm with respect to the historical annual average (1986-2005 average). The ensemble average of six dynamically downscaled models is presented. In the centre of the Southland region, the probability of annual PED exceeding 200 mm increases under both future time slices and RCPs. The projections for 2040 under both RCPs, and 2090 under RCP4.5, are relatively similar. Under these scenarios, increases in probability of 20-30% is common for much of the central part of the region, with some areas projecting increases of 30-40%, particularly in the eastern Waiau catchment at 2090 under RCP4.5. At 2090 under RCP8.5, some parts of the eastern Waiau catchment and the northern

Ōreti and Matāura catchments are expected to increase the probability of PED exceeding 200 mm by 40-50%. Based on the historic probabilities presented in Figure 6-18 plus the changes in Figure 6-20, some of these areas are projected to experience > 200 mm of PED almost every year (i.e., close to 100% probability). However, much of the Southland region retains low probabilities with climate change, with Fiordland and the southern part of the region mostly projected to experience a very small increase or even a decrease in probability of exceeding 200 mm of PED per year. This is due to the projections of increased rainfall totals for those areas (Section 6.1.2).

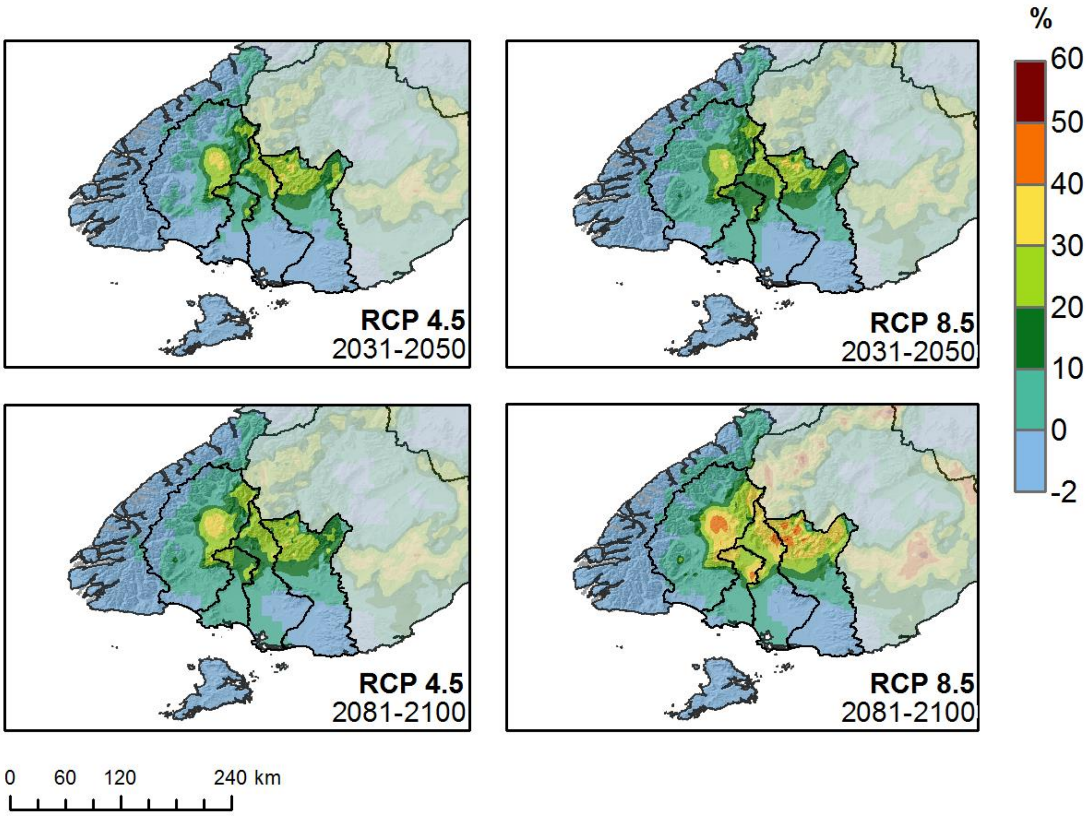

Figure 6-20: Projected changes in the probability of annual Potential Evapotranspiration Deficit (PED) exceeding 200 mm for Southland, for RCP4.5 (left panels) and RCP8.5 (right panels), at 2040 (2031-2050) and 2090 (2081-2100). Projected change in PED is relative to 1986-2005. Results show the average of six global climate models. Catchments are (west to east): Fiordland, Waiau, Aparima, Ōreti, Matāura.

7 Sea-level rise and changes in tides and storm-tide levels

This section covers variability in seasonal and annual MSL and historic trends in Southland alongside future New Zealand projections of sea-level rise (SLR), relative to a baseline period 1986–2005 used by IPCC. Present-day normal high-tide and storm-tide exceedance levels are provided with an indication of the changing frequency of occurrence on the back of rising seas. A general understanding of how storm surge, waves and coastal shoreline position will respond is provided.

A summary of the coastal risk exposure in Southland is given for areas where LiDAR surveys have been undertaken (south coast and parts of Invercargill) and generally across the Southland coast based on a less-accurate national topography model.

7.1 Datums

Several vertical datums are used in the Southland region. Those most commonly used are, with offsets provided between some of them:

- Bluff Vertical Datum–1955 (BVD-55)

One of the regional vertical datums established by the forerunner of Land Information NZ (LINZ) covering the southern part of coastal Southland. It is based on tide-gauge measurements over a period (discontinuous) from 1918 to 1934 at the Port of Bluff (Hannah and Bell, 2012). BVD-55 is defined as 7.0089 m below the Bluff Fundamental Bench Mark (LINZ Code ABCC)[13], which means BVD-55 is 1.611 m above Chart Datum (CD) at Bluff.

However, since these early measurements to establish BVD-55, annual MSL has risen. The MSL averaged over the period 1999–2008 is 0.131 m above BVD-55, and should be used as the baseline MSL to add on SLR projections. The MSL over the last 5 years (2013–2017) was around 3 cm higher at 0.159 m above BVD-55.

- Port of Bluff Chart Datum (CD)

Established over years of tidal measurements at the Port of Bluff, so that only rarely, the lowest low tide dips below this zero datum (excluding weather influences such as anticyclones and winds blowing offshore that can further reduce predicted low-tide levels). CD is defined as 8.620 m below the Bluff Fundamental Bench Mark (LINZ Code ABCC). CD is –1.611 relative to BVD-55. LINZ publish MSL values over the 19-year nodal tide cycle for standard ports in the Nautical Almanac and web site, with a MSL at Bluff of 1.74 m relative to CD over the averaging period 1998–2016.

- NZ Vertical Datum 2016 or NZVD-2016

NZVD-2016 zero is 6.6890 m below the Bluff Fundamental Bench Mark (LINZ Code ABCC), which is set at 0.320 m above BVD-55.

- Dog Island gauge zero

The NIWA sea-level gauge at Dog Island currently operates on an assumed datum, where the tide-gauge zero was arbitrarily set when installed in 1997. A comparison of

[13] This is the level updated on 14-Jan-2018 by LINZ

annual MSL over the past 4 years (2014–2017) with the equivalent MSL measured at the Port of Bluff results in an offset of around 1.806 m to be subtracted from Dog Island data to convert to BVD-55. This is only an interim offset until such time that a geodetic survey is undertaken to establish the datum for the Dog Island gauge.

7.2 Impacts of sea-level rise

One of the major and most certain (and so foreseeable) consequences of increasing concentrations of carbon dioxide[14] and associated warming, is the rising sea level (Parliamentary Commissioner for the Environment, 2015). IPCC (2013a) found that warming of the climate system is unequivocal, and many of the changes observed since the 1950s are unprecedented over timescales of decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice globally have diminished, causing sea level to rise.

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

- gradual inundation of low-lying marsh and adjoining dry land on spring high tides;
- escalation in the frequency of nuisance and damaging coastal flooding events (which has been evident in several low-lying coastal margins of New Zealand);
- exacerbated erosion of sand/gravel shorelines and unconsolidated cliffs (unless sediment supply increases);
- increased incursion of saltwater in lowland rivers and nearby groundwater aquifers, raising water tables in tidally-influenced groundwater systems.

These impacts will have increasing implications for existing development in coastal areas, along with environmental, societal and cultural effects. Infrastructure and its levels of service or performance will also be increasingly affected, such as wastewater treatment plants, potable water supplies, and particularly capacity and performance issues with stormwater and overland drainage systems (particularly gravity-driven networks). Transport infrastructure (roads, ports, airports) in the coastal margin will also be affected, both by increased nuisance shallow flooding of saltwater (e.g., vehicle corrosion) and more disruptive flooding and damage from elevated storm-tides and wave overtopping.

There are three types of SLR in relation to observations and projections:

- absolute (or eustatic) rise in ocean levels, measured relative to the centre of the Earth, and usually expressed as a global mean (which is used in most sea-level projections e.g., IPCC);
- offsets (or departures) from the global mean absolute SLR for a regional sea, e.g., the sea around New Zealand, which will experience slightly higher rises (5–10%) than the global average rate. There can be significant variation in the response to warming and wind patterns between different regional seas around the Earth;
- relative sea-level rise (RSLR), which is the net rise in sea level experienced on coastal margins from absolute, regional-sea offsets and local vertical land

[14] Global average now above 400 ppm.

movement (measured relative to the local landmass). Local or regional adaptation to SLR needs to focus on RSLR, particularly if the coastal margin is subsiding.

The first two types of SLR are measured directly by satellites, using radar altimeters, or by coalescing many tide-gauge records globally (after adjusting for local vertical land movement and ongoing re-adjustments in the Earth's crust following ice loading during the last Ice Age[15]).

RSLR is measured directly by tide gauges. One advantage of knowing the RSLR from gauge measurements is that this directly tracks the SLR that needs to be adapted to locally, or over the wider region represented by the gauge. If, for instance, the local landmass is subsiding, then the RSLR will be larger than the absolute rise in the adjacent ocean level acting alone. The landmass in the Bluff region is currently uplifting at a relatively small rate (see text below), so for the application of New Zealand-wide SLR projections to Southland, it can be effectively discounted.

7.3 Historic trend in SLR focused on Southland and Otago

Hannah and Bell (2012) analysed SLR trends at 10 gauge sites around New Zealand, to extend the picture of local trends at wider range of locations than just the four main port sites (Auckland, Wellington, Lyttelton, Dunedin), where records exist from 1900 onwards. While the additional 6 sites (which include Bluff) comprised shorter records, longer term SLR could be inferred by connecting the modern digital records with historic tide measurements (from LINZ archives) used to establish the local vertical datums around New Zealand. In the case of Bluff, a digital record exists from 1999 (Figure 7-1), to which Hannah and Bell (2012) used inference to connect earlier measurements at the Port of Bluff from 1918–1934 (from discontinuous government archives used to zero BVD-55), with the modern digital record up to 2008. They estimated the long-term rate at 1.8 ±0.15 mm/year up to 2008.

An updated analysis to 2015 by Emeritus Professor John Hannah for the Coastal Guidance (MfE 2017), with 7 more years of data to 2015, resulted in a rate 1.67 ±0.13 mm/year, with a lower standard deviation (Figure 7-3). This does not mean SLR has slowed, but rather is influenced by the long intervening gap in the record and the very short modern record up to 2008 for the earlier analysis (Figure 7-1). This was just slightly below the New Zealand average rate of 1.76 mm/year covering gauges at ten sites across New Zealand for records up to and including 2015 (Figure 7-3).

Averaged over the past 5 years (2013–2017) the MSL at the Port of Bluff has reached 0.159 m above BVD-55 – but again is a relatively short period.

Given the short Southland sea-level records, for a wider context we have plotted the annual MSL from the two long-term South Island port gauges at Dunedin Wharf and Lyttelton since 1900, relative to the baseline period (1986–2005) and annotated the equivalent annual MSL data from Bluff and Dog Island gauges. The resulting plot (Figure 7-2) shows a close agreement of the Southland data with the more recent upward trend over the past 2-3 decades evident from the two long-term sites. The highest annual MSL to date at most gauge sites around New Zealand occurred in 2016. The year-to-year variability arises predominately from the El Niño–Southern Oscillation (ENSO), generally with lower MSL in El Niño episodes and higher in La Niña years.

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

Records from all four main New Zealand port tide gauges (>110-year records) indicates a doubling in the rate of sea-level rise around the New Zealand coastline over the last five to six decades, from an average of approximately 1 mm/year earlier last century to nearly 2 mm/year from 1961 to 2015 (MfE, 2017). A summary of historic rates of relative SLR across 10 sites in New Zealand is provided in Figure 7-3, with the New Zealand wide average of nearly 1.8 mm/year up to 2015.

Global coverage (between 66°N and 66°S) of satellite altimeters, which measure the ocean surface, commenced in 1993. The global-average rate for absolute SLR from satellite altimetry in the period 1993 to 1 June 2018 is running at ~3.2 mm/year, which is about twice the long-term global rate since 1900. In the ocean waters around New Zealand, the trend since 1993 to present has been higher than the global average, with absolute SLR in the Otago/Southland area trending at just under 4 mm/year (Figure 7-4). The NZ-wide average was 4.4 mm/year up to the end of 2015 (see Figure D-3, Appendices; MfE, 2017). Some of this increase in the rate of rise is due to the Interdecadal Pacific Oscillation (IPO), a 20–30-year climate cycle, which is in its negative phase at present, leading to increased sea-surface temperature and therefore sea-surface height in the Western Pacific (see darker colours in Figure 7-4), but also is influenced by a warming atmosphere.

Figure 7-2 also shows the projected SLR for the lowest RCP2.6 scenario and the RCP8.5 scenario in the near term to 2020 from MfE (2017). Due to the closeness of trajectories between the high and low projections in the near term, it is not possible to distinguish which path New Zealand SLR measurements will follow, and may require another 1-2 decades of monitoring to conclusively determine which RCP trajectory applies. But, SLR trajectories (relative to the RCP scenarios) may change again in the future if polar ice-sheet instabilities emerge later this century and/or global emissions continue to track high or indeed global emissions may be substantially reduced if the 2015 Paris Agreement is adhered to. This future uncertainty is the reason why the Coastal Guidance (MfE 2017) recommends the use of all four SLR scenarios (see below) to plan for and test adaptation options in an adaptive planning framework.

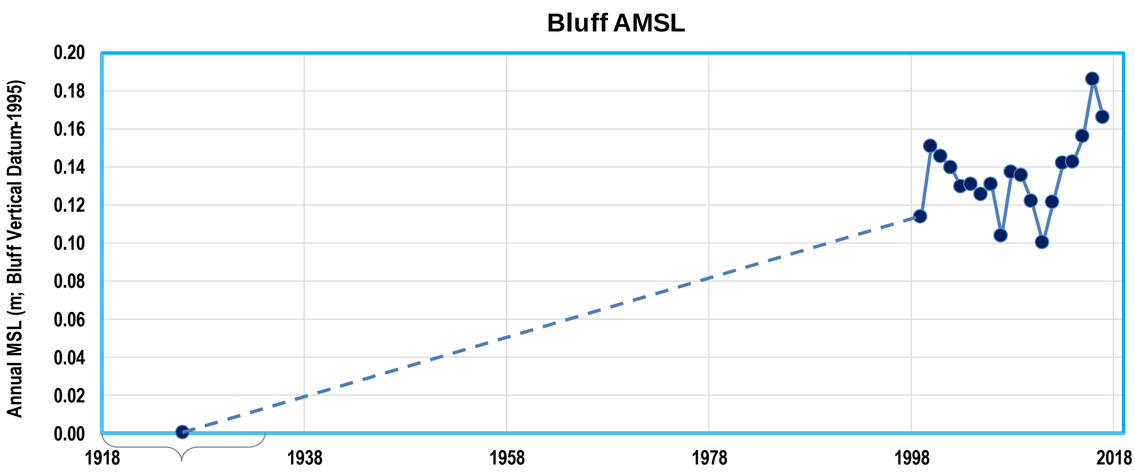

Figure 7-1: Annual MSL at the Port of Bluff. The modern digital record covers the period 1999-2017. The origin of BVD-55 was set using tide data from 1918-1934 (discontinuous archive records). Note: Hannah and Bell (2012) based the trend on data up to 2008, and the recent update of the trend (MfE 2017), covered data up to 2015.

