NIWA
Taihoro Nukurangi

# Climate change impacts on agricultural water resources and flooding

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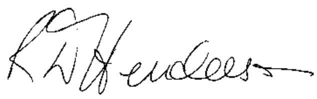
|  | Reviewed by: | Roddy Henderson |
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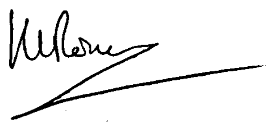
|  | Approved for release by: | Helen Rouse |

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The global climate system is changing and with it the global and New Zealand water cycles. These changes will have implications for New Zealand's agricultural sector in terms of both productivity and hazard exposure, and 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, this report addresses potential impacts of climate change on the components of hydrology related to the agricultural sector.

The effects of climate change 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 detailed hydrological effects were aggregated into a suite of statistics with bearing on agricultural water supply, soil moisture conditions, and flood hazard exposure, and were done so to compare mid- and late-century conditions with recent historical conditions.

The projected effects of climate change on New Zealand's agricultural hydrology are complex and difficult to generalise across the country and within regions due to the interactions among climate, topography, geology, and land use. It is also impossible at this stage to attribute the modelled differences between two time periods solely to climate change, as natural climate variability is also present and may add to or subtract from the climate change effect. With these caveats in mind, the changing climate over this century is projected to lead to the following hydrological effects:

- Average river flows tend to increase in the west and south of the South Island and decrease in the east and north of the North Island.
- Low flows are expected to become even lower and dry conditions reached earlier following the wet season over most of the country, with the exception of the west of the South Island. This leads to general declines in flow reliability – the duration of time river abstraction are unconstrained.
- Floods, in contrast, are expected to become larger everywhere, particularly in the south.
- Soil conditions are projected to become drier over much of the country during spring and summer, with earlier onset of dry conditions, while soil conditions are expected to become wetter during winter.

The implications for agricultural water resource and hazard management vary with the hydrological changes. In most cases water demand is projected to increase, but the opportunity to abstract water in these areas is generally expected to decline, putting greater pressure on water resource management and agricultural productivity. The flood hazard is projected to remain about the same or increase; in some areas the increases are substantial. Increased flood exposure is projected for areas with minimal increases in water shortage as well as severe increases, potentially compounding the challenges faced by local agricultural activities.

# Technical summary

The global climate system is changing and with it so are the global and New Zealand water cycles. These changes will have implications for New Zealand's agricultural sector, in terms of both productivity and hazard exposure, and 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 (Ministry for the Environment 2016), this report addresses potential impacts of climate change on 10 hydrological statistics related to agricultural water demand, water supply, and flood hazard.

Assessment of climate change impacts on hydrological regimes was carried out by using climate change projections (Ministry for the Environment 2016) to drive NIWA's national hydrological model (TopNet). The assessment was carried out across 43,862 catchments within New Zealand (with an average catchment area of approximately 6 $km^2$) driven by a combination of four radiative forcing scenarios (named as 'Representative Concentration Pathways', RCPs) and six climate models (Global Circulation Models, GCMs) run over the period 1971-2099. This provided for the first time a 24-member ensemble that may be used to identify patterns of hydrological change at regional and sub-regional scales. This allows an unprecedented level of detail and an estimation of the robustness in the information provided at national and regional scale.

The major changes in climate reported by Ministry for the Environment (2016) were:

- The mid-range estimate of projected New Zealand temperature change is for an expected increase of about 0.8°C by 2040 and 1.4°C by 2090, relative to the baseline 1986-2005 period. However, owing to the different possible pathways for changing concentrations of greenhouse gases in the atmosphere, as well as the differences in climate model response to those pathways, the possible projections of future warming span a wide range: 0.2–1.7°C by 2040, 0.1–4.6°C by 2090.
- Projected changes in rainfall show a marked seasonality and variability across regions. It is very likely that for winter and spring there will be an increase in rainfall for the west of both the North and the South Island, with drier conditions in the east and north. This is a robust prediction both in 2040 and 2090, caused by the westerly winds over New Zealand increasing during these seasons. For summer it is likely that there will be more rainfall in the east of both islands, with less in the west and central North Island.
- Extreme daily rainfall is likely to increase in most areas, with the largest increases being seen in areas where mean rainfall is also increasing, such as the West Coast.
- Climate drought severity is projected to increase in most areas of the country, except for Taranaki-Manawatu, West Coast and Southland.

At the national scale the main findings with regard to hydrological changes are as follows:

- Change in mean flows are spatially and temporally variable. Mean annual flows are expected to decrease with the increased radiative forcing in Northland-Auckland and the east coast of the North Island, while both increased and decreased mean flows are seen for the rest of the North Island. For the South Island, reductions are expected to become more pronounced with the strength of the radiative forcing for Marlborough and inland Canterbury, however mean flows are expected to increase with the increased radiative forcing for the rest of the South Island with time.

- Mean annual low flows (MALF) are generally expected to decrease for the North Island with increased radiative forcing and with time. The situation is more contrasted for the South Island, where there is a marked trend in decreased mean annual low flow except for parts of Otago, the West Coast region and some coastal areas of South Canterbury.

- Low flow conditions are expected to be reached earlier in the water year (spanning July to June) for much of the North Island and eastern South Island, increasingly so with higher radiative forcing scenarios and towards the end of the century. The West Coast, however, shows pronounced delays in the onset of low flow conditions.

- Changes in flow reliability are spatially and temporally variable, with both increases and decreases. Declines are most pronounced for the highest radiative forcing scenario towards the end of the century.

- The mean annual flood (MAF) generally increases with the strength of the radiative forcing and with time, although less for Northland, central Waikato, East Cape and northern Marlborough.

- Changes in mean seasonal soil moisture and soil moisture deficits exhibit both large temporal and spatial variations. From an agricultural use point of view, soil moisture conditions during spring, summer and autumn seasons are expected to remain about the same or become slightly wetter by mid-century for the lowest radiative forcing scenario. With increased radiative forcing and time, soil moisture conditions are expected to become drier in the North Island and in South Canterbury, Otago and Southland. Soil moisture is expected to increase in coastal South and North Canterbury.

- Low soil moisture conditions are generally reached earlier in the year for most of New Zealand, increasingly so towards the end of the century and with higher radiative forcing scenarios.

- Soil moisture reliability tends to decline in the northern and eastern North Island, Tasman, Marlborough and western Canterbury. Soil moisture reliability increases for the West coast and parts of eastern Canterbury.

Table 1-1 summarises the key findings of this report for each administrative region. Late-century end-points for low and high climate change scenarios are presented in Figure 1-1 to Figure 1-4 for changes in mean discharge, mean annual low flow, mean annual flood, and mean summer soil moisture deficit; the changes are relative to the baseline period of 1986-2005. Chapter three provides much greater detail on the change in hydrological statistics, and the variation between models from which inferences can be drawn about consistency and confidence in the projections. These hydrological projections are the most scientifically robust to date and should be used to understand the general patterns and trends of climate change, but they are not without limitations. They are not predictions of what will happen, but are estimates of what may happen depending on changes in radiative forcing (including global emissions and land use change), and based on current understanding of climate and hydrological processes.