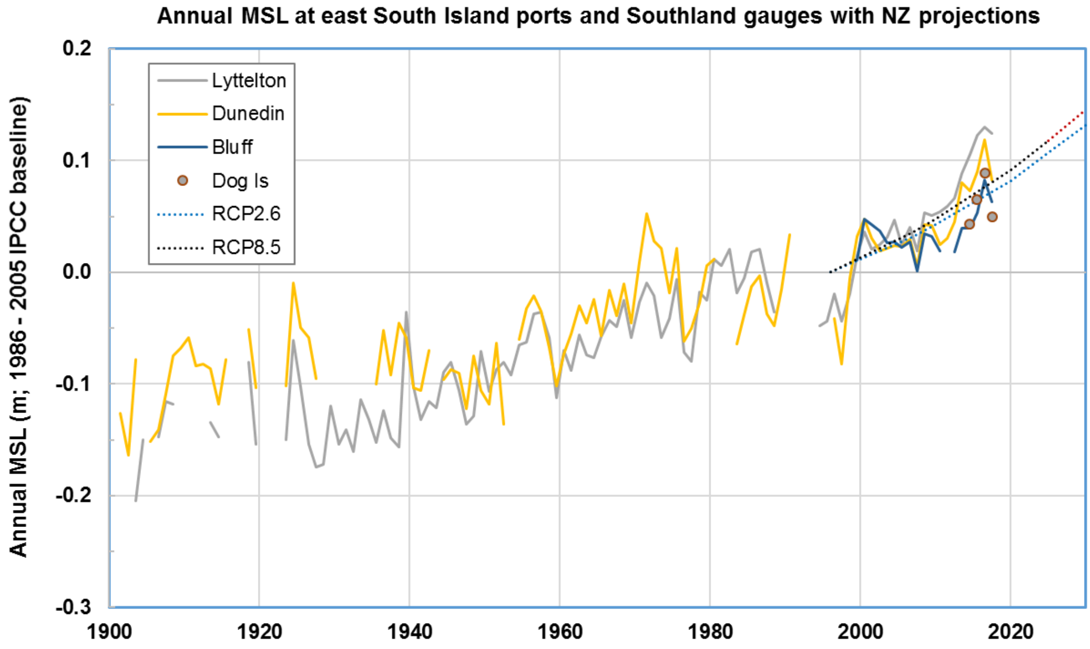

Figure 7-2: Change in annual MSL for Dunedin Wharf and Lyttelton from 1900–2017, annotated with recent annual MSL from Port of Bluff and Dog Island. The near-term projections for NZ-based SLR for RCP2.6 and RCP8.5 are plotted to 2030 (MfE 2017). Baseline period is 1986-2005, used in the IPCC projections. Bluff and Dog Island data were scaled back to this period (as Bluff data started in 1999) using the difference in average MSL between 1986-2005 and 2000-2010 at Dunedin (~0.03 m).

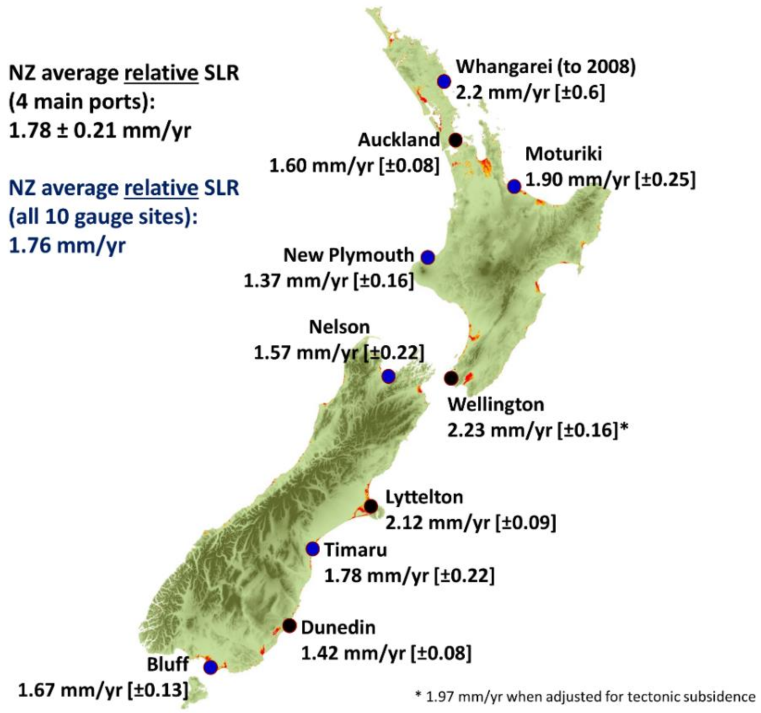

Figure 7-3: Relative SLR rates up to and including 2015 (excluding Whangarei), determined from longer sea-level gauge records at the four main ports and shorter records from the other sites. Determined from >100-year gauge records at the four main ports (black circles) and inferred rates from gauge station records, used in the first half of the 1900s to set the local vertical datums, spliced with modern records (blue circles). Standard deviations of the trend are listed in the brackets. [*Source*: Figure 19; MfE (2017)].

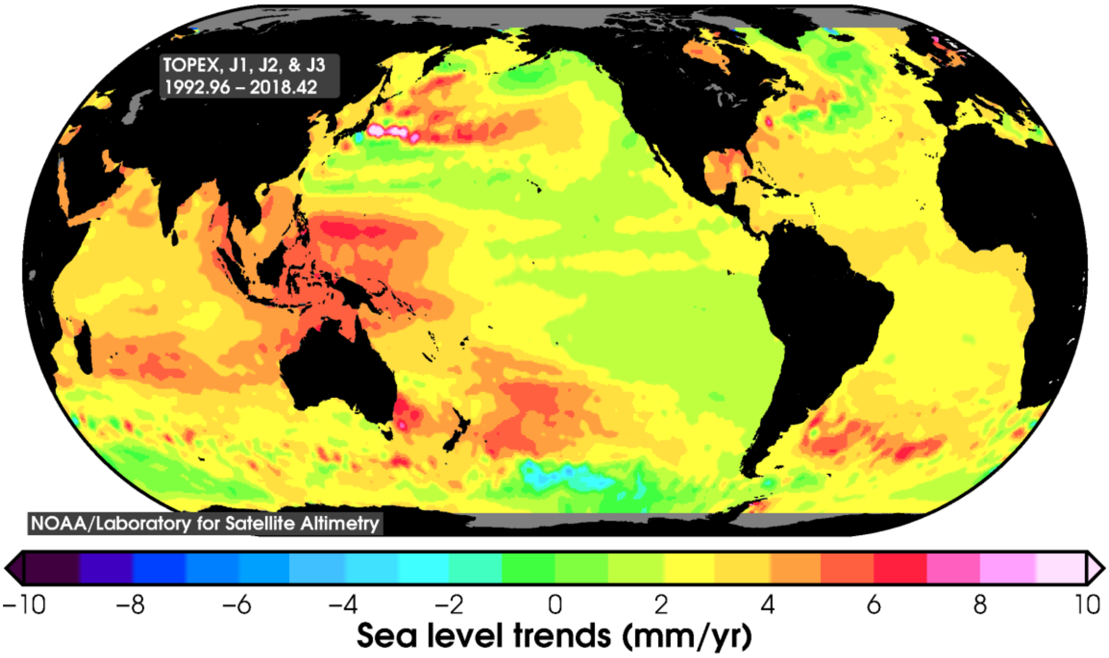

Figure 7-4: Map of regional trend in SLR from 1993 to 1 July 2018 based on satellite altimetry missions.
Source: NOAA/NESDIS Center for Satellite Applications and Research.

Relative SLR along the Southland coast also incorporates a component due to vertical land movement. A continuous GPS station has been operated at Bluff by GeoNet and LINZ since 2005. Up to 2011, the vertical land movement was a small uplift rate of 0.4 mm/year (Beavan and Litchfield 2012; Figure 20 MfE 2017). To the west at Puysegur Point, slightly higher uplift occurred (over a shorter record).

Further updated analysis on vertical land movement around New Zealand, and the implications for long-term sea-level rise, is a component of a new Endeavour Fund research project NZSeaRise, coordinated by Victoria University of Wellington.

In the interim, for Southland, the above results indicate that only small rates of uplift[16] are presently occurring (but uncertain whether they will persist for decades), so the New Zealand-wide SLR scenarios in the Coastal Guidance (Chapter 5; MfE 2017) should be applied directly to the Southland coastal margin without any adjustment (as would definitely be required for subsidence) and the historic rate of SLR at Bluff is close to the New Zealand average.

7.4 Projections for New Zealand sea-level rise.

A synthesis of the historic and future projections of SLR, both globally and for New Zealand, is available in the Ministry for the Environment (MfE) guidance for local government: *Coastal Hazards and Climate Change* (MfE 2017) and an accompanying Summary[17] and set of Fact Sheets.[18]

Chapter 5 of the Coastal Guidance provides four specific New-Zealand based SLR scenarios to use when assessing and planning adaptation to coastal climate change in New Zealand (Figure 7-5). The

[16] Uplift means the relative SLR is smaller than the absolute rise in the ocean surface (subsidence means it is larger)
[17] http://www.mfe.govt.nz/publications/climate-change/preparing-coastal-change-summary-of-coastal-hazards-and-climate-change
[18] http://www.mfe.govt.nz/publications/climate-change/preparing-coastal-change-fact-sheet-series

SLR scenarios in the Coastal Guidance largely follow the synthesis of the IPCC Fifth Assessment Report (IPCC 2013a; Church et al. 2013), but are extended from 2100 to 2150, utilising the longer-range probabilistic projections of Kopp et al. (2014). Further, an adjustment has been made for ocean waters around New Zealand, where climate-ocean models have shown that SLR in our Pacific region will be somewhat higher than the global average rise – with IPCC projections couched in terms of the global average. The adjustment built into the New Zealand scenarios, for the regional ocean around New Zealand, is up to 0.05 m by 2100 for the higher RCP scenarios. A lesser pro-rata increment applies for the lower-emission RCPs.

The Coastal Guidance also listed a table of the time periods for which particular increments of SLR (relative to the 1986-2005 baseline) could be reached for the four different scenarios (Table 7-1). This information on time brackets can be applied to low-lying coastal areas, once the adaptation threshold SLR is known and agreed on from hazard and risk assessments, beyond which outcomes are not tolerable. All the details on developing firstly, hazard and risk assessments, then adaptation plans using the SLR scenarios, are available in the Coastal Guidance and Appendices (MfE 2017).

Table E-1, Appendices of MfE (2017) lists local values of sea level to use around New Zealand for the baseline (generally the 1986-2005 average MSL), to which the SLR projections are added. Based on the Port of Bluff, the baseline MSL of 0.13 m BVD-55 should be used for Southland when adding future SLR projections from Table 7-1 or Figure 7-5.

Table 7-1: Approximate years, from possible earliest to latest, when specific sea-level rise increments (metres above 1986–2005 baseline) could be reached for various projection scenarios of SLR for the wider New Zealand region. The earliest year listed is based on the RCP8.5 (83rd percentile) or H+ projection and the next three columns are based on the New Zealand median scenarios, with the latest possible year assumed to be from a scenario following RCP2.6 (median), which approximates the fully globally-implemented Paris Agreement. [*Source*: Table 11 in; MfE 2017]. **Note:** year for achieving the SLR is listed to the nearest five-year value.

Approximate year for the relevant New Zealand-wide SLR percentile scenario to reach increments of SLR (relative to baseline of 1986–2005)				
SLR (m)	Year achieved for RCP8.5 H+ (83%ile)	Year achieved for RCP8.5 (median)	Year achieved for RCP4.5 (median)	Year achieved for RCP2.6 (median)
0.3	2045	2050	2060	2070
0.4	2055	2065	2075	2090
0.5	2060	2075	2090	2110
0.6	2070	2085	2110	2130
0.7	2075	2090	2125	2155
0.8	2085	2100	2140	2175
0.9	2090	2110	2155	2200
1.0	2100	2115	2170	>2200
1.2	2110	2130	2200	>2200
1.5	2130	2160	>2200	>2200
1.8	2145	2180	>2200	>2200
1.9	2150	2195	>2200	>2200

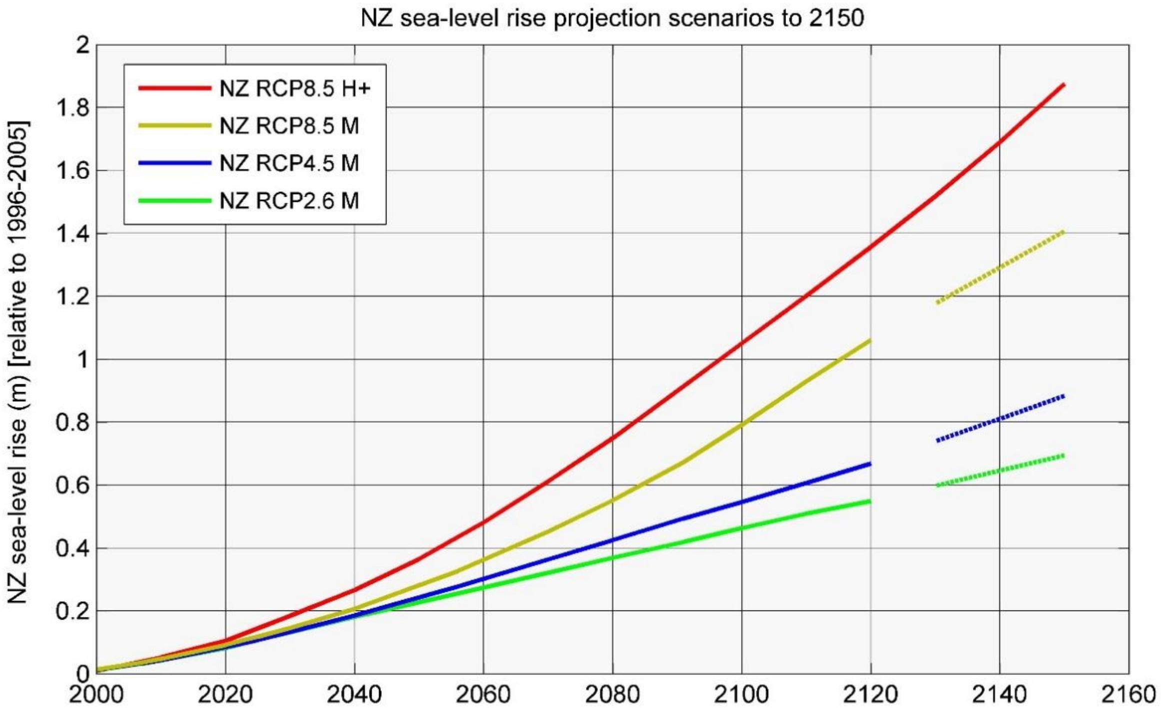

Figure 7-5: Four scenarios of New Zealand-wide regional SLR projections for use with this guidance, with extensions to 2150 based on Kopp et al. (2014)–K14. New Zealand scenario trajectories are out to 2120 (covering a minimum planning timeframe of at least 100 years), and the NZ H+ scenario trajectory is out to 2150 from K14. No further extrapolation of the IPCC-based scenarios beyond 2120 was possible, hence the rate of rise for K14 median projections for RCP2.6, RCP4.5 and RCP8.5 are shown as dashed lines from 2130, to provide an indication of the extension of projections to 2150. Note: All scenarios include a small SLR offset from the global mean SLR for the regional sea around New Zealand. [*Source*: Figure 27 MfE 2017]

7.5 Tides and the effect of rising sea level

7.5.1 Mean Spring tide levels

The present-day high tide marks are updated regularly by LINZ on web site: https://www.linz.govt.nz/data/geodetic-system/datums-projections-and-heights/vertical-datums/tidal-level-information-for-surveyors

At the Port of Bluff, the Mean High Water Spring (MHWS) mark is 2.82 m CD with a Mean Low Water Spring (MLWS) mark of 0.57 m CD, with a mean spring-tide range of 2.25 m. The tide marks are based on averages of all spring tides in the 19-year forward period (1 January 2000 - 31 December 2018) using a set of tidal harmonic constituents extracted from the Bluff data record. The equivalent levels in Bluff Vertical Datum are MHWS= 1.21 m BVD-55 and MLWS= –1.04 m BVD-55. These tide marks are based on a MSL of 1.74 m CD or 0.13 m BVD-55, averaged over the period 1998–2016.

7.5.2 High-tide exceedances and effect of SLR

The full range of possible high tides (excluding weather, climate and SLR influences) was predicted over 100 years, covering all possible tidal combinations, based on tides extracted from the Bluff record. The resulting high-tide exceedance curve is shown in Figure 7-6 (lower curve), in the form of a cumulative frequency of occurrence of high waters and with levels relative to NZVD-2016 (top panel) and BVD-55 (bottom panel). The tidal range at the offshore Dog Island is slightly higher than Bluff, with the range in high waters 0.1 m higher at Dog Island.

At Bluff, high tides cover a range of 0.89 m from the maximum HW (Max HW)[19] of 1.48 m BVD-55 or 1.16 m NZVD-2016, to the lowest neap high tide of 0.596 m (BVD-55) or 0.276 m (NZVD-2016). Other high-tide mark shown in Figure 7-6 is the Mean High Water Spring 10 percentile (MHWS-10), which at 1.254 m (BVD-55) or 0.934 m (NZVD-2016), is the high tide above which only 10% of all predicted high tides exceed it for the present-day situation. MHWS-10, which can be consistently defined around the New Zealand coast, was used in the recent national coastal risk exposure study for the Parliamentary Commissioner for the Environment (PCE) in 2015 (Bell et al. 2015; PCE 2015). As a comparison, the LINZ-defined MHWS level from the previous sub-section (7.5.1) for Bluff is exceeded by 14% of all high tides.

Putting aside storm events, SLR will continually lift the base MSL, on which the tide rides, which means there will be an increasing percentage of normal high tides which exceed a given present-day elevation e.g., street level, berm or stopbank crest or present MHWS-10. Figure 7-6 shows the effect of changing high-tide inundation using two example SLR values of 0.4 and 0.8 m SLR (Table 7-1 shows that 0.4 m SLR would arise between 2055–2090, while the latter between 2085–2175). Based on the example of the present-day MHWS-10 level, which is exceeded by only 10% of all high tides (tide-only), a 0.4 m SLR will mean that same ground or tidal elevation will be exceeded by 80% of all high tides (up from 10%) and the higher 0.8 m SLR will increase that to exceedances occurring on every high tide. Actually, for Bluff, the present MHWS-10 level will start to be exceeded by all high tides when SLR reaches 0.66 m. These results exclude the influence of weather and storm surges on water level and assume the tidal characteristics for Bluff don't change substantially – rather they focus just on normal upper tidal inundation levels as seas rise.

[19] Sometimes called the Highest Astronomical Tide (HAT)

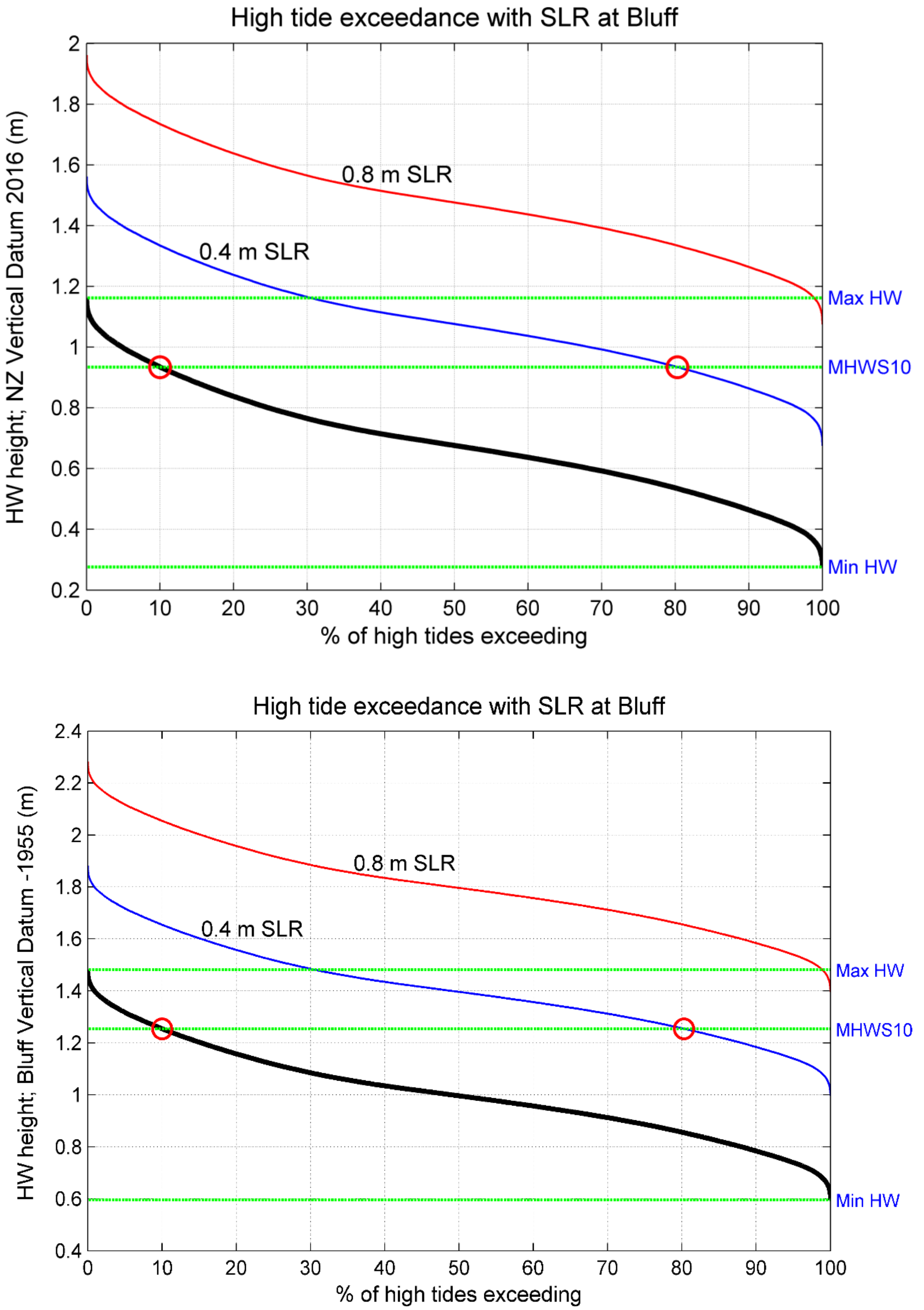

Figure 7-6: High-tide exceedance curve for all predicted high tides at Bluff (excluding effects of weather, climate and SLR). Datum is: (top), NZ Vertical Datum 2016 - NZVD2016 (using offset of 0.185 m for present MSL ; and (bottom) BVD-55 (using offset of 0.135 m for present MSL). Based on tidal constituents extracted from the Bluff gauge dataset by LINZ, and processed by NIWA to predict all high tides over a 100-year period (excluding SLR for the heavy black line).

7.6 Storm-tide elevations and effect of SLR

7.6.1 Components of storm-tide

High storm-tides and waves have contributed to coastal erosion and coastal/estuarine flooding on both the open-coast and estuaries in the Southland region.

There are several meteorological and astronomical processes involved in a combined extreme storm-tide and wave event, and these processes can combine in a number of ways to flood low-lying coastal margins, or cause coastal erosion. Storm-tide is defined as the sea-level peak (Figure 7-7) reached during a storm event, from a combination of:

- high tide;
- monthly mean sea-level anomaly (MSLA);
- storm surge – the temporary elevation in sea level above the predicted tide during low-pressure weather systems (through the inverted barometer effect that relaxes the water level as pressure drops) and wind setup.

Future storm-tide levels will be raised directly by SLR. Waves also further raise the effective storm-tide level at the coastline. Wave setup is the increase in the sea level within the surf zone from the release of wave energy as waves break and wave runup is the vertical height reached, usually defined as the level only exceeded by 2% of waves. Freshwater flows, from rivers, streams and stormwater, may also exacerbate coastal flooding when the flood discharge is constrained inside narrower sections of estuaries e.g., north of the Stead Street water level gauge.

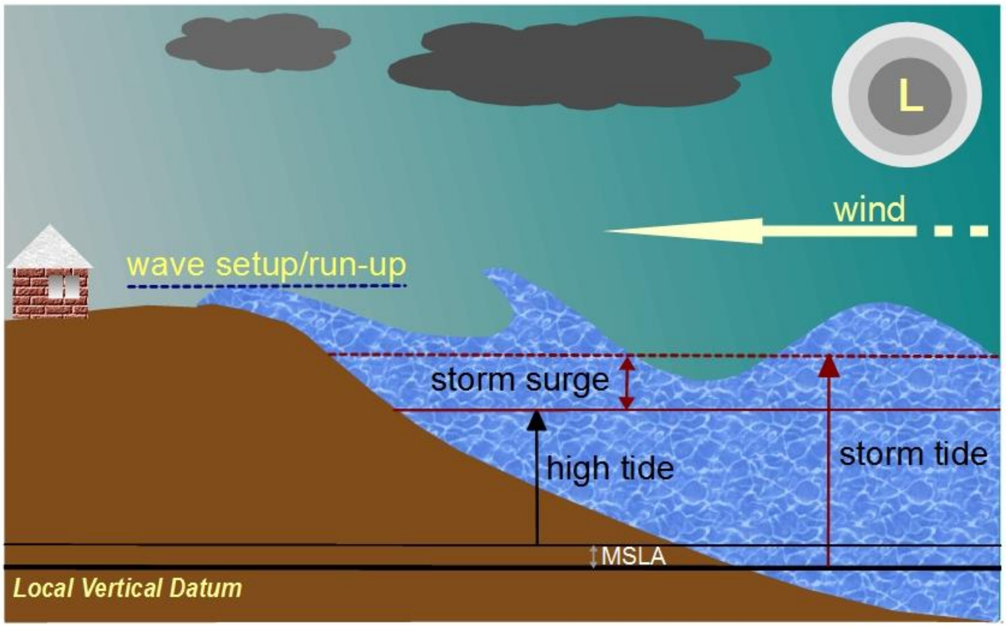

Figure 7-7: Components that contribute to storm-tide and wave overtopping. MSLA = monthly MSL anomaly or monthly variability in MSL, which can vary by around ±0.2 m. L= low-pressure weather system.

MSLA is the month-to-month variation in MSL from climate and persistent weather patterns, which can vary by around ±0.2 m, and therefore can be an important contributor to storm-tide levels and wave overtopping. Contributors to this monthly variability are the seasonal cycle in sea-surface height, and the effect of the 2–4 year El Niño-Southern Oscillation (ENSO) and the longer 20–30-year Interdecadal Pacific Oscillation (IPO). La Niña episodes and the negative phase of the IPO (which is what we currently have) usually result in higher-than-normal sea level. The averaged seasonal cycle in monthly sea-surface height from the Port of Bluff record is shown in Figure 7-8. The peak sea level is reached in May, which is on average 0.04 m higher than the annual MSL. This means that storm-tide and wave overtopping events in May coincide with a slightly-elevated background MSLA from the seasonal peak.

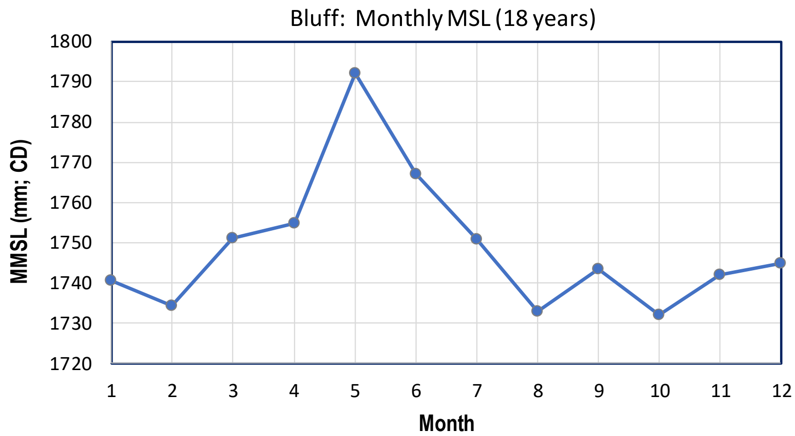

Figure 7-8: Seasonal cycle in monthly sea level at the Port of Bluff averaged over the period 2000-2017. Month 1 is January to Month 12 (December). Levels are in mm to Bluff Chart Datum.

7.6.2 Extreme storm-tide levels (New River Estuary)

NIWA recently carried out an analysis of storm-tide and wave overtopping levels in New River Estuary for Invercargill City Council (Gorman et al. 2018).

Water level data were provided by Environment Southland from their water level gauge located at the eastern end of the Stead Street estuary crossing of the Waihõpai. The record analysed comprises water levels at 15-minute intervals, from March 25, 1992 to 2 February 2018.

The two largest recorded storm-tide events occurred on 11 March 2016 (2.497 m BVD-55) and 30 March 1998 (2.470 m BVD-55), both of which were associated with observed overtopping of the Stead Street stopbank (Gorman et al. 2017). The 3rd and 4th highest events occurred on 7 June 2008 (2.237 m BVD-55) and 27 May 2013 (2.333 m BVD-55). The latter event was the highest recorded event offshore at Dog Island (~1.9 m BVD-55) over a similar period. It should be noted that setup in estuary level at high tide from onshore winds can be substantial within New River Estuary, adding to the open-coast storm-tide level. In the wider open estuary, there is only a small contribution to water level from river floods when events coincide with a prior period of high rainfall.

Coastal flooding is known to have occurred elsewhere along the coast during other events over that period, e.g., at Colac Bay/Ōraka on 16 April 1999 (D. Bradley, pers. comm.).

The main result of the analysis of Gorman et al. (2018) for upper New River Estuary is listed in Table 7-2 for extreme water levels, covering storm-tide and a small contribution from wave setup, for the 2% AEP and 1% AEP total water-level events (i.e., the AEPs are for the joint occurrence of the contributing processes to total water level). The methodology used generated 1000's of simulations sampling from probability distributions of each of the components (high tide, skew surge[20] – which includes the monthly MSLA, and wave setup), as they do not necessarily all achieve their individual extreme values simultaneously e.g., it would be a very rare event if the highest possible high tide coincided with the highest possible storm surge and monthly MSLA. Table 7-2 lists the average component values for high tide, surge and wave setup from all the many simulations that jointly produce the listed total still water level (bottom row) within ±0.05%.

Table 7-2: Average values of contributors to the joint 2% and 1% Annual Exceedance Probability (50- and 100-year Average Recurrence Interval - ARI) values of total still water level at Stead Street stopbank (New River Estuary) for the present-day situation. [Source: Table 4-10 in; Gorman et al. 2018].

	2% AEP (50-year ARI)	1% AEP (100-year ARI)
High tide (metres above MSL=0)	1.153	1.154
Skew surge height incl. MSLA (m; BVD-55)	1.269	1.319
Wave setup (metres)	0.018	0.018
Total Still Water Level (m; BVD-55)	**2.44**	**2.49**

Additional extreme water levels that included wave runup and overtopping were also generated by Gorman et al. (2018) but are more specific to the Stead Street stopbank. Wave runup is highly dependent on the beach slope and backshore profile (e.g., rock revetment, natural berm, seawall), so locally-derived runup levels need to be determined to add onto estuary or open-coast storm-tide and wave setup levels.

SLR projections from Section 8.4 should then be added directly to present-day storm-tide or runup levels. The key observable indicator of rising seas will come from an increasing frequency of coastal flooding events in low-lying coastal areas (Stephens 2015; PCE 2015).

Locally, in New River Estuary, a present rare storm-tide event (1% annual exceedance probability (AEP) with a 100-year average recurrence interval), would become, for example, an annual event on average after a SLR of around 0.45 m (Gorman et al. 2018). This ongoing change in frequency as seas rise is likely to apply generally along the Southland coast, but with the required SLR reducing eastwards, being just under 0.4 m SLR required on the Dunedin coast to become an annual event (Table 3.2 in PCE 2015). From Table 7-1, the time window for such rare present-day coastal flooding events to become an annual occurrence (e.g., SLR of 0.45 m for this example) is anytime between 2055-2060 and 2100 (depending on global emission reductions and polar ice-sheet response to warming).

Leaving aside SLR, climate change will also have some effect on waves and storm surges, although the projected changes from the present wave and storm surge climatologies are more difficult to discern above natural variability at regional and local scales than is the case for SLR. Small increases

[20] Skew surge is the difference between the maximum observed storm-tide water level and the maximum predicted high-tide level, which may occur at different times either side of high tide (not necessarily at predicted time of high tide).

are expected in wave heights around New Zealand of the order of 0–5% by 2070–2100 – particularly along the southern coast (Southland), which is exposed to south-westerly and southerly swell (MfE 2017). Anticipated changes in storm surge around New Zealand will be somewhat less, with only South Taranaki Bight and the south Otago coast showing possible increases above 5% (e.g., +0.03 m). So, while changes to waves/swell and storm surge will be secondary to the direct effect of SLR, the Coastal Guidance (MfE 2017) recommends sensitivity testing for coastal risk assessments of up to 10%, especially for higher risk developments or infrastructure.

Ongoing SLR will also raise groundwater levels in coastal and estuarine fringes, particularly where presently groundwater levels exhibit a tidal influence.

7.7 Generic impacts of climate change on coastal erosion

The Southland coast has experienced several known hotspots of coastal erosion in parts of Toetoes Bay and Estuary, Te Waewae Bay (Figure 7-9), western Kawakaputa Bay, Colac Bay/Ōraka, Jacobs River Estuary, Omaui (New River Estuary entrance) and Waipapa Point to Lake Brunton and Porpoise Bay (Catlins) (Bradley 2009).