**Table 1-1: Main features of hydrological change projections per administrative region.**

| Region Authority | Summary of change |
|---|---|
| Northland Region | Drier conditions are seen across Northland for MALF, the mean and Q5 (flow exceeded 5% of the time) discharges, and for soil moisture, resulting in lower reliability and earlier onset of dry conditions. This contrasts with slight increases in MAF. Spring and summer experience the largest reduction in soil moisture. |
| Auckland | Drier conditions are seen across Auckland for MALF, Q5 discharge, and soil moisture, with lower flow and soil moisture reliability and earlier onset of dry conditions. This contrasts with slight increases in MAF, and somewhat mean discharge. Spring and summer experience the largest reduction in soil moisture. |
| Waikato Region | Waikato shows a regional patchwork of increases and decreases in the various hydrological statistics. Mean and high flows increase while low flows broadly decrease, and reliability of both flow and soil moisture tend to decline. These changes indicate an increase in the variability of hydrological conditions across the region, with extremes becoming more extreme. |
| Bay of Plenty Region | Bay of Plenty shows a mix of wetter and drier conditions, with a tendency towards drier for most statistics, but wetter for MAF. |
| Gisborne District | Gisborne is projected to become drier across river flow and soil moisture statistics alike. MAF shows only a slight increase compared to other regions. |
| Taranaki Region | Taranaki shows mixed hydrological responses to change, with general increases in flows and soil moisture conditions, but also some declines. |
| Manawatu-Wanganui Region | Two overall patterns are seen in the hydrological results: i) the extremes become more extreme – the dry become drier and the wet become wetter –; and ii) there is a west-east gradient in response to climate change with the west tending towards wetter conditions and the east towards drier. |
| Hawkes Bay Region | Across most statistics, Hawke's Bay is projected to become progressively drier, although the severity of change varies within the region. The main exception is that the high flows – Q5 and more so MAF – show increases. |
| Wellington Region | While the MAF is projected to increase, in general, for Wellington, most other hydrological statistics indicate a decline in the availability of water. |
| Tasman District and Nelson City | In general, Tasman District and Nelson City are projected to become drier, in terms of both river flows and soil moisture. However MAF is projected to increase. |
| Marlborough District | Wet and dry conditions are projected to both become more extreme under climate change, particularly for MAF and spring and summer soil moisture conditions. |
| West Coast Region | The West Coast is generally projected to become wetter under climate change, particularly for higher scenarios and late-century. The north of the region, however, shares some properties with adjoining Tasman and is projected to become drier. |
| Canterbury Region | Canterbury exhibits the most complicated response to climate change of all the regions as well as some of the most extreme changes. These include substantial decreases in water availability as well as increases, which are particularly high in south Canterbury; MAF also increases substantially in parts of the region. |
| Otago Region | Otago shows a mix of increases and decreases in water availability, whether river flow or soil moisture. The mean annual flood is also projected to increase substantially in parts of the region. |
| Southland Region | While some area of Southland are projected to become dry for some hydrological statistics, the region is generally projected to become wetter. This is particularly true for the MAF. |

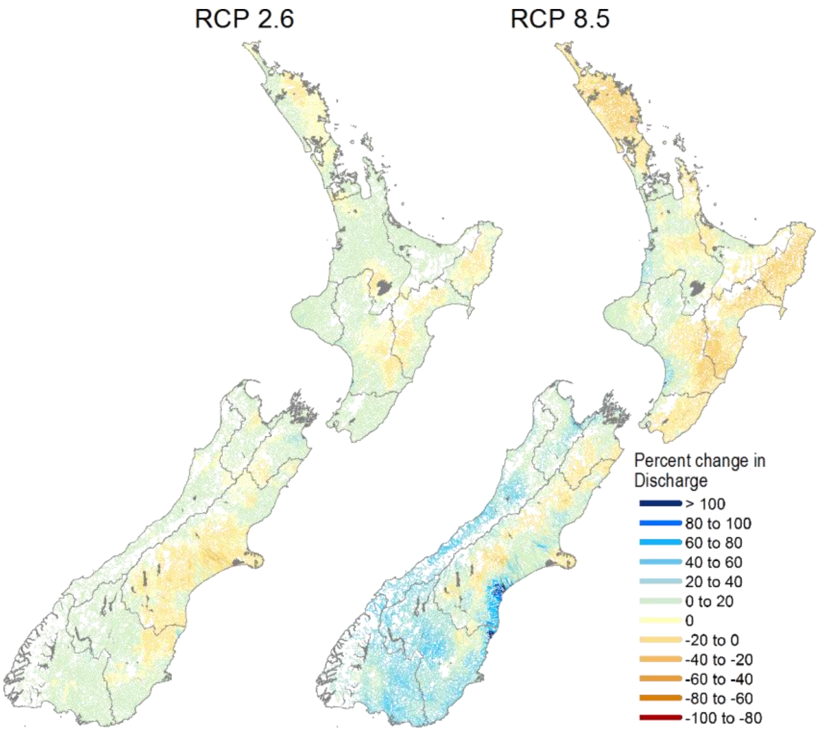


**Figure 1-1: Late-century multi-model median changes (%) in mean discharge for the low (RCP2.6) and high (RCP8.5) climate change scenarios.**

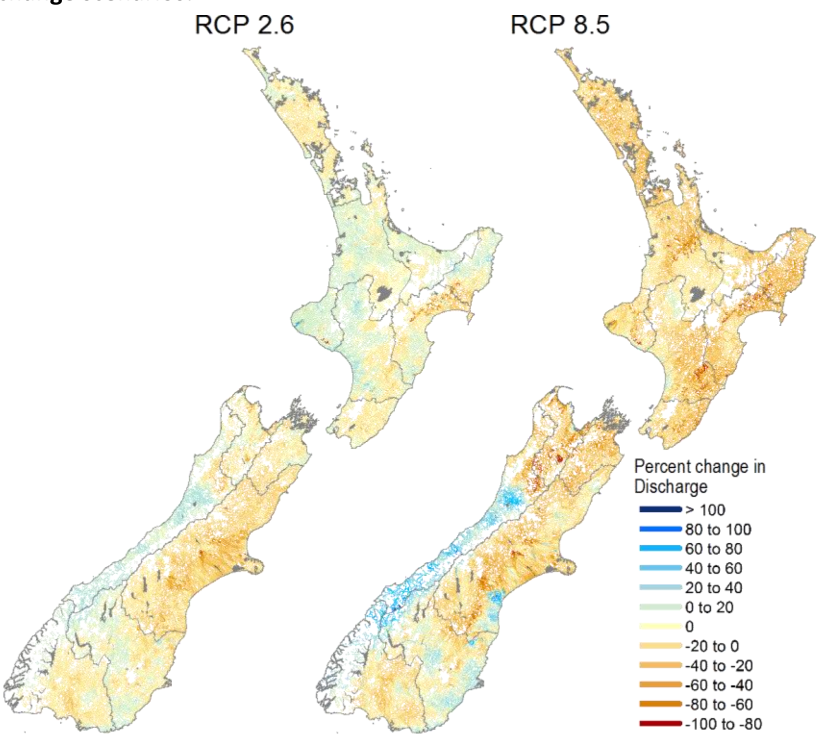


**Figure 1-2: Late-century multi-model median changes (%) in mean annual low flow (MALF) for the low (RCP2.6) and high (RCP8.5) climate change scenarios.**

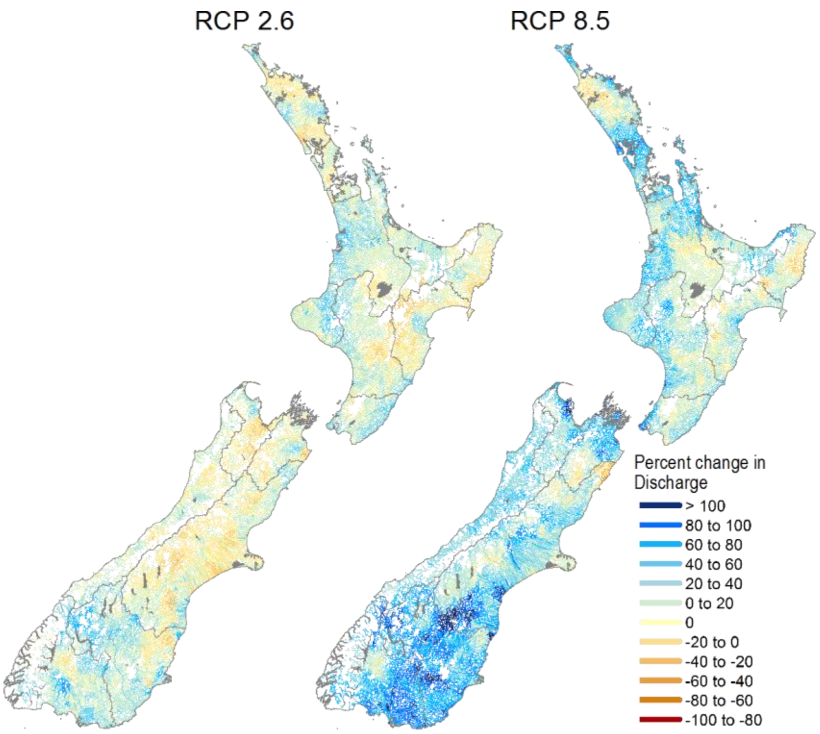


**Figure 1-3:** **Late-century multi-model median changes (%) in mean annual flood for the low (RCP2.6) and high (RCP8.5) climate change scenarios.**