Because of the complex nature of coastal shoreline change (erosion, accretion or remaining stable), arising from the interactions between sediment budgets (marine and riverine), geomorphology, sequences of storms, waves/swell patterns and variations in MSL, an analysis of present-day and future changes in different localities is not possible in the timeframe for this report.

Figure 7-9: Coastal erosion of the Papatotara Coast Road along Te Waewae Bay (2007). Credit: Environment Southland.

Generally, SLR will exacerbate situations where erosion has historically been an issue, but as the New Zealand-wide coastal sensitivity index (Figure 7-10) shows for Southland (Goodhue et al. 2012), the response to climate change will vary along the coast depending on the local geomorphology, sediment type and wave exposure. The coastal sensitivity index does not include the present state of erosion or accretion – but rather the future net change that could be anticipated from climate change and SLR ranging from low to high sensitivity to erosion.

Useful summaries of the generic effects of climate change on shoreline erosion are given by PCE (2015; Chapter 4) and the Coastal Guidance (MfE 2017; Section 6.4.2 and Appendix J).

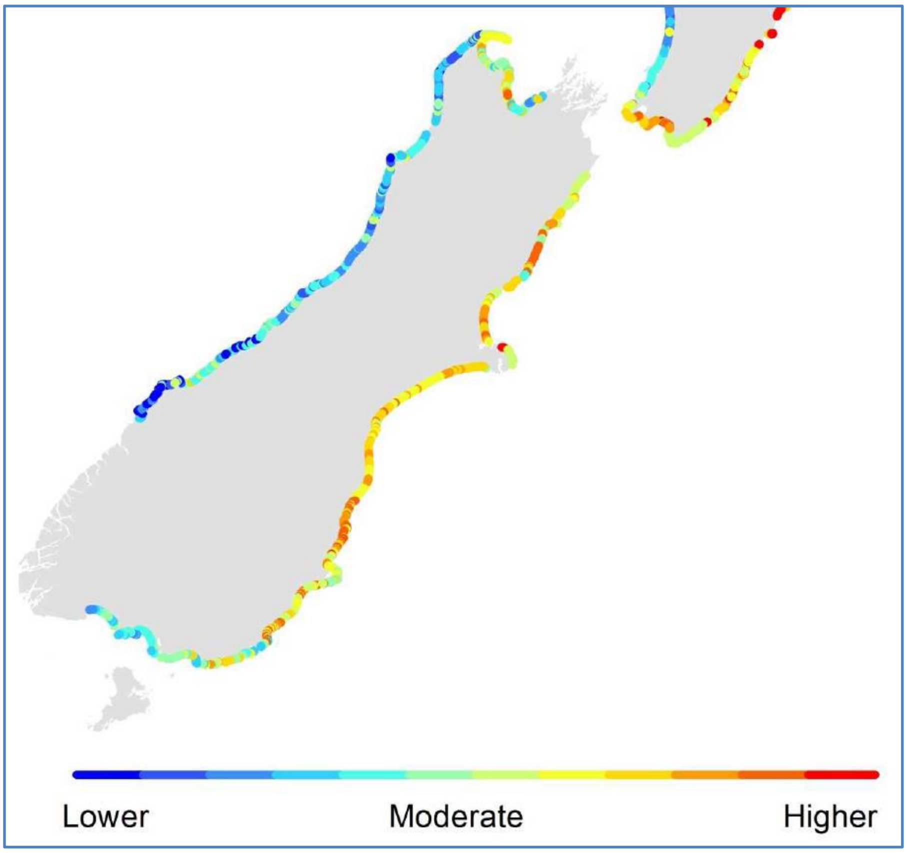

Figure 7-10: New Zealand coastal sensitivity index for future coastal erosion from climate change. *Source*: Figure 3-4, Goodhue et al. (2012).

7.8 Coastal risk exposure to storm-tide flooding and SLR

NIWA carried out a national coastal risk-exposure screening project for the Parliamentary Commissioner for the Environment (PCE) in 2015 (Bell et al. 2015; PCE 2015). The premise was to use best available topographic datasets, and assume land elevation above MHWS as a proxy for hazard exposure to coastal flooding and SLR, then undertake a risk census of people and assets in bands of elevation up to 3 m above MHWS.

For Southland, no LiDAR[21] digital elevation models (DEM) were available at the time, so the results reported in these two reports is based on the enhanced national DEM of New Zealand, which is only accurate to around 3–4 m in elevation in flatter coastal areas. Therefore, the risk exposure enumeration for Southland coastal areas was aggregated for the entire band of 0–3 m elevation above MHWS. Comparison of the risk-exposure results in areas where LiDAR DEMs were available

[21] Light Detection And Ranging – an aerial laser scanning survey technique that can achieve land elevation accuracies down to 0.1–0.15 m

revealed that the results using the enhanced national DEM substantially underestimated the numbers of assets (excluding foreshore/marine assets), building value and people by around 50%.

Currently, NIWA is completing a project under the Deep South Science Challenge to update the 2015 PCE national-wide assessment using a realistic 1% AEP storm-tide scenarios with 0.1 m SLR increments up to 3 m above local MHWS-10 (Figure 7-6) rather than rely on land elevation as a proxy for hazard exposure as used in the PCR report.

Further LiDAR datasets have become available to the Deep south Science Challenge project team including parts of Invercargill and Bluff (from Invercargill City Council) and the Waituna Lagoon catchment (Environment Southland), which is sparsely populated in the low-lying coastal area (Figure 7-11).

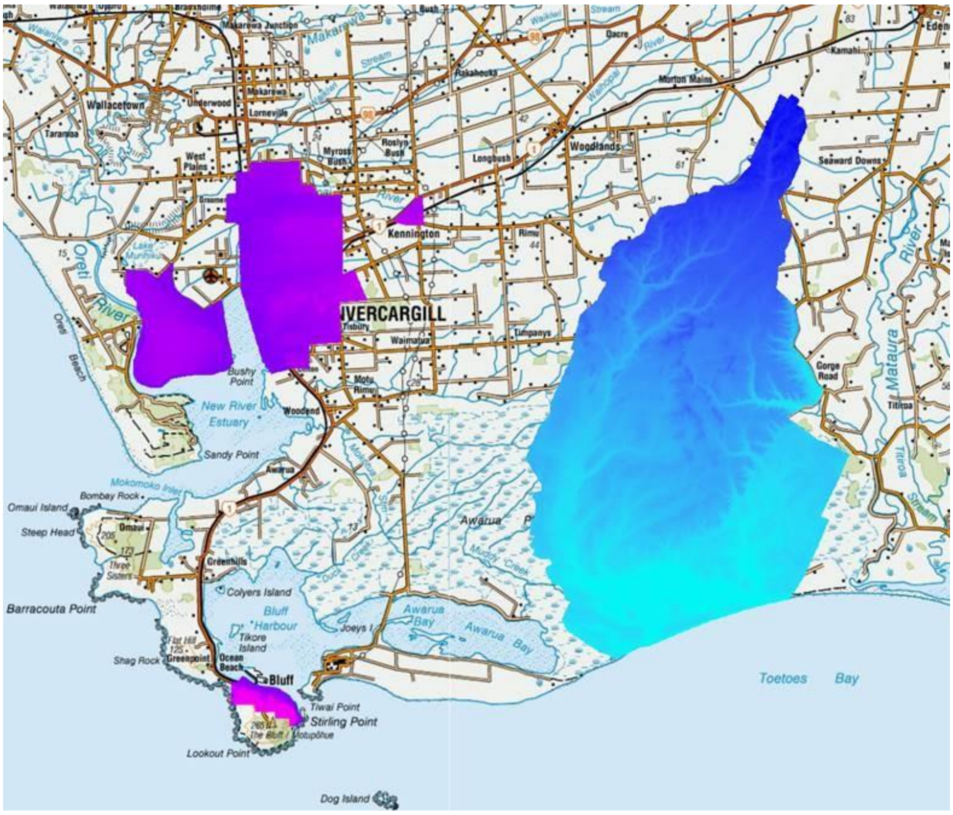

Figure 7-11: Coverage of LiDAR elevation surveys in Southland used for the NIWA Deep South Science Challenge project on national coastal risk exposure. The grading of the blue colour represents land elevation *Source*: Invercargill City Council and Environment Southland.

7.8.1 Provisional risk-exposure results (Deep South Challenge project)

NIWA is currently processing risk-exposure results for an update of the PCE (2015) assessment, by overlaying coastal flooding levels for a 1% AEP storm-tide polygon and applying constant 0.1 m increments in SLR up to 3 m above MHWS-10.

Some provisional results for different types of buildings and roads (combining all types) covering only the LiDAR survey areas (Figure 7-11), are listed in Table 7-3, but limited to cumulative regional counts 0.4 m increments of SLR combined with 1% AEP storm-tide levels. These values may be subject to change as the full analysis and review has not been completed. Note: critical facilities cover buildings such as civil defence centres, police, fire, education facilities, hospitals/clinics, council buildings/depots, government buildings, engineering lifeline /utilities.

Based on these provisional results for buildings and total replacement costs in areas covered by LiDAR surveys, the counts in Table 7-3 predominately relate to Invercargill City, as the LiDAR areas (Figure 7-11) mainly cover parts of the city. The area around Waituna Lagoon is sparsely populated. It is important to note that these are counts of assets potentially exposed to coastal flooding now and in the future (i.e., akin to a risk screening assessment), but may not necessarily be damaged or affected directly in such an event. An indeterminate number of these counts will be for assets behind protection works (e.g., stopbank), but nevertheless pose a residual risk to overtopping, breaching of banks and more importantly, more regular elevated groundwater levels. To quantify the direct and indirect risks would require more detailed district or city flood hazard modelling and application of RiskScape to determine the relative level of damage for each building or asset or which sections of road are likely to be affected.

The key result is that the coastal risk exposure to 1% AEP flooding for present-day mean sea level is already substantial (column 2 in Table 7-3) primarily in Invercargill City (but not known at this stage of the project how that extends to the entire Southland region). For 0.4, 0.8 and 1.2 m SLR, the increases in all types of buildings exposed to 1% AEP coastal flooding would be 20%, 44% and 72% increases relative to the present MSL. For replacement costs of those buildings, there would be 32%, 63% and 98% increases (for 0.4, 0.8 and 1.2 m SLR).

This comparison highlights the crucial benefit of having available accurate LiDAR surveys and DEMs, as the replacement costs of buildings exposed in the LiDAR areas already available is considerable at ~$0.6–1.2B for a range of 0–1.2 m SLR (not counting other infrastructure such as roads, 3-waters, rail, airport etc.).

Table 7-3: Provisional results from counts of buildings and replacement costs (2011) and roads (combining all types) exposed to a 1% AEP storm-tide level + 0.4 m increments in SLR for areas of Southland where LiDAR DEM was available. Note: these values may be subject to change prior to publication of the Deep South Challenge project report. [*Source*: Ryan Paulik, NIWA, pers. comm.].

	Cumulative counts for Southland (LiDAR areas only) as SLR increases for a 1% AEP storm-tide			
Receptors	**Present MSL**	**0.4 m SLR**	**0.8 m SLR**	**1.2 m SLR**
Buildings (total)	1,581	1,895	2,284	2,718
Residential	1,222	1,438	1,734	2,074
Commercial	39	62	78	104
Industrial/primary production	297	365	438	495
Critical facilities	13	13	13	15
Community	7	13	17	25
Other	3	4	4	5
All buildings replacement cost ($NZ-2011)	$600M	$796M	$976M	$1.19B
Roads (km) [all types]	38	49	61	71

8 Hydrological impacts of climate change

This section covers the projected differences in several hydrological statistics between the baseline period (1986-2005) and two future periods. These are mid-century (2036-2056) and late-century (2086-2099), and are slightly different from the corresponding time slices of the atmospheric modelling because the modelling was done before this project was initiated. We do not expect that the conclusions drawn would be substantively different if the periods were aligned. The statistics include:

- The Q95% flow[22];
- Mean annual and seasonal discharges;
- The mean annual flood (MAF); and
- Water supply reliability

8.1 Low flow

The projected future differences in the Q95% flows for the two RCPs and two time periods are presented in Figure 8-1. There are both increases and decreases projected for the four management zones of interest, with the more pronounced differences generally manifesting themselves during the late-century period and under higher RCPs. Increases in Q95% are more tangible in the west, in the headwaters of the Waiau, climbing over +50%; decreases are modelled in all zones but particularly the Matāura, Ōreti, and Aparima, dropping below -20%.

[22] Q95: Flow that is exceeded 95 percent of the time

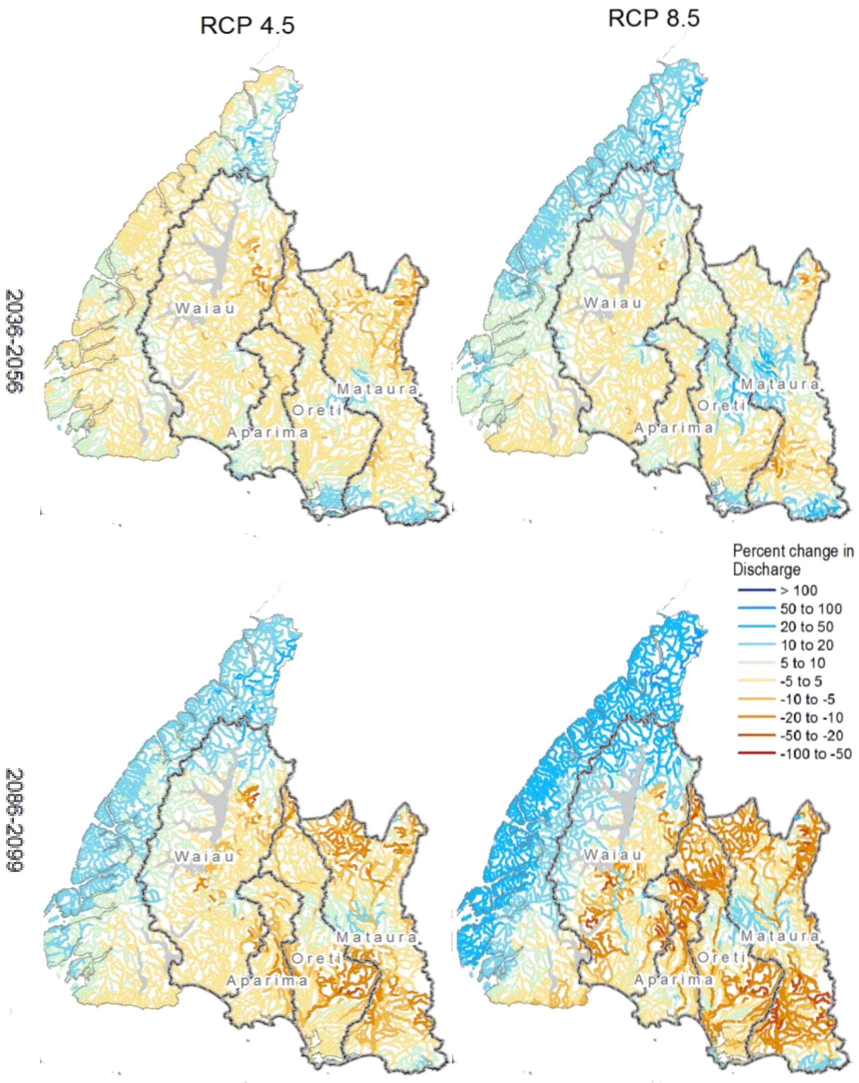

Figure 8-1: Percent changes in multi-model median Q95% across Southland for mid (top) and end of century (bottom).

8.2 Mean annual and seasonal discharge

The projected future differences in the annual and seasonal mean discharges for two RCPs and two time periods are presented in Figures 8-2 to Figure 8-6. At the annual scale, mean discharges remain roughly the same or increase; there are no appreciable decreases. Of the five catchments, the Matāura and Ōreti exhibit the larger increases, many climbing to the range 20-50% late-century under RCP 8.5.

As the annual mean discharge is an averaged representation of flows across the year, more detail and more patterns can arise from seasonal mean discharges. Starting near the beginning of the water year, mean spring discharges tend to remain about the same or increase across Southland, with the increases focused in the Matāura and Ōreti catchments, particularly for the late-century projections under RCP 8.5.

For summer, mean flows tend to remain the same or decrease, with some increases seen within Ōreti and Matāura, depending on the time slice and RCP. For autumn, flows tend to remain the same or increase, with the increases primarily falling within the Matāura and Ōreti catchments, although the increases are less pronounced than during spring. Lastly, for winter, flows tend to remain about the same or increase, with the increases greater for the Waiau, the northern parts of the Ōreti and Matāura catchments. For RCP 8.5, essentially all of Southland is projected to experience increases in mean winter discharge, in many parts by over 50%.