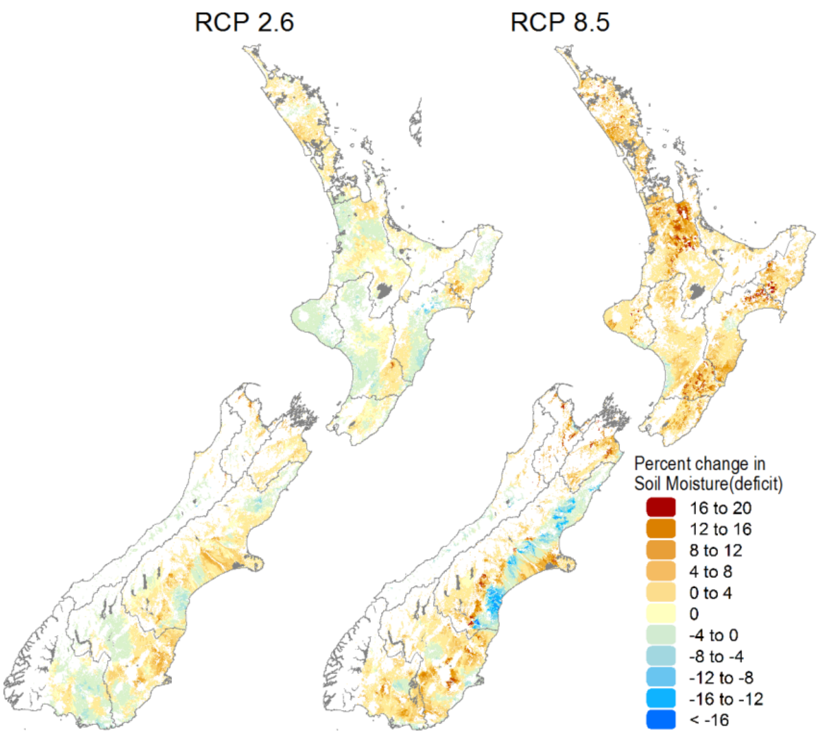


**Figure 1-4:** **Late-century multi-model median changes (%) in mean summer soil moisture deficit for the low (RCP2.6) and high (RCP8.5) climate change scenarios. Negative change equates to wetter soils.**

The implications for agricultural water resource and hazard management vary with the hydrological changes. In most cases water demand is projected to increase, but the opportunity to abstract water in these areas is generally expected to decline, putting greater pressure on water resource management and agricultural productivity. The flood hazard is projected to remain about the same or increase; in some areas the increases are substantial. Increased flood exposure is projected for areas with minimal increases in water shortage as well as severe increases, potentially compounding the challenges faced by local agricultural activities.

# 1 Introduction

Freshwater is important to a wide range of ecosystem goods and services of value to New Zealand, including agricultural activity. As a whole, irrigation is consented to abstract about 2 per cent of New Zealand's total freshwater resource (10 per cent of Canterbury's) and contributes $4.8 billion to New Zealand's real GDP (Collins et al. 2012) (NZIER and AgFirst Consultants NZ 2014). These benefits of freshwater availability to agricultural productivity are particularly tangible when regions experience severe drought. At the other extreme, floods are also of concern to the agricultural sector, cause millions of dollars of damage to infrastructure and soils as well as loss of life (Pearson and Henderson 2004). While these agriculturally related freshwater issues pose challenges today, global climate change and consequent shifts in the hydrological cycle are likely to change agricultural productivity and vulnerability to hazards (Collins et al. 2012; IPCC 2014; Collins and Tait 2016).

Evidence of these shifts is mounting globally (IPCC 2014) and has begun to accrue in New Zealand (Harrington et al. 2014). Temperatures have increased in New Zealand by about 1°C over the past century (Mullan et al. 2010) and are projected to increase further (Ministry for the Environment 2016). Previous assessment based on IPCC4 assessment (IPCC 2007; Ministry for the Environment 2010) estimated that projected hydrological changes include reductions in snow cover (Hendrikx et al. 2012), shrinking glaciers (Anderson et al. 2010), shifts in mean river flow as well as their seasonal timing (Zammit and Woods 2011; Collins 2016), accentuated droughts (Clark et al. 2011) and floods (McMillan et al. 2010), and reductions in groundwater recharge (Aqualinc Research 2008). These will affect both agricultural water demand and supply, but there is as yet no national assessment of such impacts. Furthermore, these projections were made using now-outdated climate change projections, thus there is a need to update the hydrological analysis. This information is vital to understanding the vulnerability of New Zealand's agricultural sector to climate change, how this vulnerability differs across the country and century, and how agricultural activities may adapt to changing water resources.

To provide this information, the Ministry for Primary Industries (MPI) contracted NIWA to estimate what would be the expected future changes in hydrological regimes across New Zealand agricultural landscapes based on the IPCC Fifth Assessment Report (AR5) climate simulations (IPCC 2014). The analysis carried out in this report focuses on changes in river flow and soil moisture statistics. This analysis is expected to serve as a base for targeted assessments of climate change impacts and implications for agricultural resources as part of future MPI projects on Sustainable Land Management and Adaptation under Climate Change.

# 2 Data and methods

Assessing the potential impacts of climate change on agricultural water resources and flooding over the 21st century can best be assessed using continuous hydrological modelling driven by climate change projections from a suite of models. The data, models and methods are described below.

## 2.1 Climate data

The primary input for the hydrological simulations is climate data generated from a suite of Regional Climate Model (RCM) simulations with sea surface forcing taken from Global Climate Models (GCMs). These coupled climate models are driven by natural climate forcing such as solar irradiance and historical and modelled anthropogenic forcing driven by emissions of greenhouse gases and aerosols based on 4 Representative Concentration Pathways (RCPs), but are otherwise free-running in that they are not constrained by historical climate observations applying data assimilation. As part of the fifth IPCC assessment report (AR5) (IPCC 2014), NIWA assessed up to 41 GCMs from the AR5 model archive for their suitability for the New Zealand region. Validation of those GCMs was carried out through comparison with large scale climatic and circulation characteristics across 62 metrics (Ministry for the Environment 2016). This analysis provided performance based ranking based on New Zealand's historical climate. The GCMs were then used by NIWA to drive statistically based regional climate simulations for performing change impact assessments across New Zealand. The six best performing independent models, where projections across all four RCPs were available (van Vuuren et al. 2011), were selected for dynamical downscaling; that is, sea surface temperatures (SST) and sea ice concentrations from the six models are used to drive an atmosphere-only global circulation model, which in turn drives a higher resolution Regional Climate Model (RCM) over New Zealand. The output data fields are bias-corrected relative to a 1980-1999 climatology and subsequently further downscaled to an approximate 5 km grid (Sood 2014). The RCM output (bias-corrected and downscaled to 5 km) is then provided as input to a hydrological model which produces soil moisture and river flow.

The NIWA dynamical procedure effectively involves a free-running atmospheric GCM (AGCM) (i.e., not constrained by historical observations), in this case HadAM3P (Anagnostopoulou et al. 2008), forced by SST and sea ice fields from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Ackerley et al. 2012). Due to the nature of the climate runs for each GCM, year-to-year variability in the models does not correspond with observed variability; they are a deterministic consequence of the initial conditions and the solar and anthropogenic drivers. Further details on the validation of the six GCMs can be found in Sood (2014) and Ministry for the Environment (2016). Model and parameter uncertainty are discussed in section 5.

The downscaled climate data used here run from 1971 to 2100. From 2005 onward, as per IPCC recommendations, each GCM is in turn driven by four RCPs that encapsulate alternative scenarios of radiative forcing and reflect alternative trajectories of global societal behaviour with regard to greenhouse gas emissions and other activities. The range of RCPs used can help shed light on the utility of climate change mitigation. Descriptions and trajectories of the four RCPs are provided in Table 2-1 and Figure 2-1. By mid-century, the temperature trajectory of RCP2.6 is the coolest and RCP8.5 the warmest, with RCP4.5 and RCP6.0 producing intermediate warming. While RCP6.0 ends the century with more forcing than RCP4.5, early and mid-century it is RCP4.5 that has higher greenhouse gas emissions and a stronger radiative forcing; this is somewhat reflected by the mid-century temperature change ranges for the New Zealand seven-station network (Table 2-1). RCP6.0 overtakes RCP4.5 after the middle of century. The climatic and hydrological effects of the RCPs are not simply a linear or monotonic progression from the lowest to highest RCP. Furthermore, the spatial patterns of climatic change across New Zealand are different from RCP to RCP.