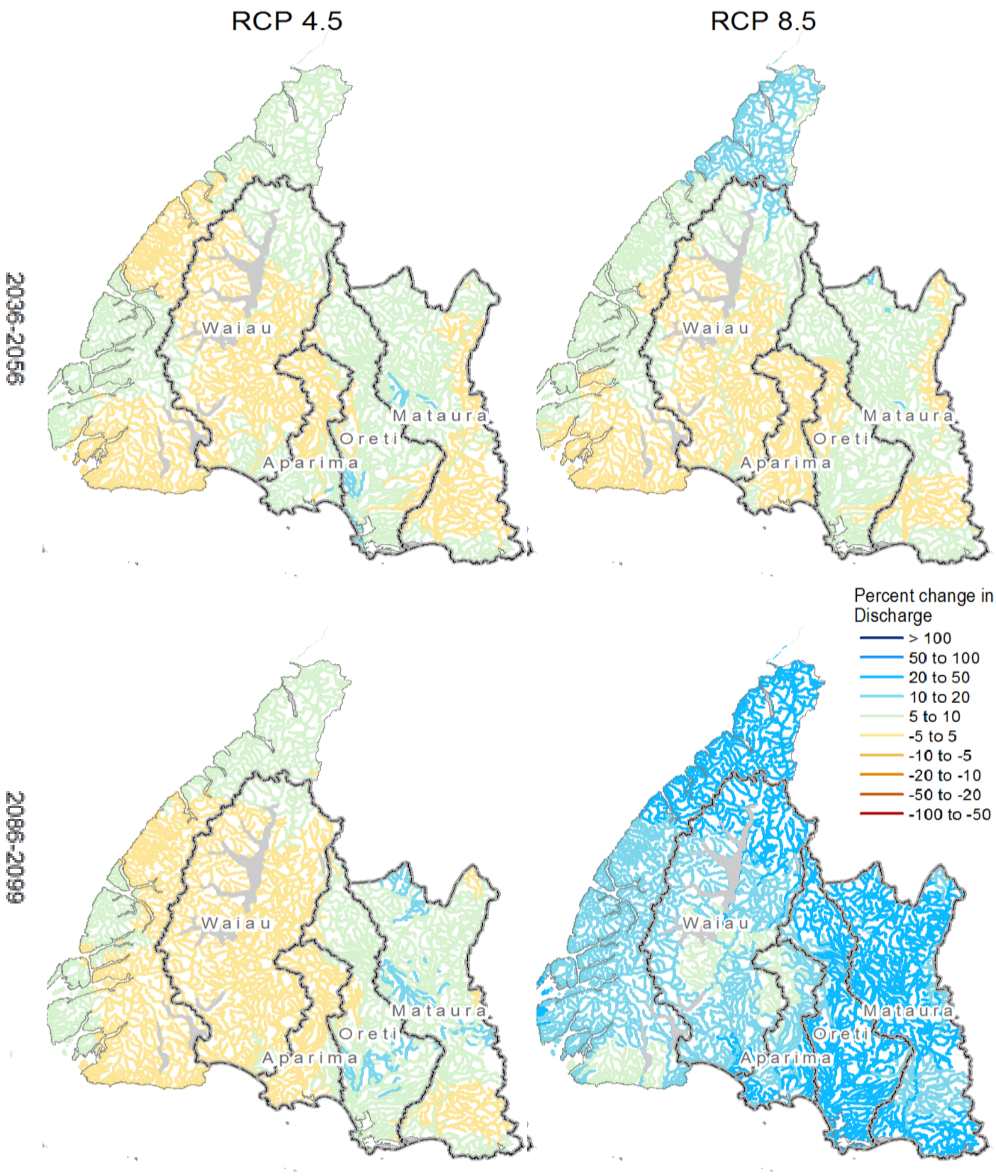

Figure 8-2: Percent changes in multi-model median of the mean discharge across Southland for mid (top) and late-century (bottom).

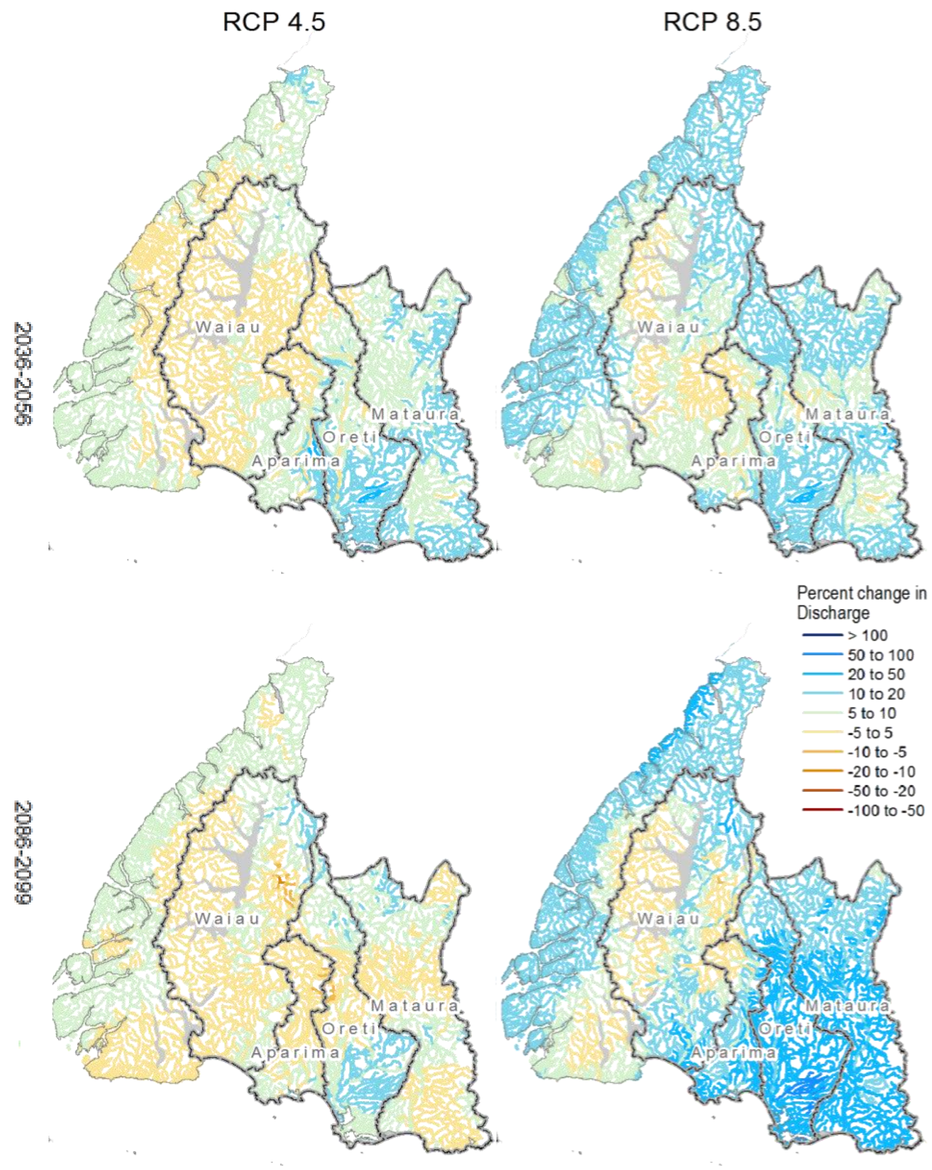

Figure 8-3: Percent changes in multi-model median of the mean spring discharge across Southland for mid (top) and late-century (bottom).

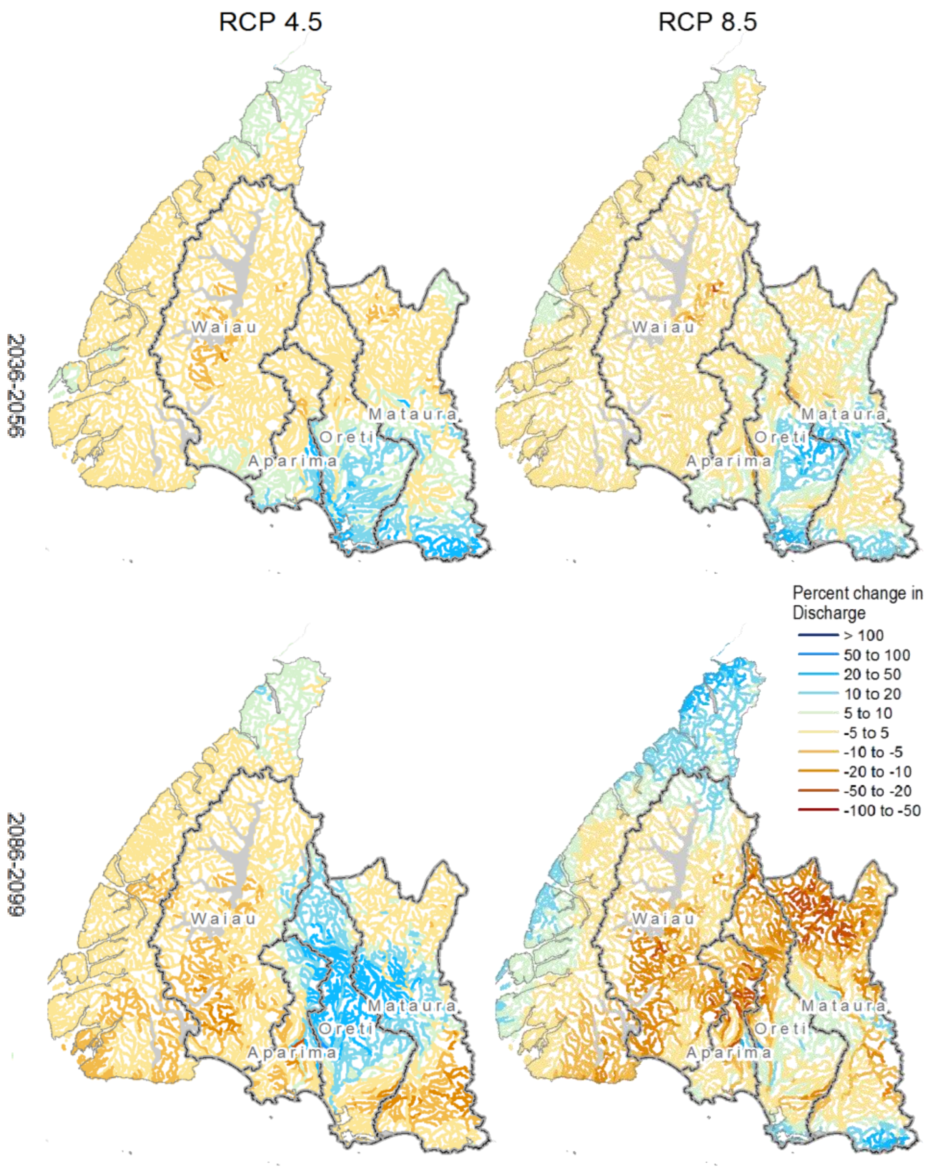

Figure 8-4: Percent changes in multi-model median of the mean summer discharge across Southland for mid (top) and late-century (bottom).

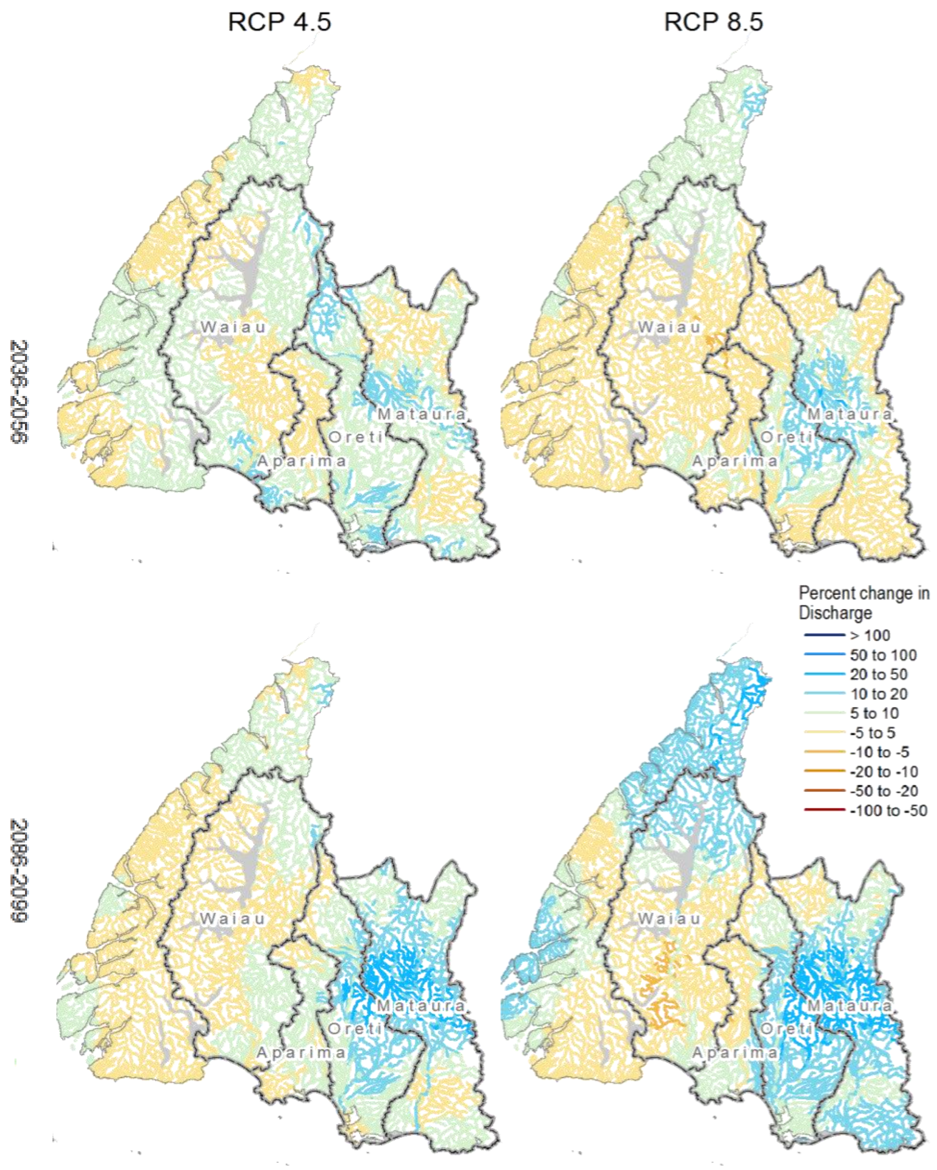

Figure 8-5: Percent changes in multi-model median of the mean autumn discharge across Southland for mid (top) and late-century (bottom).

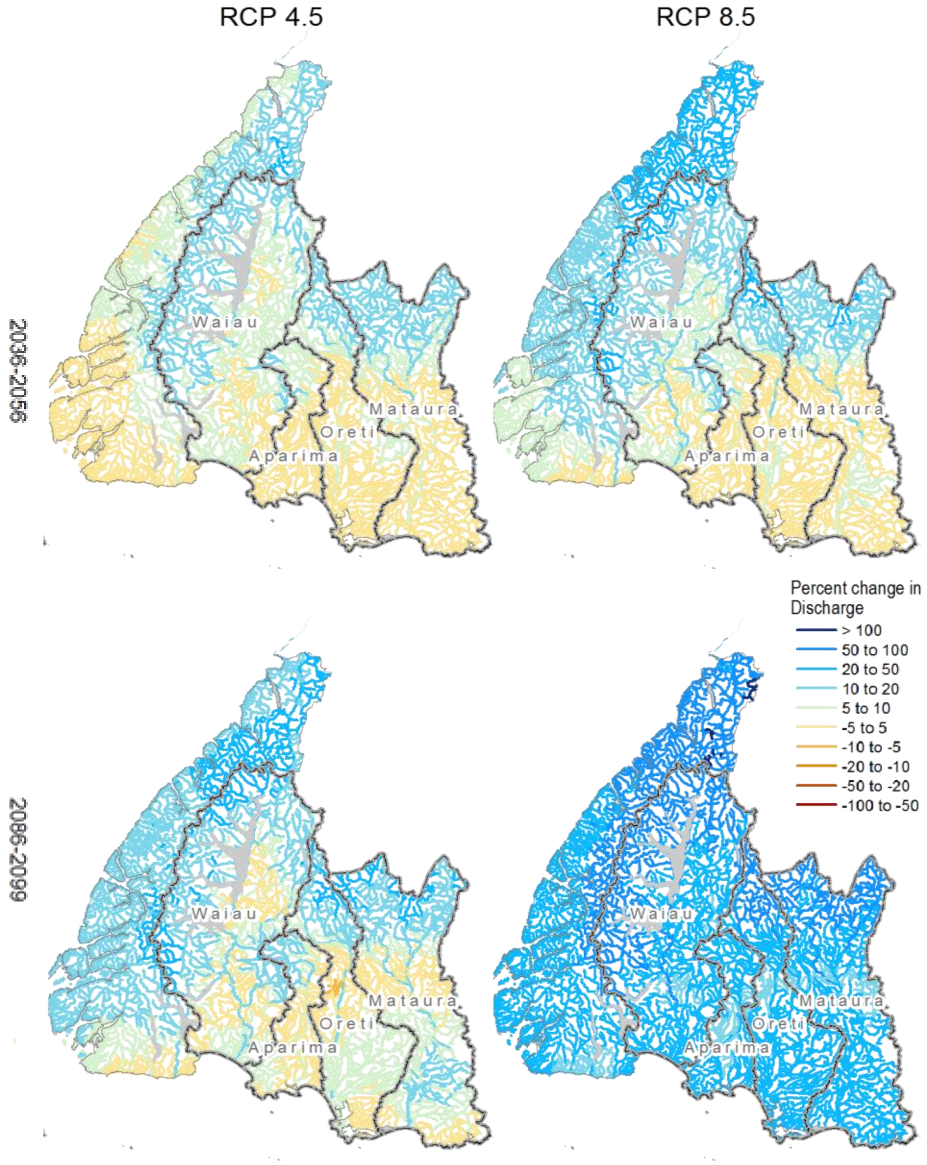

Figure 8-6: Percent changes in multi-model median of the mean winter discharge across Southland for mid (top) and late-century (bottom).