**Table 2-1: Descriptions of the Representative Concentration Pathways (RCPs).** Temperature changes are the GCM mean (°C) and, in brackets, the likely ranges.

| Representative Concentration Pathway | Description | Seven-station temperature change (Ministry for the Environment 2016) | | Global surface temperature change for 2081-2100 (IPCC 2014, Table 2.1) |
|---|---|---|---|---|
| | | 2031-2050 | 2081-2100 | |
| RCP2.6 | The least change in radiative forcing considered, by the end of the century, with +2.6 W/m$^2$ by 2100 relative to pre-industrial levels. | 0.7 (0.2, 1.3) | 0.7 (0.1, 1.4) | 1.0 (0.3, 1.7) |
| RCP4.5 | Low-to-moderate change in radiative forcing by the end of the century, with +4.5 W/m$^2$ by 2100 relative to pre-industrial levels | 0.8 (0.4, 1.3) | 1.4 (0.7, 2.2) | 1.8 (1.1, 2.6) |
| RCP6.0 | Moderate-to-high change in radiative forcing by the end of the century, with +6.0 W/m$^2$ by 2100 relative to pre-industrial levels. | 0.8 (0.3, 1.1) | 1.8 (1.0, 2.8) | 2.2 (1.4, 3.1) |
| RCP8.5 | The largest change in radiative forcing considered, by the end of the century, with +8.5 W/m$^2$ by 2100 relative to pre-industrial levels. | 1.0 (0.5, 1.7) | 3.0 (2.0, 4.6) | 3.7 (2.6, 4.8) |

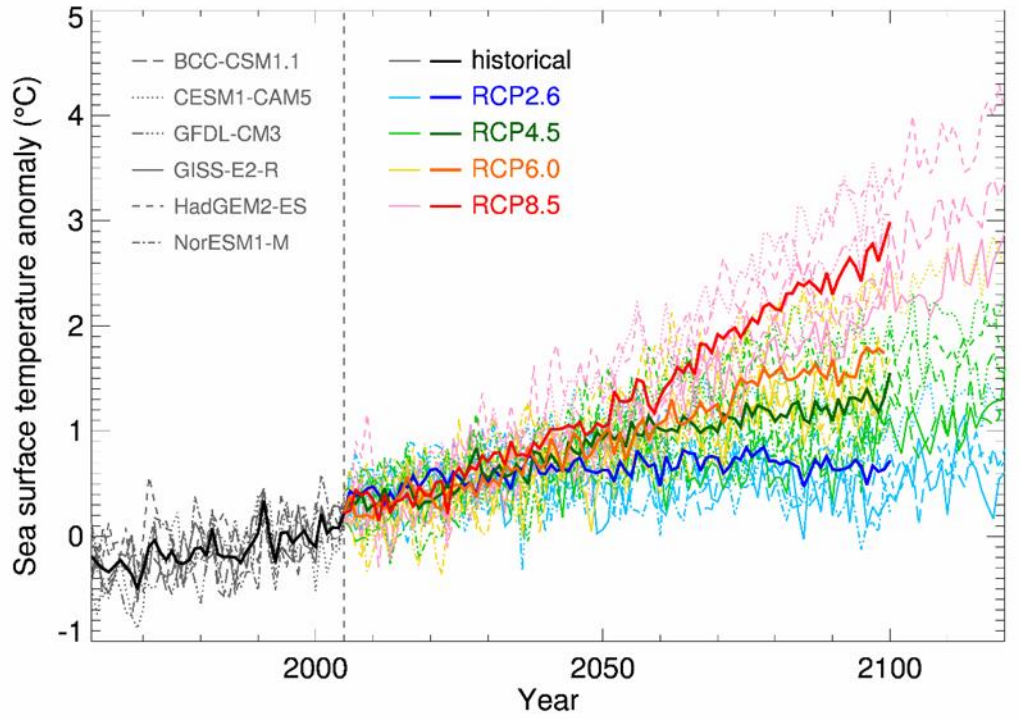


**Figure 2-1: Bias-adjusted SSTs, averaged over the RCM domain, for 6 CMIP5 global climate models (2006-2120), the historical simulations (1960-2005), and four future simulations (RCPs 2.6, 4.5, 6.0 and 8.5), relative to 1986-2005 (Sood 2015).** Individual models are shown by thin dotted or dashed or 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.

## 2.2 Land use coverage

The focus of the present study is on water resources relevant to agriculture, specifically water supply and soil moisture conditions. Results are reported only for parts of New Zealand that correspond to agricultural and irrigable land uses. Drawing from the Land Cover Database (LCDB v.2, Newsome et al. 2000) these include:

- Short-rotation cropland;
- Orchard, vineyard and other perennial crops;
- High-producing exotic grassland;
- Low-producing exotic grassland; and
- Depleted grassland.

Depleted grassland is included as it may have been or may once more serve as agricultural land. The full extent of these land uses is depicted in Figure 2-2, with a total area of 111,485 km$^2$. TopNet is currently configured to use LCDB v.2, reflecting 2001 land cover, rather than the latest version, version four, which corresponds to 2011. There will be differences in land use between the two, and these may have hydrological consequences, although they are likely to be small in comparison with changes up to 2100. During the course of the simulations from 1971 to 2100, however, land use is kept constant. The purpose of this is to isolate the effects of changing climate on the hydrological response; incorporating land use changes would confound interpretation of the results.

When reporting results for tracts of land, only the agricultural areas are presented. While both agricultural and non-agricultural land is modelled only river reaches that have some agricultural land in their immediate watersheds are presented in this report. The rationale for this is that water for irrigation or storage is most likely to be taken from the closest river; accounting for longer water transfers and anticipating future water abstraction patterns is beyond the scope of the present study. Given that there are many small areas of potential agricultural land across New Zealand, this means that the river-based maps presented in the results will appear to cover a larger area than the soil moisture maps.

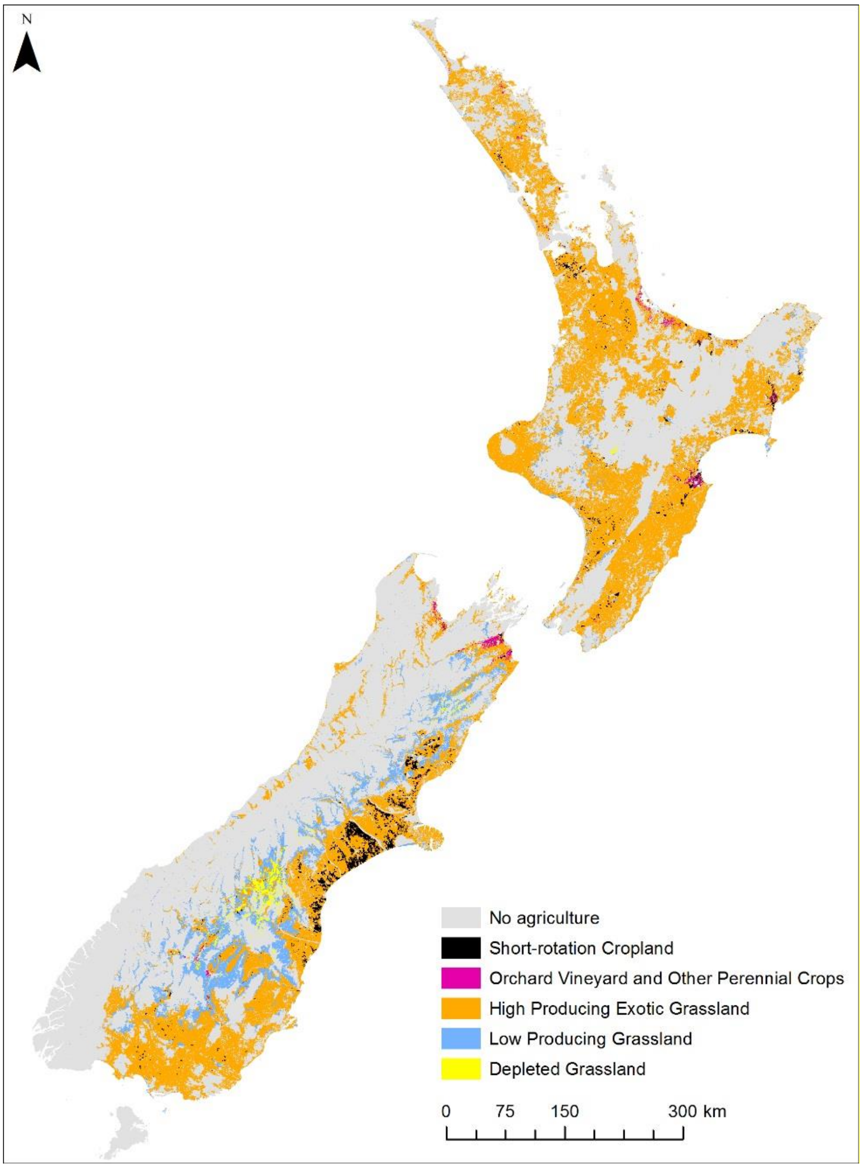


**Figure 2-2: Agricultural land covers based on the LCDB version 2 (Newsome et al. 2000).** Note however that there are many small areas of potential agriculture that cannot be seen at this scale. These affect the inclusion of rivers when discussing flow statistics.

## 2.3 Modelling

In order 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 used in this study is TopNet (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 TopNet used in this application, spatial information in TopNet is provided by national datasets as follows:

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

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

To carry out the simulations required here, TopNet is run continuously from 1971 to 2100, with the spin-up period 1971 excluded from the analysis. The climate inputs (briefly described in section 3.1) are stochastically disaggregated from daily to hourly time steps. As the GCM simulations are "free-running" (based only on initial conditions, not updated observations after 1971) we can ensure that comparisons between present and future hydrological conditions can be made directly (i.e., apples with apples- 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 version 1 network aggregated up to Strahler[1] catchment order three (approximate average catchment area of 6 $km^2$) to reduce simulation times and data sizes to manageable levels while still providing useful information; residual coastal catchments of smaller stream orders remain included. For the current application simulations are carried out across 43,862 catchments at hourly time steps generating over 270 TB of model results. The simulation results 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 output data only river flows and soil moisture information were preserved; all the other state variables and fluxes are available on demand once regenerated.

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 agricultural land uses.

## 2.4 Analysis

The model results are analysed in order to highlight the important changes in agricultural water resources and flooding due to climate change. In consultation with MPI and in light of preliminary results 10 hydrological statistics were selected for reporting. Each statistic is derived from the two modelled projection periods spanning 2036 to 2055 (‘mid-century’) and 2086 to 2099 (‘late-century’), as well as the ‘baseline' period spanning 1986 to 2005 as per IPCC AR5 guidelines (IPCC 2014). The second projection period is cut short of the recommended 2105 end of time slice year as several GCM-RCP combinations are not available from 2100 onwards (Ministry for the Environment 2016). Results for each RCP are summarised across the six GCMs. Strahler order 3 catchments that contain no agricultural land are excluded from the analysis.

The ten statistics are:

1. Mean river flow – River flow averaged over the period of analysis.
2. Mean annual low flow (MALF) – The mean of the lowest 7-day average flows in each year of a projection period.
3. Low flow timing – The mean number of days into the water year (i.e., after July 1, until June 30 the following year) before discharge first drops to a minimum flow threshold related to water abstraction. This threshold is based on the Proposed National Environmental Standard for Ecological Flows (Ministry for the Environment 2008):

$$Q_{min} = \begin{cases} 0.9 \times MALF, \bar{Q} \leq 5m^3/s \\ 0.8 \times MALF, \bar{Q} > 5m^3/s \end{cases}$$

While this method has not been put into practice everywhere, it does provide a means of assessing low flow conditions everywhere in the country under the same policy assumptions.

4. Flow reliability – The fraction of time that the flow is equal to or below the NES minimum flow threshold as defined previously, and in this case without accounting for any water takes.

[1] 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.

This ranges from 0 to 1 (or 0 to 100 per cent) and is often between 0.9 and 1.0 for New Zealand's rivers.

5. Mean annual flood (MAF) – The mean of the largest peak flows for each year. For New Zealand rivers, this flow is typically exceeded less than one per cent of the time and has a return period of between two and three years.
6. Q5 – The river flow exceeded five per cent of the time. This is typically a lower flow than the mean annual flood.
7. Mean seasonal soil moisture – The mean soil moisture, calculated separately for each season.
8. Mean soil moisture deficit – The mean difference between the varying soil moisture and the soil's field capacity, calculated separately for each season. This is always positive and is a measure of the severity of water deficits and agricultural droughts.
9. Low soil moisture timing – The mean number of days into the water year (i.e., after July 1, until June 30 the following year) before the soil moisture first drops to a dry threshold, here designated as above wilting point by 25 per cent of the difference between wilting point and field capacity. This is an indication of how quickly water deficits or droughts are reached after winter.
10. Soil moisture reliability – The fraction of time that unirrigated soil moisture is at or below the soil moisture threshold used for the low soil moisture timing. This is a measure of the time spent under water-short or drought conditions.

The change in these 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 a multi-model median (discussed below), and the results of the RCPs are kept separate. This provides eight maps for each statistic, representing median changes in that statistic between baseline and mid-century and baseline and late-century. All maps for each statistic are displayed on a single page for ease of comparison. Results are reported for each of New Zealand's 16 administrative regions alongside a national assessment. Changes in hydrological statistics are reported for the lower end of river reaches that have potential agricultural land uses within their catchment, while change in soil moisture statistics are reported on the surface water catchments where agricultural activities are present.

In reporting the hydrological changes, neither the statistical nor agricultural significance of the changes are assessed here. Large changes may not be statistically significant if the variability among GCMs is comparatively large. And equivalent changes in two different places may not be equally significant in agricultural terms because this depends on the magnitude of the local dependence of agriculture on that hydrological statistic.

Analysis is focused on describing the hydrological changes. Results are also discussed in the context of Ministry for the Environment (2016), drawing connections between reported changes in climatic and hydrological statistics.

### 2.4.1 Multi-model averaging: mean versus median

One of the important elements of climate change projections is the use of multiple different GCMs. Each GCM is in essence a plausible representation of the climate system as far as a particular research group is concerned. Using a suite of different GCMs allows us to compensate somewhat for uncertainties in climate science; the central tendency or 'multi-model average' of the suite of GCM results may be considered the most plausible climate change outcome. In statistics, however, there is no single definition of 'average' – it depends on how one defines the "centre". The most commonly used measure of average is the 'mean', calculated as the sum of a series of numbers divided by the number of numbers. The 'median' is another kind of average and describes the middle-most number (i.e., half of the numbers are above the median and half are below the median). Lastly, the 'mode' is the value that occurs most often. Each type of average has its place depending on the nature of the data and the insights being sought from the data.

In climate science multi-model averages have more often been represented as means, and this has been the case for the key studies in New Zealand (e.g., Ministry for the Environment 2016), but multi-model medians have also been used internationally (e.g., IPCC 2014). The mean is reasonable if the distribution of a dataset is normal (or Gaussian), but for hydrological variables (particularly soil moisture and discharge) normal distributions may not be a good approximation. Furthermore, the median gives a truer indication of the central tendency when decisions are to be made based on likelihood (i.e., 50 per cent chance that the results will be greater than the median and 50 per cent chance they will be lower) as they are less affected by outliers, which is more appropriate when averaging across alternative representations of reality and aligns better with the IPCC's use of likelihood percentages. As a result, multi-model averages will be represented in this report as medians.

# 3 Results

Changes in the statistics are presented as multi-model medians calculated across GCMs. This applies across the four RCPs and two projection periods (mid- and late-century). Results are grouped by region, and summarised at the national scale then for each region. Both patterns and trends are derived visually from finer resolution equivalents of the maps produced here; the colour scales are the same. Only qualitative descriptions are provided, not quantitative.

## 3.1 National

### 3.1.1 Mean flow

Median changes in the mean flow are presented in Figure 3-1. Mean discharge exhibits a sub-regional patchwork of increases and decreases, depending on the RCP and projection period. Most of the North Island (except Northland and East Cape) is projected to have increased flows by mid-century under RCP2.6. By the end of the century, areas experiencing decreased discharge are projected to expand across most of the North Island under the higher scenarios, except for western portions of Waikato, Taranaki, Manawatu-Wanganui and Wellington where slight increases in mean flow are expected. The South Island is also expected to move towards slight increases in mean flow by mid-century under RCP2.6, with localised pockets of decreases in eastern inland areas from Marlborough south to Otago. There are slight expansions in the lower-discharge areas with higher scenarios. By the end of the century, reduced mean flows are expected for the inland-east, northeast of the South Island, with the area affected contracting with higher scenarios. Mean flow is projected to increase for most of the remaining areas of the South Island, with some increases of 50-100 per cent and above for the higher scenarios. The lower reaches of large catchments tend to reflect changes in their (typically wetter) headwaters rather than resembling the changes of the shorter lowland neighbouring rivers (e.g., Canterbury, Manawatu-Wanganui, and Marlborough).