8.3 Mean annual flood

The projected future differences in the mean annual flood (MAF) for two RCPs and two time-slices are presented in Figure 8-7. While there are some pockets of little change or decreasing MAF, in general Southland is projected to experience an increase in MAF, with some increases exceeding 100%. There is little difference among the RCPs during the mid-century period, but by late-century, the increases in MAF become larger and more extensive progressively from RCP 4.5 to 8.5.

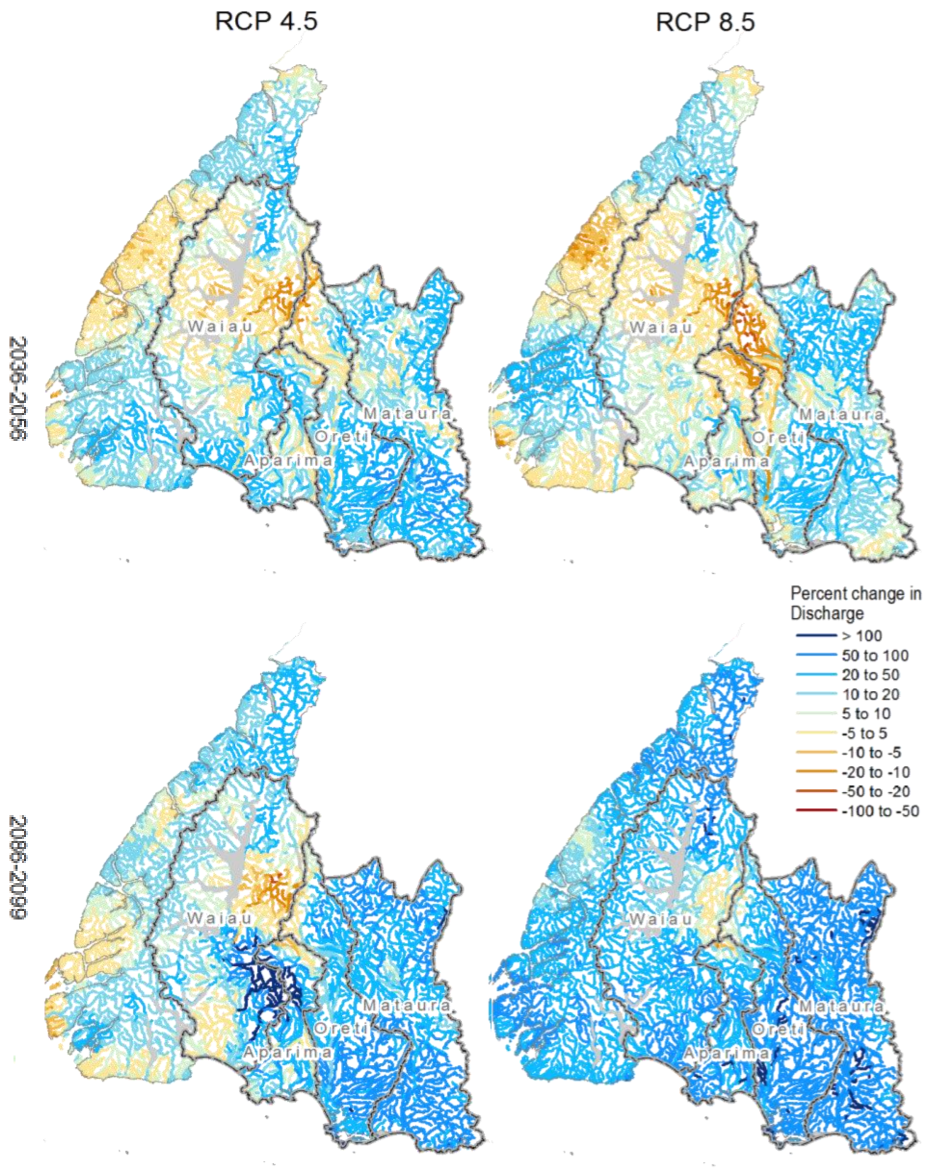

Figure 8-7: Percent changes in multi-model median of MAF across Southland for mid (top) and end of century (bottom).

The increase in MAF is a change that is largely consistent with the changes to rainfall presented in Ministry for the Environment (2016), especially with regard to the 99th percentile of daily rainfall. Analysis of flow records indicates that MAF has a strong correspondence with observed mean annual rainfall (Henderson, Collins et al. 2018). It is noteworthy that flood design standards for significant infrastructure are usually made on the basis of events with annual exceedance probabilities much smaller than that represented by MAF. Analysis of RCM rainfall projections undertaken for the High Intensity Rainfall Design project (Carey-Smith, 2018), has shown that events with small annual exceedance probability are projected to increase ubiquitously across the country in a way that scales with increasing temperatures. As such, MAF should not be considered a comprehensive metric for the possible impact of climate change on New Zealand flooding.

8.4 Water supply reliability

The projected future differences in the water supply reliability for all four RCPs and two time periods are presented in Figure 8-8. Little appreciable change in reliability is projected across Southland, with most parts of the region exhibiting slight increases but some with slight decreases. Late-century, however, the decreases become slightly more accentuated, particularly under RCP 8.5.

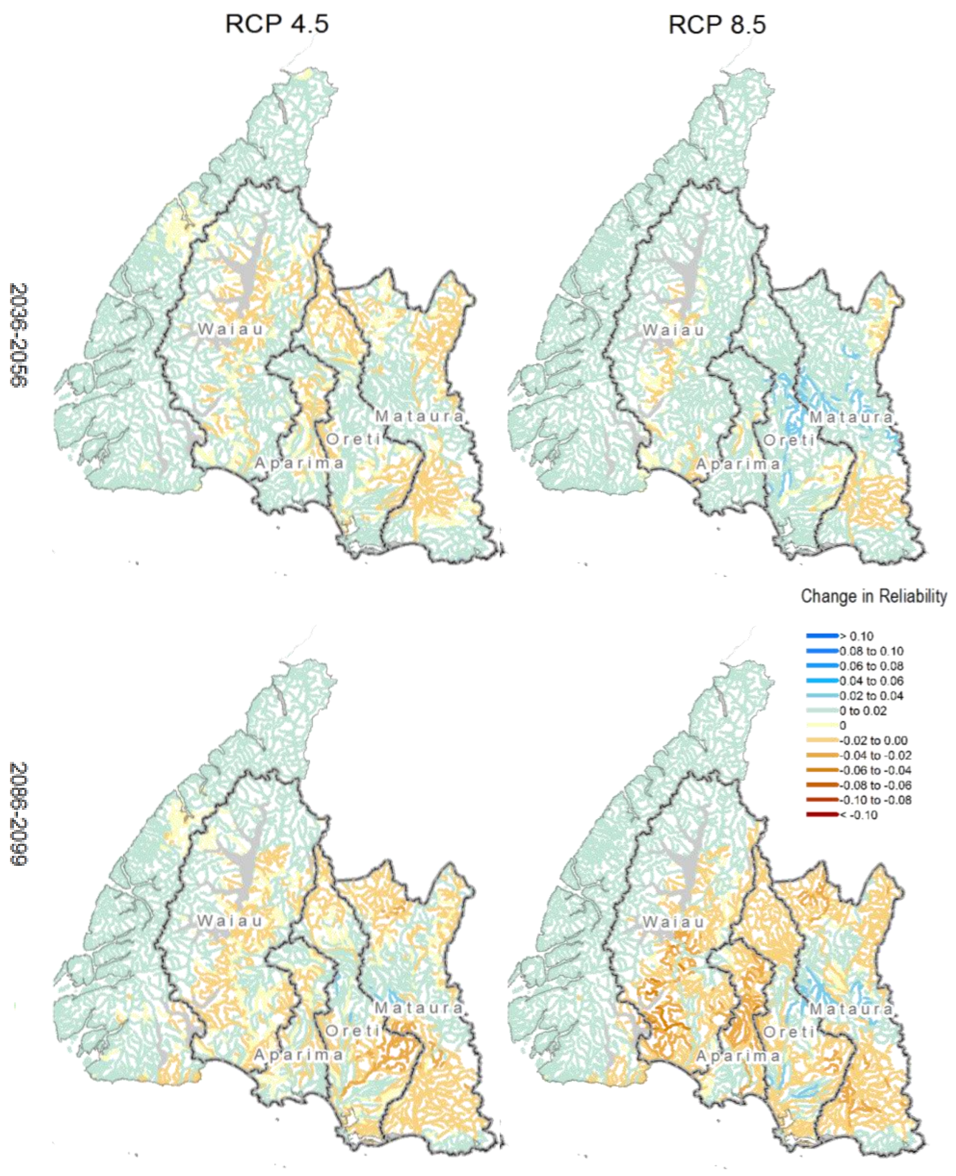

Figure 8-8: Absolute changes in multi-model median of supply reliability across Southland for mid (top) and end of century (bottom).

9 Climate change impact by industry sector

9.1 Council infrastructure

Consideration of climate change is particularly important not only for designing climate-sensitive infrastructure or assets which are likely to be around for many decades (supporting resource use and land development planning), but for management of current assets that could present a higher risk of failure due to climate change effects. The Councils manage a range of infrastructure categories across the region that are critical to ensure the smooth operation of the district for both residents and visitors alike. These include:

- **Roading:** One of the main considerations for roading is frost occurrence, which is projected to decrease significantly by the end of the century. However, higher temperatures may cause issues with road construction and heat damage (e.g., to bitumen). Another consideration is the potential for greater damage to bridges and roads in close proximity to rivers due to flood events caused by extreme rainfall, snowfall or snowmelt runoff. The issue of management and maintenance of all coastal roads under climate change needs to be considered due to the projected increase in sea level combined with spring tides (Table 7-3).

- **Water supply**: Demand for potable water is likely to increase as temperatures rise, together with a likely increase in urban development across the region. Climate change impact on hydrological processes associated with increased temperature, current land practices and freshwater ecological demand are likely to increase competition for access to freshwater systems and current water supply capacities (quantity and quality).

- **Stormwater and wastewater**: Stormwater and wastewater systems are particularly vulnerable to climate change as the discharge points of these systems are often at the lowest elevation of populated areas. As a result, small changes in rainfall extremes (intensity or duration), can overwhelm the current design capacity of these systems (White et al. 2017).

  In low-lying areas where groundwater is linked to the sea, sea-level rise will affect the performance of stormwater systems and wastewater systems where infiltration occurs. Droughts will also affect the performance and maintenance of wastewater systems, through reduction of the hydraulic loading with attendant increasers in concentration of bio-chemical oxygen demands (De Zellar and Maieir 1980, White et al. 2017).

- **Waste:** In urban areas climate change could impact the handling of sewage sludge with increased maximum temperatures combined with increase in green-waste volume (due to increase in favourable growing conditions).

9.2 Agriculture

Climate change is likely to have significant impacts on agricultural productivity due to changes in temperature and precipitation, and the resulting impacts on pests and diseases. Projected changes in national pasture production for dairy, sheep, and beef pastures range from an average reduction of 4% across IPCC AR4 climate scenarios for the 2030s, to increases of up to 4% for two scenarios in the 2050s (Reisinger et al. 2014). New Zealand agri-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.

9.2.1 Drought impacts on pasture and crops

It is likely that parts of the Southland region, particularly the central-northern part of the region, will experience more drought conditions in the future than at present, with increases in the number of dry days projected for much of the Waiau catchment and significant increases in PED projected for the northern Matāura catchment. For primary production, rainfall is one of the most important climate drivers, as there are limits (both too much and not enough water) where plants cease to grow or experience harm. When other climatic factors are not limiting, precipitation levels within these limits can have a direct and proportional relationship to productivity (Clark et al. 2012). Changes in rainfall patterns are important when considering future yield variability of broad-acre crops. This is because crops respond to both amounts and timing of water supply in relation to demand.

A plant's demand for water and its sensitivity to water stress varies throughout the plant's annual cycle. Therefore, timing of drought is critical: drought in late summer when plants have largely completed growth does not have the devastating impact of late winter/early spring drought that prevents achievement of full productive potential (McGlone et al. 2010).

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

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

Conversely, projections for increased rainfall in parts of Southland, particularly in the winter, could make management of dairy farming areas difficult. In addition, potential changes to flood regimes could affect agricultural production located on vulnerable land.

9.2.2 Terrestrial biosecurity

Climate change is widely regarded as one of the greatest challenges facing indigenous ecosystems in the coming century. As New Zealand (and Southland) has an economy based on very efficient primary production systems, the risk of exotic pests and diseases affecting the primary industries also needs to be minimised. Climate change will create new biosecurity challenges by allowing establishment of new exotic pest animals, weeds and diseases which are currently prevented by Southland's climate. The potential establishment of current seasonal immigrants are of greatest concern, along with species 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). Regional winds and currents may affect the ability of potential invaders to reach New Zealand and establish.

Big headed (*Pheidole megacephla*) and Argentine (*Linepithema humile*) ants are some of the worst invasive pest species in the world, as they have the capacity to wreak havoc on the native arthropod fauna, and they are already present in New Zealand. Continued warming and drying of eastern climates are likely to encourage their spread (McGlone and Walker, 2011). Fruit flies are already considered major threats to the New Zealand horticulture industry. Central and eastern Southland is the South Island region with the greatest potential for increase in fruit fly establishment (in terms of climate suitability) in the late 21st century (although Southland will remain less suitable than many North Island regions; Figure 9-1) (Kean et al. 2015).