### 3.1.2 Mean annual low flow

Median changes in the MALF are presented in Figure 3-2. Changes exhibit a different spatial pattern from the changes in mean annual flow, indicating a change in the distribution of different flows at each river reach. Increases in MALF are generally restricted to western North Island under RCP2.6, and western and south-eastern South Island for all scenarios, but decreases are also projected for parts of these regions. Decreases in MALF are most severe, in percentage terms, in parts of Canterbury, Manawatu-Whanganui, Hawke's Bay, and Waikato regions, and for RCP8.5. By the end of the century, mean annual low flows are expected to decrease substantially across all scenarios in the North Island. Large decreases in MALF are expected in the east part of the North Island as well as Northland-Auckland and lower Waikato. The analysis is more contrasted for the South island where large reductions of MALF are expected with higher scenarios in Marlborough, North and mid Canterbury. Higher MALFs are expected on the southern West Coast, and some areas of coastal South Canterbury and inland Otago under most scenarios. In contrast with the mean discharge, the lower reaches of large catchments reflect the local shorter river patterns instead of their headwater changes.

### 3.1.3 Low flow timing

Median changes in the timing of low flow conditions are presented in Figure 3-3. Low flow conditions are reached earlier after winter for all scenarios and time periods over a large fraction of New Zealand. Exceptions include the West Coast and will be discussed further in the regional sections below. There is little difference among multi-model medians except that RCP8.5 reaches the low flow threshold even earlier.

### 3.1.4 Flow reliability

Median changes in flow reliability are presented in Figure 3-4. Flow reliability exhibits both increases and decreases across New Zealand depending on the scenario and time period. The spatial extent of changes in flow reliability is different from those of change in MALF, highlighting the importance of using the low flow metrics appropriate to the application. The divergence between MALF and flow reliability may stem from a number of causes. Percentage changes in MALF are not directly related to absolute changes in reliability, in part because reliability is assessed relative to baseline minimum flow thresholds, and in part because the thresholds are a function of both MALF and mean discharge. More areas show decreases across all RCP-time period combinations than they do increases, and the decreases tend to be more pronounced late-century under the higher RCPs, particularly inland Canterbury, Marlborough, and Waikato. Some areas within Canterbury are also the areas of the largest increases in flow reliability, particularly south Canterbury, and the major Alps-draining rivers tend to reflect changes in their alpine source areas rather than their low-land neighbours.

### 3.1.5 Mean annual flood

Median changes in the mean annual flood (MAF) are presented in Figure 3-5. Overall, the simulations indicate increases in MAF for most of the country's agricultural areas, with only slight reductions in the rest. The percentage increases tend to be greater for the more extreme RCPs and late-century, with swathes of particularly large increases in several parts of the country depending on the RCP and time period: south Auckland down to west Waikato; central Manawatu-Wanganui; southern Hawke's Bay; and much of Canterbury, Otago and Southland. The substantial increases observed in Southland are the most consistent late century.

### 3.1.6 Q5 discharge

Median changes in the Q5 discharge are presented in Figure 3-6. The Q5 discharge generally increases along the west of the South Island and southern Canterbury for all scenarios and time periods, with the exception of northern West Coast and Tasman. Southern South Island and western North Island show increases for some scenarios and time periods, but not all. The remainder of the North Island, the north of the South Island, and inland Canterbury and Otago show decreases. The decreases are most widespread and extreme for RCP8.5 during the latter part of the century; the increases in the South Island are also the largest. The differences between the Q5 discharge and the mean annual flood reflect the latter's sensitivity to increases in storm intensity, whereas Q5 retains a substantial influence from longer-term catchment water balance; it is merely a higher-than-average flow rather than a flood and typically smaller than bank-fill flow.

### 3.1.7 Mean seasonal soil moisture

Median changes in mean seasonal soil moisture are presented in Figure 3-7 to Figure 3-10. Shifts in mean seasonal soil moisture conditions show distinct patterns regionally among seasons, time periods and RCPs, and no season exhibits consistent shifts in one direction. Change in summer mean soil moisture (Figure 3-7) shows the most extreme changes of all the seasons, with many regions becoming drier, particularly in the North Island (in general, but not all time-RCP combinations). Parts of Marlborough, Canterbury and Otago also show consistent and substantial wetting, becoming more extreme for higher scenarios late-century. Change in autumn mean soil moisture (Figure 3-8) sees swathes of both islands become wetter or drier, and the same parts of Canterbury become notably wetter. During winter (Figure 3-9), soils almost everywhere tend to become wetter, particularly for Otago and southern Canterbury, but not for the north and east of the North Island which become drier; portions of Otago and south Canterbury become particularly wet late-century under RCP8.5. By mid-century spring (Figure 3-10) soils tend to be drier for northern and eastern parts of the North Island and inland and north-eastern parts of the South Island; this becomes more pronounced late-century and for higher scenarios. Soil moisture conditions tend to be drier mid-century for RCP4.5 than RCP6.0, reflecting the warmer temperatures in the former for this time period.

### 3.1.8 Mean seasonal soil moisture deficit

Median changes in mean seasonal soil moisture deficits are presented in Figure 3-11 to Figure 3-14. Note the reversal of the colour bar as a decrease in soil moisture deficit is a wetter outcome. Patterns of soil moisture deficit closely resemble those for soil moisture for all seasons, time periods and RCPs, only with slight differences in magnitude. Extreme changes in soil moisture deficit (either positive or negative) are less extensive for all seasons. Change hotspots include portions of Canterbury, with lower deficits, and Waikato and Hawke's Bay, with higher deficits.

### 3.1.9 Low soil moisture timing

Median changes in low soil moisture timing are presented in Figure 3-15. Low soil moisture conditions are generally reached earlier in the year for most of New Zealand, particularly in the north and east of the North Island and the north and southeast of the South Island. Low soil moisture conditions are reached earlier in the year with higher scenarios. However, there are areas expected to reach dry conditions later; while scattered in small pockets across many regions, they are most pronounced in the West Coast and southern Canterbury.

### 3.1.10 Soil moisture reliability

Soil moisture reliability (Figure 3-16) tends to decline in northern and eastern North Island (including northern parts of Waikato), Tasman, Marlborough, and western Canterbury. In the West Coast and parts of eastern Canterbury, soil moisture reliability increases.

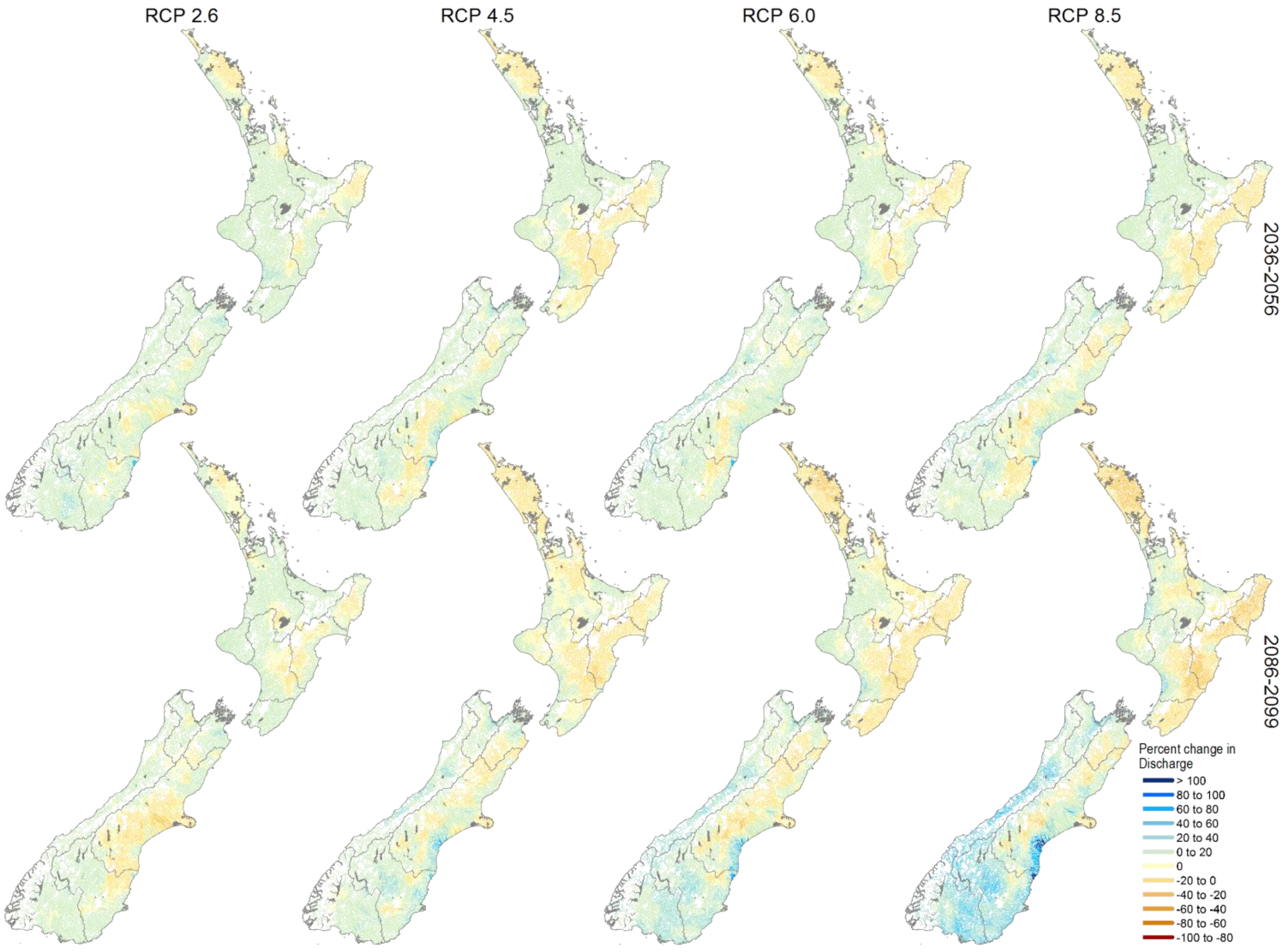


**Figure 3-1: Multi-model median changes in mean discharge (%).**

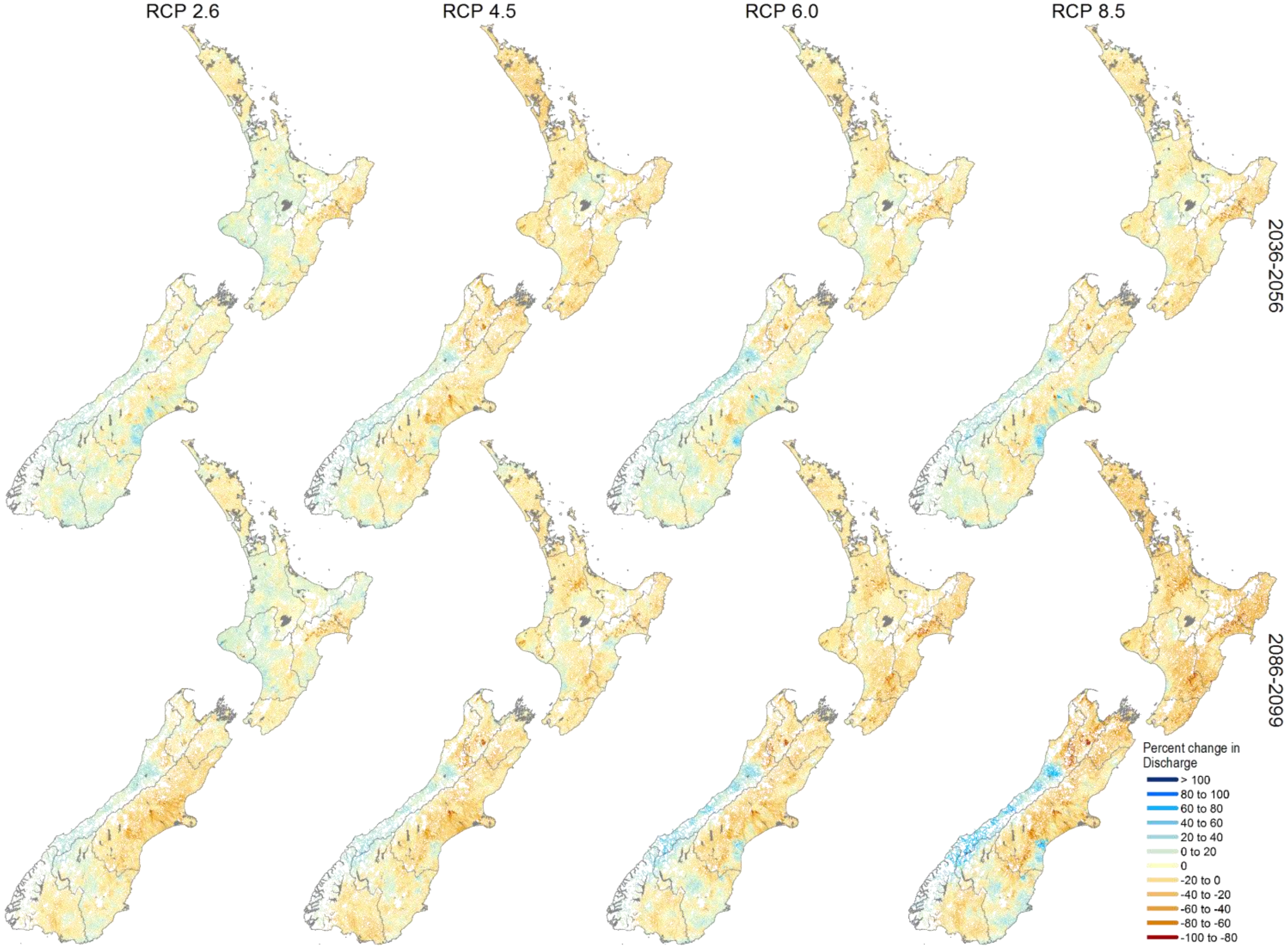


**Figure 3-2: Multi-model median changes in mean annual low flow, MALF, (%).**

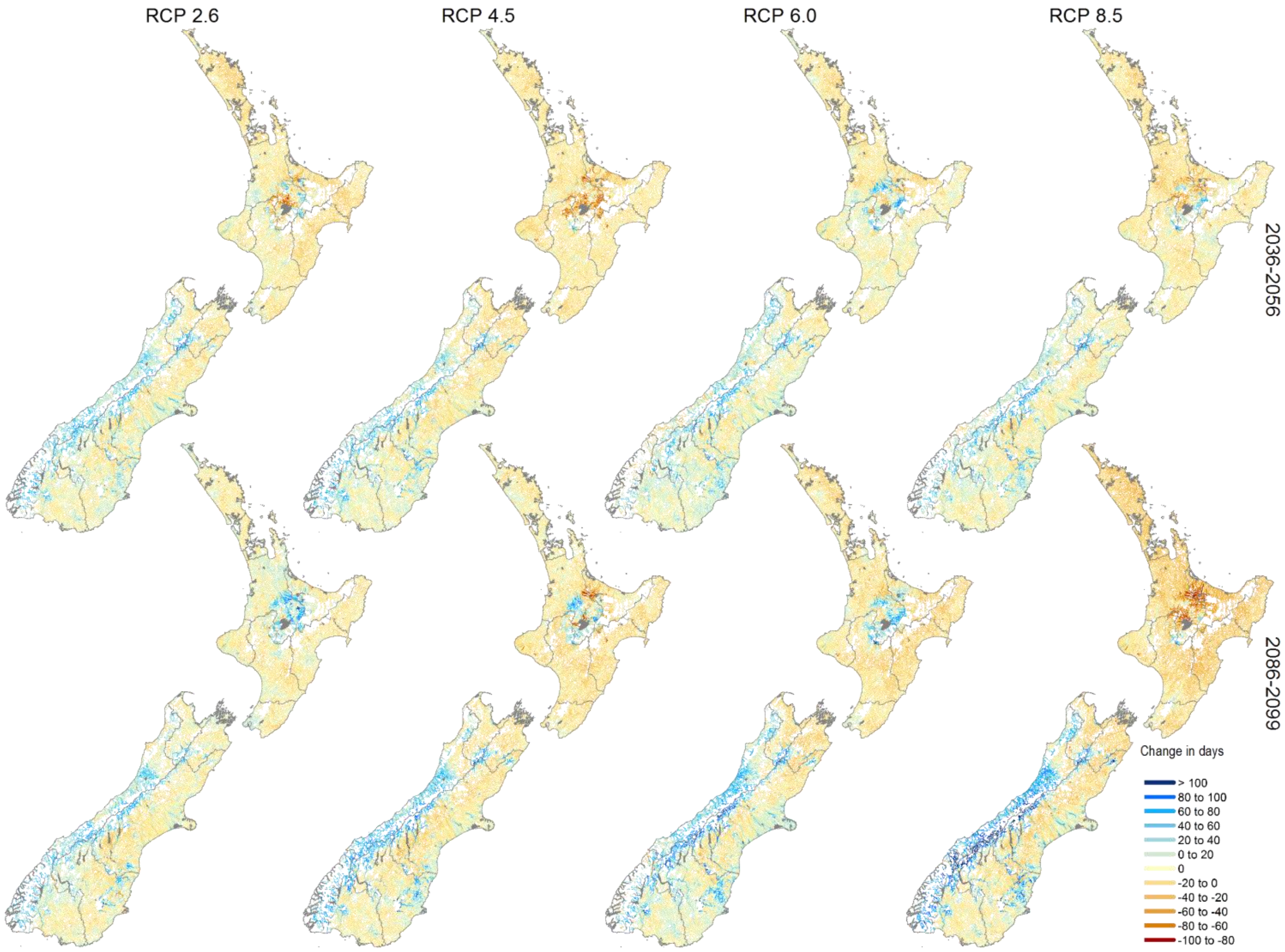