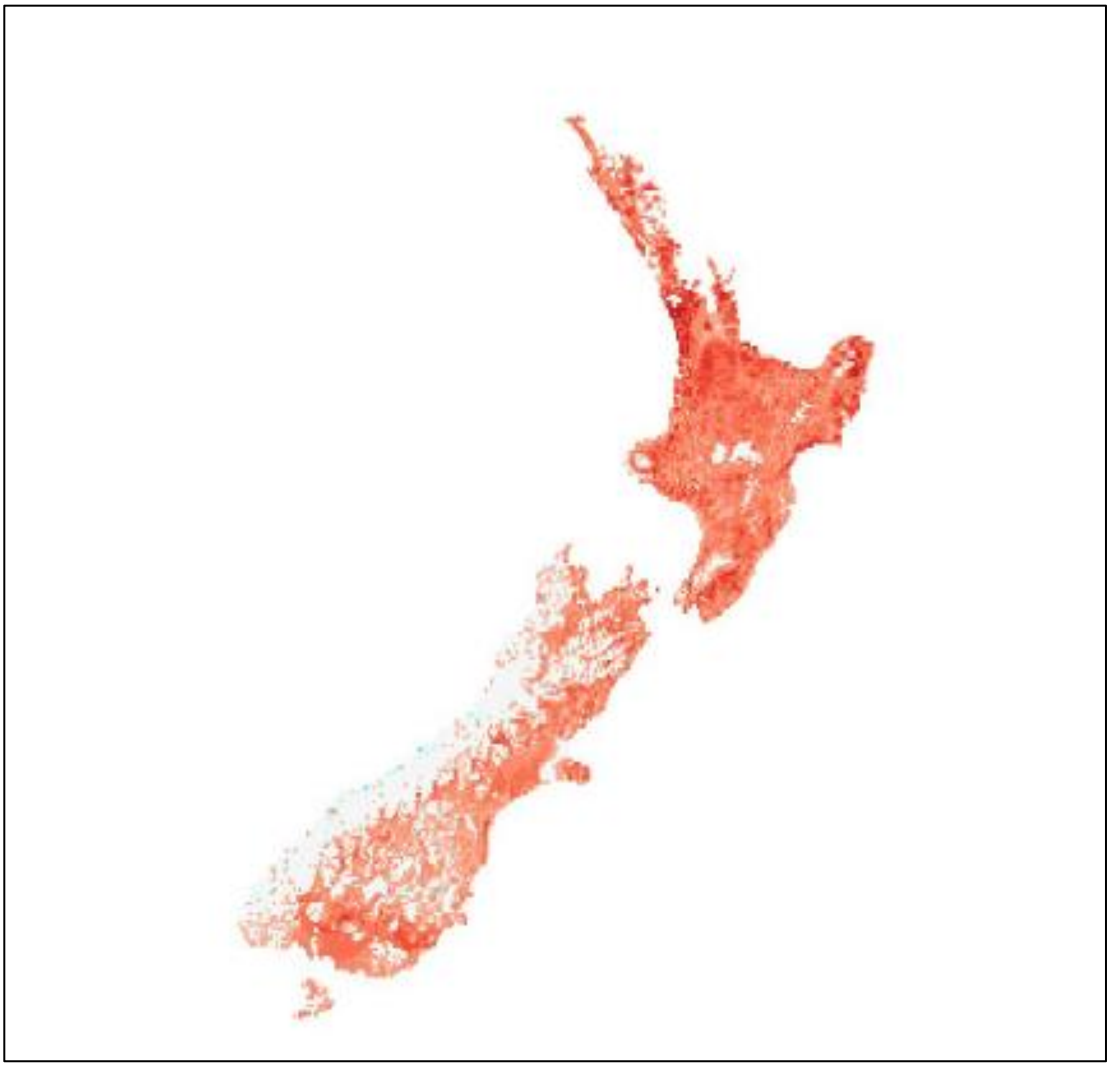

Figure 9-1: Change in climate suitability from 2015 to 2090 for 17 different fruit fly species. Darker shades of red indicate the greatest increase in the number of species that might establish. From Kean et al. (2015).

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

Zealand. Ornamental plants may escape cultivation when climatic constraints (such as frosts) are reduced and subsequently may naturalise and become invasive (Sheppard et al. 2016).

It is important to note that although much of the biosecurity risk with climate change will come from beyond New Zealand's borders, many of the future's pest, disease and weed problems are currently dormant in New Zealand, awaiting some perturbation, such as climate change, to allow them to spread and flourish. These types of pests are often weeds but may also be invertebrates. A few examples of sleeper invertebrate pests that are affected by temperature include migratory locust (*Locusta migratoria)* and tropical armyworm (*Spodoptera litura)* (Kean et al. 2015):

9.2.3 Infectious diseases

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

9.3 Fishing and aquaculture

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

Long-term changes in marine environmental variables, such as seawater temperature, may lead to new ecological compatibilities and may alter existing host-pathogen interactions. It is commonly accepted that warmer sea and fresh water temperatures modify host-pathogen interactions by increasing host susceptibility to disease. Such changes could contribute to the emergence of aquatic diseases in new regions (Castinel et al. 2014).

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

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

9.4 Forestry

The Otago-Southland wood supply region (as of 2014) is planted in *Pinus radiata* (63%), Douglas-fir (*Pseudotsuga menziesii;* 26%), and eucalypts (7%)[23]. Warming is expected to increase *Pinus radiata* growth in the cooler south, as the growing season will be longer (Reisinger et al. 2014). *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 increase in the cooler regions such as Southland where it could offset temperature-driven improved plantation growth. The severity of Swiss needle cast, caused by *Phaeocryptopus gaeumannii,* which is the most widespread disease of Douglas-fir is likely to increase with climate change as the abundance of this pathogen is strongly correlated with winter temperature (Watt et al. 2008). Therefore, it is likely that the anticipated increase in this pathogen will reduce the productivity of Douglas-fir in New Zealand.

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

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

Afforestation with exotic tree species (e.g., *Pinus radiata*), one of the most popular climate change mitigation strategies, may increase the fire hazard in the Southland region. Exotic tree plantations may lead to a higher risk of wildfire than from pasture or native shrubland or forest (exotic conifer and gum plantations create the equivalent of North American and Australian forests, respectively) (McGlone and Walker, 2011). *Pinus radiata* has a very low tolerance to fire, but Douglas-fir and eucalypts are more fire-adapted. New Zealand indigenous plants are generally not very flammable (Singers et al. 2017).

9.5 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 (Hendrikx et al. 2013, Reisinger et al. 2014). Warmer and drier conditions mostly benefit tourism but wetter conditions and extreme climate events undermine tourism (Reisinger et al. 2014). A large part of the tourism industry in New Zealand is dependent on river flow (e.g., fishing, jet boating, rafting, river crusing) so changes to flows will have a direct effect on these tourism operations all year around (Becken et al. 2014).

[23] https://www.southernwoodcouncil.co.nz/wp-content/uploads/2015/11/Otago-Southland-Forestry-Profile-2015-03.pdf

10 Summary

The global climate system is changing and with it New Zealand's climate and environment. These changes will have implications not only for New Zealand's climate and weather systems but also for freshwater availability for downstream users and for hazard exposure (inland and coastal). Due to the nature of climate change, trends will vary across the country, over the course of the century, and among scenarios of climate change. Building on the assessment of future changes in New Zealand's climate (based on six model projections), this report addresses potential impacts of climate change on a range of components of climate, hydrology and coastal processes across Southland using downscaled GCM outputs from 1971-2099 under different global warming scenarios. The combination of six GCMs and four warming scenarios allows us to consider a plausible range of future trajectories of greenhouse gas emissions and climatic responses.

It is impossible at this stage to attribute the modelled differences between two time periods (in this report, mid-century and end of century) solely to climate change, as natural climate variability is also present and may add to, or subtract from, the climate change effect. The resulting potential impacts of climate change are presented through averaging of the six model projections, which does reduce the underlying natural variability to some extent. With these caveats in mind, the potential effects of changing climate over this century are summarised as follows:

1. The projected Southland temperature changes increase with time and emission scenario. Future annual average warming spans a wide range: 0.5-1°C by 2040, and 0.7-3°C by 2090, largely dependent on scenario. Seasonally, autumn is the season where most of the warming occurs across all time periods and scenarios. Diurnal range (i.e., difference between minimum and maximum temperature during the day) is expected to increase with time and emission scenarios.

2. Changes in extreme temperatures reflect the changes in the average annual signal. The average number of hot days is expected to increase with time and scenario spanning from 0-10 days by 2040 to 5-55 days by 2090. Consequently, the number of heatwave days (i.e., number of consecutive days where the temperature is higher than 25°C) is projected to increase (largest increase with elevation). As expected, the number of frost days is expected to decrease by 0-5 days by mid-century, and by 10-20 frost days by the end of the century.

3. Projected changes in rainfall show a marked seasonality and variability across the Southland region. Annual rainfall is expected to slightly increase by mid-century (0-5%), while the increase spans 5-20% (with a larger increase in the northern part of the region) at the end of the century. Seasonally the largest increases are projected during winter, while summer precipitation is expected to decrease in the Waiau catchment (by up to 10% at the end of the century).

4. By mid-century, the number of wet days is expected to decrease by up to 10 days across most of the region. However, wet days are expected to increase by the end of the century for most of the region, except the Waiau where 10-20 fewer wet days are expected.

5. The number of heavy rain days (i.e., days where the total precipitation exceeds 50mm) is projected to increase throughout the Southland region at all time slices and RCPs,

except for a small area in the eastern Waiau catchment where a small decrease in the number of heavy rain days is projected for mid-century.

6. By mid-century, decreases in annual maximum 5-day rainfall are projected for the centre of the Southland region (up to 15 mm) and increases are projected for the rest of the region, with Fiordland facing the largest increases of 15-30 mm in some parts. At the end of the century, almost the whole Southland region (except the eastern Waiau under mid-range emission scenario) is projected to experience increases in annual maximum 5-day rainfall of up to 15-30 mm.

7. By mid-century the number of dry days are expected in increase up to 10 more days for much of the region except the central part of the region and northern and western Fiordland, for which up to 10 fewer dry days are expected. By the end of century, a decrease in dry days (up to 10-20 days) is projected for most of the region except for the Waiau catchment (increase up to 10-20 days), eastern Fiordland, and Stewart Island/Rakiura.

8. Changes in meteorological drought (assessed using Potential Evaporation Deficit or PED) indicate that the central-northern part of the Southland region is projected to experience the largest increases in PED in the future across both time slices and all emission scenarios. By mid-century, PED is expected to increase by 40-80mm per year for most of the regions, rising to over 100 m per year for the highest emission scenario by 2090.

9. Changes in sea level-rise are expected to be between 0.2-0.3 m by 2040 and increasing to 0.4-0.9 m by 2090. Putting aside storm events, those changes will result in an increasing percentage of normal high tides exceeding given present-day design for coastal infrastructure.

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

    - Annual average discharge is expected to remain stable or slightly decrease by mid-century (except North Fiordland). By the end of the century and with increased emissions, average annual flows are expected to increase across the region (up to 50% in Ōreti and Matāura catchments). From a seasonal aspect, spring flows are expected to be slightly higher, summer flows are expected to slightly decrease, while autumn and winter flows are expected to increase.

    - Low flow (expressed as Q95% flow) changes are expected to be variable across the Southland region. Low flows in Fiordland and the headwaters of the Waiau catchment are expected to increase with time and emission scenario. Low flows for the remainder of the region are expected to decrease, except for the coastal areas of the Ōreti and Matāura catchments.

- Floods (characterised by the Mean Annual Flood) are expected to become larger everywhere, with increases up to 100% in some locations by the end of the century.
- Change in water supply reliability are characterised by little appreciable change across Southland by mid-century, with most parts of the region exhibiting slight increases and some with slight decreases. Late-century, however, the decreases become slightly more accentuated, particularly under a high emissions scenario.

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

11 Glossary of abbreviations and terms

Term/abbreviation	Definition
99th percentile	The top 1 percent of a population.
Adaptation	The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.
Afforestation	Planting of new forests on lands that historically have not contained forests, or have not recently contained forests.
Air mass	A widespread body of air, the approximately homogeneous properties of which (1) have been established while that air was situated over a region of the Earth's surface, and (2) undergo specific modifications while in transit away from the source region.
Annual exceedance probability (AEP)	The probability of a given event (e.g., flood or sea level or wave height) being equalled or exceeded in elevation, in any given calendar year. AEP can be specified as a fraction (e.g., 0.01) or a percentage (e.g., 1%).
Anomaly	The deviation of a variable from its value averaged over a reference period.
Anthropogenic	Human-induced; man-made. Resulting from or produced by human activities.
Anthropogenic emissions	Emissions of greenhouse gases, greenhouse gas precursors, and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use changes, livestock production, fertilization, waste management, and industrial processes.
AR5	5th Assessment Report of IPCC – published in 2013/14 covering three Working Group Reports and a Synthesis Report.
Atmosphere	The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium and radiatively active greenhouse gases such as carbon dioxide (0.035% volume mixing ratio) and ozone. In addition, the atmosphere contains the greenhouse gas water vapour, whose amounts are highly variable but typically around 1% volume mixing ratio. The atmosphere also contains clouds and aerosols.
Augmentation factor	The percentage increase of rainfall per degree of warming contained within depth-duration-frequency tables in this report.
Average recurrence interval (ARI)	The average time interval (averaged over a very long time period and many "events") that is expected to elapse between recurrences of an infrequent event of a given large magnitude (or larger). A large infrequent event would be expected to be equalled or exceeded in elevation, once, on average, every "ARI" years, but with considerable variability.
Baseline/reference	The baseline (or reference) is the state against which change is measured. A baseline period is the period relative to which anomalies are computed.

Bias correction	Procedures designed to remove systematic climate model errors.
Business as Usual (BAU)	Business as usual projections assume that operating practices and policies remain as they are at present. Although baseline scenarios could incorporate some specific features of BAU scenarios (e.g., a ban on a specific technology), BAU scenarios imply that no practices or policies other than the current ones are in place. RCP8.5 is known as the 'business as usual' climate change scenario.
Carbon dioxide (CO_2)	A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas and coal of burning biomass, of land use changes and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1.
Carbon dioxide (CO_2) fertilisation	The enhancement of the growth of plants because of increased atmospheric carbon dioxide (CO_2) concentration
Clausius–Clapeyron equation/relationship	The thermodynamic relationship between small changes in temperature and vapour pressure in an equilibrium system with condensed phases present. For trace gases such as water vapour, this relation gives the increase in equilibrium (or saturation) water vapour pressure per unit change in air temperature.
Climate	Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, rainfall and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.
Climate change	Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.
Climate change scenario	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.
Climate model	A numerical representation of the climate system based on the physical, chemical and biological properties of its components,

	their interactions and feedback processes, and accounting for some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented or the level at which empirical parametrizations are involved. Coupled Atmosphere–Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near or at the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and inter-annual climate predictions.
Climate projection	A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/ radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.
Climate system	The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land use change.
Climate variability	Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).
Climate variable	An element of the climate that is liable to vary or change e.g., temperature, rainfall.
CMIP5	Coupled Model Inter-comparison Project, Phase 5, which involved coordinating and archiving climate model simulations based on shared model inputs by modelling groups from around the world. This project involved many experiments with coupled atmosphere-ocean global climate models, most of which were reported on in the IPCC Fifth Assessment Report, Working Group I. The CMIP5 dataset includes projections using the Representative Concentration Pathways.

Coastal squeeze	A narrowing of coastal ecosystems and amenities (e.g., beaches, salt marshes, mangroves, and mud and sand flats) confined between landward-retreating shorelines (from sea-level rise and/or erosion) and naturally or artificially fixed shorelines including engineering defences (e.g., seawalls), potentially making the ecosystems or amenities vanish.
Cold nights	In this report, a cold night (or frost) is defined when the daily minimum temperature is below 0°C.
Confidence	The validity of a finding based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement. Confidence is expressed qualitatively.
Depth duration frequency table	Rainfall depth-duration-frequency (DDF) curves or tables describe rainfall depth as a function of duration for given return periods and are important for the design of hydraulic structures.
Diurnal temperature range	The difference between the maximum and minimum temperature during a 24-hour period.
Downscaling (statistical, dynamical)	Deriving local climate information (at the 5 kilometre grid-scale in this report) from larger-scale model or observational data. Two main methods exist – statistical and dynamical. Statistical methods develop statistical relationships between large-scale atmospheric variables (e.g., circulation and moisture variations) and local climate variables (e.g., rainfall variations). Dynamical methods use the output of a regional climate/weather model driven by a larger-scale global model.
Drought (meteorological, hydrologic)	A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term; therefore, any discussion in terms of rainfall deficit must refer to the rainfall-related activity that is under discussion. For example, shortage of rainfall during the growing season impinges on crop production or ecosystem function in general (due to soil moisture drought, also termed agricultural drought), and during the runoff and percolation season primarily affects water supplies (hydrological drought). Storage changes in soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in rainfall. A period with an abnormal rainfall deficit is defined as a meteorological drought. A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.
Emission scenario	A plausible representation of the future development of emissions of substances that act as radiative forcing factors (e.g., greenhouse gases, aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships.
Ensemble	A collection of model simulations characterizing a climate prediction or projection. Differences in initial conditions and model formulation result in different evolutions of the modelled system and may give information on uncertainty associated with model error and error in initial conditions in the case of climate forecasts

	and on uncertainty associated with model error and with internally generated climate variability in the case of climate projections.
ENSO	El Niño-Southern Oscillation. A natural global climate phenomenon involving the interaction between the tropical Pacific and the atmosphere, but has far-reaching effects on the global climate, especially for countries in the Pacific rim. ENSO is the strongest climate signal on time scales of one to several years, characteristically oscillating on a 3-7-year timescale. The quasi-periodic cycle oscillates between El Niño (unusually warm ocean waters along the tropical South American coast and west-central equatorial Pacific) and La Niña (colder-than-normal ocean waters off South America and along the central-east equatorial Pacific).
Eustatic sea-level rise	Absolute level of sea-level rise, measured relative to the centre of the Earth. In contrast to relative sea-level rise which is measured relative to the land nearby.
Evapotranspiration	The combined process of evaporation from the Earth's surface and transpiration from vegetation.
Extra-tropical cyclone or mid-latitude cyclone	A large-scale (of order 1000 km) storm in the middle or high latitudes having low central pressure and fronts with strong horizontal gradients in temperature and humidity. A major cause of extreme wind speeds and heavy rainfall especially in wintertime.
Field capacity	The amount of soil moisture or water content held in the soil after excess water has drained away and the rate of downward movement has decreased. This usually takes place 2–3 days after rain or irrigation in pervious soils of uniform structure and texture.
Flood	The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.
GCM	Global climate model. These days almost all GCMs are AOGCMs (atmosphere-ocean global climate models). See also climate model.
GIS	A geographic information system (GIS) is a system designed to capture, store, manipulate, analyse, manage, and present all types of geographical information for informing decision making.
Global mean surface temperature	An estimate of the global mean surface air temperature. However, for changes over time, only anomalies, as departures from a climatology, are used, most commonly based on the area-weighted global average of the sea surface temperature anomaly and land surface air temperature anomaly.

Greenhouse effect	The radiative effect of all infrared-absorbing constituents in the atmosphere. Greenhouse gases, clouds, and (to a small extent) aerosols absorb terrestrial radiation emitted by the Earth's surface and elsewhere in the atmosphere. These substances emit infrared radiation in all directions, but, everything else being equal, the net amount emitted to space is normally less than would have been emitted in the absence of these absorbers. This is because of the decline of temperature with altitude in the troposphere and the consequent weakening of emission. An increase in the concentration of greenhouse gases increases the magnitude of this effect; the difference is sometimes called the enhanced greenhouse effect. The change in a greenhouse gas concentration because of anthropogenic emissions contributes to an instantaneous radiative forcing. Surface temperature and troposphere warm in response to this forcing, gradually restoring the radiative balance at the top of the atmosphere.
Greenhouse gas (GHG)	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are many entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).
Groundwater recharge	The process by which external water is added to the zone of saturation of an aquifer, either directly into a geologic formation that traps the water or indirectly by way of another formation.
Growing degree-days (GDD)	Growing degree-days (GDD) express the sum of daily temperatures above a selected base temperature (e.g., 10˚C) that represent a threshold of plant growth. The daily GDD total is the amount the daily average temperature exceeds the threshold value (e.g., 10°C) per day. For example, a daily average temperature of 18°C would have a GDD base 10°C value of 8 and a GDD base 5°C value of 13. The daily GDD values are accumulated over the period 1 July to 30 June to calculate an annual GDD value.
Hazard	The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts.

Heatwave days	A heatwave is defined as at least three consecutive days when the temperature is 25 °C or above.
HIRDS	High Intensity Rainfall Design System (http://hirds.niwa.co.nz). HIRDS uses a regionalized index-frequency method to predict rainfall intensities at ungauged locations and returns depth-duration-frequency tables for rainfall at any location in New Zealand. Temperature increases can be inserted and corresponding increases in rainfall for each duration and frequency are calculated.
Holocene	The Holocene Epoch is the most recent geologic subdivision in the Quaternary Period, extending from 11.65 ka (thousand years before 1950) to the present. It is also known as Marine Isotopic Stage (MIS) 1 or current interglacial.
Hot days	In this report, a hot day is defined as a day with a maximum temperature over 25°C.
Humidity	*Specific* humidity is the ratio of the mass of water vapour to the total mass of the system (water plus air) in a parcel of moist air. *Relative* humidity is the ratio of the vapour pressure to the saturation vapour pressure (the latter having a strong dependence on temperature).
Hydrologic drought	Hydrologic drought occurs when low water supply becomes evident, especially in streams, reservoirs, and groundwater levels, usually after an extended period of meteorological drought.
Ice sheet	A mass of ice of continental size that is sufficiently thick to cover most of the underlying bed, so that its shape is mainly determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base). An ice sheet flows outward from a high central ice plateau with a small average surface slope. The margins usually slope more steeply, and most ice is discharged through fast flowing ice streams or outlet glaciers, in some cases into the sea or into ice shelves floating on the sea. There are two main ice sheets in the modern world, one over Greenland and one over Antarctica. Ice sheets that are grounded below sea level, including consideration of isostatic rebound, are called marine ice sheets. West Antarctica is primarily a marine based ice sheet.
Impacts (Consequences, Outcomes)	Effects on natural and human systems. In this report, the term impacts is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of climate change on geophysical systems, including floods, droughts, and sea-level rise, are a subset of impacts called physical impacts.
Industrial Revolution	A period of rapid industrial growth with far reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other

	countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of fossil fuels and emission of, in particular, fossil carbon dioxide.
Interglacial	An interglacial period is a geological interval of warmer global average temperature lasting thousands of years that separates consecutive glacial periods within an ice age. The current Holocene interglacial began at the end of the Pleistocene, about 11,650 years ago.
IPCC	Intergovernmental Panel on Climate Change. This body was established in 1988 by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) to objectively assess scientific, technical and socioeconomic information relevant to understanding the scientific basis of risk of human induced climate change, its potential impacts and options for adaptation and mitigation. Its latest reports (the Fifth Assessment) were published in 2013/14 (see www.ipcc.ch/).
IPO	Interdecadal Pacific Oscillation – a long timescale oscillation in the ocean–atmosphere system that shifts climate in the Pacific region every one to three decades.
Land use and Land use change	Land use refers to the total of arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation). Land use change refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land use change may have an impact on the surface albedo, evapotranspiration, sources and sinks of greenhouse gases, or other properties of the climate system and may thus give rise to radiative forcing and/or other impacts on climate, locally or globally.
LiDAR	LIDAR, which stands for *Light Detection and Ranging,* is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses—combined with other data recorded by the airborne system— generate precise, three-dimensional information about the shape of the Earth and its surface characteristics. A LIDAR instrument principally consists of a laser, a scanner, and a specialized GPS receiver.
Likelihood	The chance of a specific outcome occurring, where this might be estimated probabilistically.
Mean high water springs (MHWS)	The high tide height associated with higher than normal high tides that result from the beat of various tidal harmonic constituents. Mean high water springs occur every 2 weeks approximately.
Mean sea level (MSL)	The surface level of the ocean at a point averaged over an extended period such as a month or year. Mean sea level is often used as a national datum to which heights on land are referred. Mean sea level changes with the averaging period used, due to climate variability and long-term sea-level rise.
Meridional	North-south, i.e., a meridional trend is a north-south trend.

Meteorological drought	A period with an abnormal rainfall deficit; when dry weather patterns dominate an area, and resulting rainfall is low.
Mitigation (of climate change)	A human intervention to reduce the sources or enhance the sinks of greenhouse gases.
Model spread	The range or spread in results from climate models, such as those assembled for Coupled Model Intercomparison Project Phase 5 (CMIP5). Does not necessarily provide an exhaustive and formal estimate of the uncertainty in feedbacks, forcing or projections even when expressed numerically, for example, by computing a standard deviation of the models' responses. To quantify uncertainty, information from observations, physical constraints and expert judgement must be combined, using a statistical framework.
Open coast	Coastline located outside of sheltered harbours and estuaries, in locations subject to ocean waves and swell.
Orographic rainfall	Precipitation that is produced when moist air is lifted as it moves over a mountain range. As the air rises and cools, orographic clouds serve as the source of the precipitation, most of which falls upwind of the mountain ridge.
Paris agreement	The Paris Agreement aims to respond to the global climate change threat by keeping a global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C.
PED	Potential evapotranspiration deficit. PED can be thought of as the amount of water needed to be added as irrigation, or replenished by rainfall, to keep pastures growing at levels that are not constrained by a shortage of water. The unit of PED is millimetres.
Percentiles	The set of partition values which divides the total population of a distribution into 100 equal parts, the 50th percentile corresponding to the median of the population.
Precipitation	Describes all forms of moisture that falls from clouds (rain, sleet, hail, snow, etc). 'Rainfall' describes just the liquid component of precipitation.
Pre-industrial	Conditions at or before 1750. See also Industrial revolution.
Projection	A numerical simulation (representation) of future conditions. Differs from a forecast; whereas a forecast aims to predict the exact time-dependent conditions in the immediate future, such as a weather forecast a future cast aims to simulate a time-series of conditions that would be typical of the future (from which statistical properties can be calculated) but does not predict future individual events.
Radiative forcing	A measure of the energy absorbed and retained in the lower atmosphere. More technically, radiative forcing is the change in the net (downward minus upward) irradiance (expressed in W/m^2, and including both short-wave energy from the sun, and long-wave energy from greenhouse gases) at the tropopause, due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the sun.

Regional Climate Model (RCM)	A numerical climate prediction model run over a limited geographic domain (here around New Zealand), and driven along its lateral atmospheric boundary and oceanic boundary with conditions simulated by a global climate model (GCM). The RCM thus downscales the coarse resolution GCM, accounting for higher resolution topographical data, land-sea contrasts, and surface characteristics. RCMs can cater for relatively small-scale features such as New Zealand's Southern Alps.
Relative sea level	Sea level measured by a tide gauge with respect to the land upon which it is situated. Relative sea-level rise (RSLR) is the sea-level rise relative to the land adjacent.
Representative Concentration Pathways (RCPs)	Representative concentration pathways. They describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. The four RCPs, RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m^2, respectively)
Resolution	In climate models, this term refers to the physical distance (metres or degrees) between each point on the grid used to compute the equations. Temporal resolution refers to the time step or time elapsed between each model computation of the equations.
Return period	An estimate of the average time interval between occurrences of an event (e.g., flood or extreme rainfall) of (or below/above) a defined size or intensity.
Scenario	In common English parlance, a 'scenario' is an imagined sequence of future events. The IPCC Fifth Assessment describes a 'climate scenario' as: A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. The word 'scenario' is often given other qualifications, such as 'emission scenario' or 'socio-economic scenario'. For the purpose of forcing a global climate model, the primary information needed is the time variation of greenhouse gas and aerosol concentrations in the atmosphere.
Sea ice	Ice found at the sea surface that has originated from the freezing of seawater. Sea ice may be discontinuous pieces (ice floes) moved on the ocean surface by wind and currents (pack ice), or a motionless sheet attached to the coast (land-fast ice).
Sea level change	Sea level can change, both globally and locally due to (1) changes in the shape of the ocean basins, (2) a change in ocean volume as a result of a change in the mass of water in the ocean, and (3) changes in ocean volume as a result of changes in ocean water density.
Sea surface temperature (SST)	The sea surface temperature is the subsurface bulk temperature in the top few metres of the ocean, measured by ships, buoys and drifters.

Seven-station series	This refers to seven long-term temperature records used to assess New Zealand's warming on the century time-scale. The sites are located in Auckland, Wellington, Masterton, Nelson, Hokitika, Lincoln, and Dunedin.
Simulation	Simulation is the imitation of the operation of a real-world process or system over time. The act of simulating something first requires that a model be developed; this model represents the key characteristics, behaviours and functions of the selected physical or abstract system or process. The model represents the system itself, whereas the simulation represents the operation of the system over time.
SLR	Sea-level rise
SOI	Southern Oscillation Index, representing seesaws of atmospheric pressure in the tropical Pacific, one pole being at Tahiti and the other at Darwin, Australia. Extreme states of this index are indicative of El Niño or La Niña events in the equatorial Pacific. Typically, El Niño events produce more south-westerly flow than usual over New Zealand and associated cooler conditions, with more rainfall in western parts and frequently drought conditions in the east. La Niña events produce more high pressures over the South Island and warmer north-easterly airflow over the North Island, sometimes with drought conditions in the South Island.
Soil moisture	Water stored in the soil in liquid or frozen form.
Soil moisture deficit (SMD)	A day of soil moisture deficit is considered in this report to be when soil moisture is below 75 mm of available soil water capacity. SMD is calculated based on incoming daily rainfall (mm), outgoing daily potential evapotranspiration (PET, mm), and a fixed available water capacity (the amount of water in the soil 'reservoir' that plants can use) of 150 mm. Evapotranspiration (ET) is assumed to continue at its potential rate until about half of the water available to plants is used up, whereupon it decreases, in the absence of rain, as further water extraction takes place. ET is assumed to cease if all the available water is used up.
Solar radiation	Electromagnetic radiation emitted by the Sun with a spectrum close to the one of a black body with a temperature of 5770 K. The radiation peaks in visible wavelengths. When compared to the terrestrial radiation it is often referred to as shortwave radiation.
Spatial and temporal scales	Climate may vary on a large range of spatial and temporal scales. Spatial scales may range from local (less than 100,000 km^2), through regional (100,000 to 10 million km^2) to continental (10 to 100 million km^2). Temporal scales may range from seasonal to geological (up to hundreds of millions of years).
Storm surge	The rise in sea level due to storm meteorological effects. Low-atmospheric pressure relaxes the pressure on the ocean surface causing the sea-level to rise, and wind stress on the ocean surface pushes water down-wind (onshore winds) and to the left up against any adjacent coast (alongshore winds). Storm surge has timescales of sea-level response that coincide with typical synoptic weather motions; typically 1–3 days.

Storm tracks	Originally, a term referring to the tracks of individual cyclonic weather systems, but now often generalized to refer to the main regions where the tracks of extratropical disturbances occur as sequences of low (cyclonic) and high (anticyclonic) pressure systems
Storm-tide	Storm tide refers to the total observed sea level during a storm, which is the combination of storm surge (caused by low atmospheric pressure and by high winds pushing water onshore) and normal high tide
Surface temperature	Air temperatures measured near or 'at' the surface (usually 1.5 m above the ground).
Synoptic	Weather patterns viewed at a scale of 1000 km or more to be able to see features such as high and low pressure systems.
Tide gauge	A device at a coastal or deep-sea location that continuously measures the level of the sea with respect to the adjacent land. Time averaging of the sea level so recorded gives the observed secular changes of the relative sea level
Trend	In this report, the word trend designates a change, generally monotonic in time, in the value of a variable.
Tropical cyclone	A strong, cyclonic-scale disturbance that originates over tropical oceans. Distinguished from weaker systems (often named tropical disturbances or depressions) by exceeding a threshold wind speed. A tropical storm is a tropical cyclone with 1-minute average surface winds between 18 and 32 m s^{-1}. Beyond 32 m s^{-1}, a tropical cyclone is called a hurricane, typhoon, or cyclone, depending on geographic location.
Uncertainty	A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts).
VCSN	Virtual Climate Station Network. Made up of observational datasets of a range of climate variables: maximum and minimum temperature, rainfall, relative humidity, solar radiation, and wind. Daily data are interpolated onto a 0.05° longitude by 0.05° latitude grid (approximately 4 kilometres longitude by 5 kilometres latitude), covering all New Zealand (11,491 points). Primary reference to the spline interpolation methodology is Tait et al. (2006).
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.
W/m^2	Watts per square meter (a measure of radiation intensity).

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Appendix A Downscaling methodology

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

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

The six GCMs chosen for dynamical downscaling were BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISS-E2-R, HadGEM2-ES and NorESM1-M. These models had simulations that contained hourly precipitation results from 1970 through to 2100. The native resolution of the RCM is 27 km and there are known biases in the precipitation fields derived from this model. These projections (aside from some of the extreme rainfall, relative humidity, wind, and solar radiation projections) have a bias-corrected version applied to these data at 5 km x 5 km resolution with a daily time-step. The 5 km grid corresponds to the Virtual Climate Station Network (VCSN) grid[24]. Figure A-1 shows a schematic for the dynamical downscaling method used in this report.

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

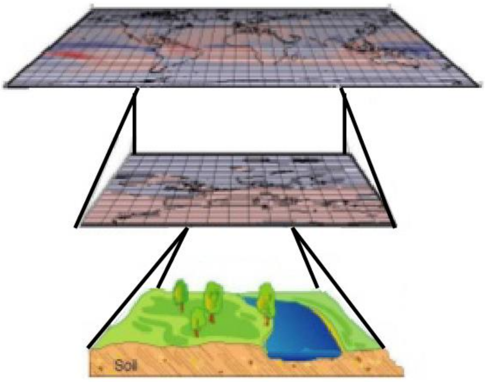

Figure A-1: Schematic showing dynamical downscaling method used in this report.

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

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

Downscaled climate projection data is presented as 5 km x 5 km square pixels over Southland. The projections mapped in this report contain some pixels around the Southland coast where no projection data are displayed, resulting in some small gaps in the projection data at the coast. Data were downscaled only where low resolution cells in the climate model consisted of land coverage and where they overlapped high resolution cells on land. In most cases, interpolating over mixed sea and land points creates artificial biases, for example lower temperatures, so the data in that cell is removed. For display purposes in the maps for this report, NIWA has undertaken interpolation to continue the climate projections to the coast. The nearest neighbour interpolation method was used to do this where the empty coastal cell was assigned the value of the nearest neighbouring cell.