**Figure 3-3: Multi-model median changes in low flow timing (days).**

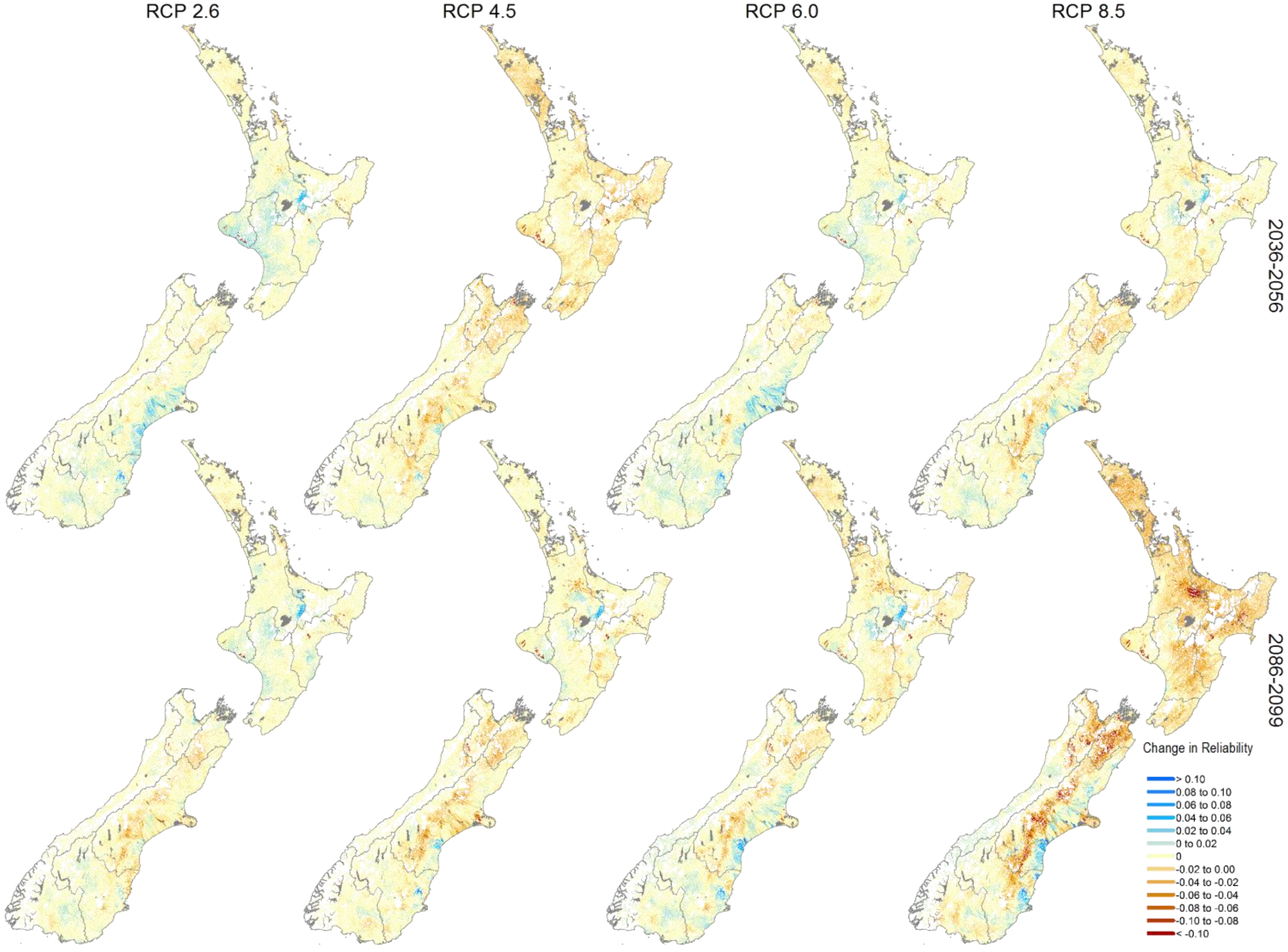


**Figure 3-4: Multi-model median changes in flow reliability.**

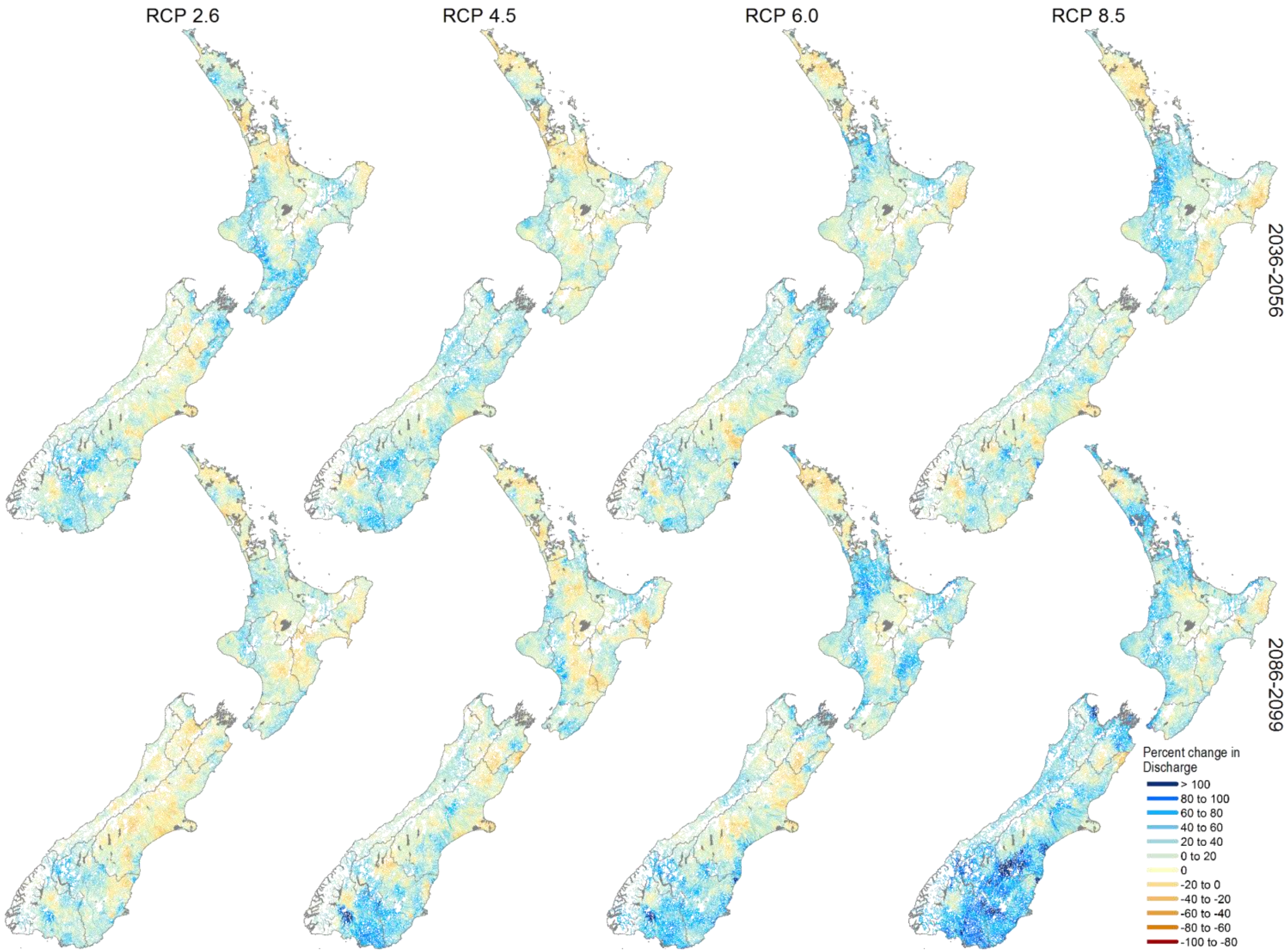


**Figure 3-5: Multi-model median changes in mean annual flood, MAF, (%).**

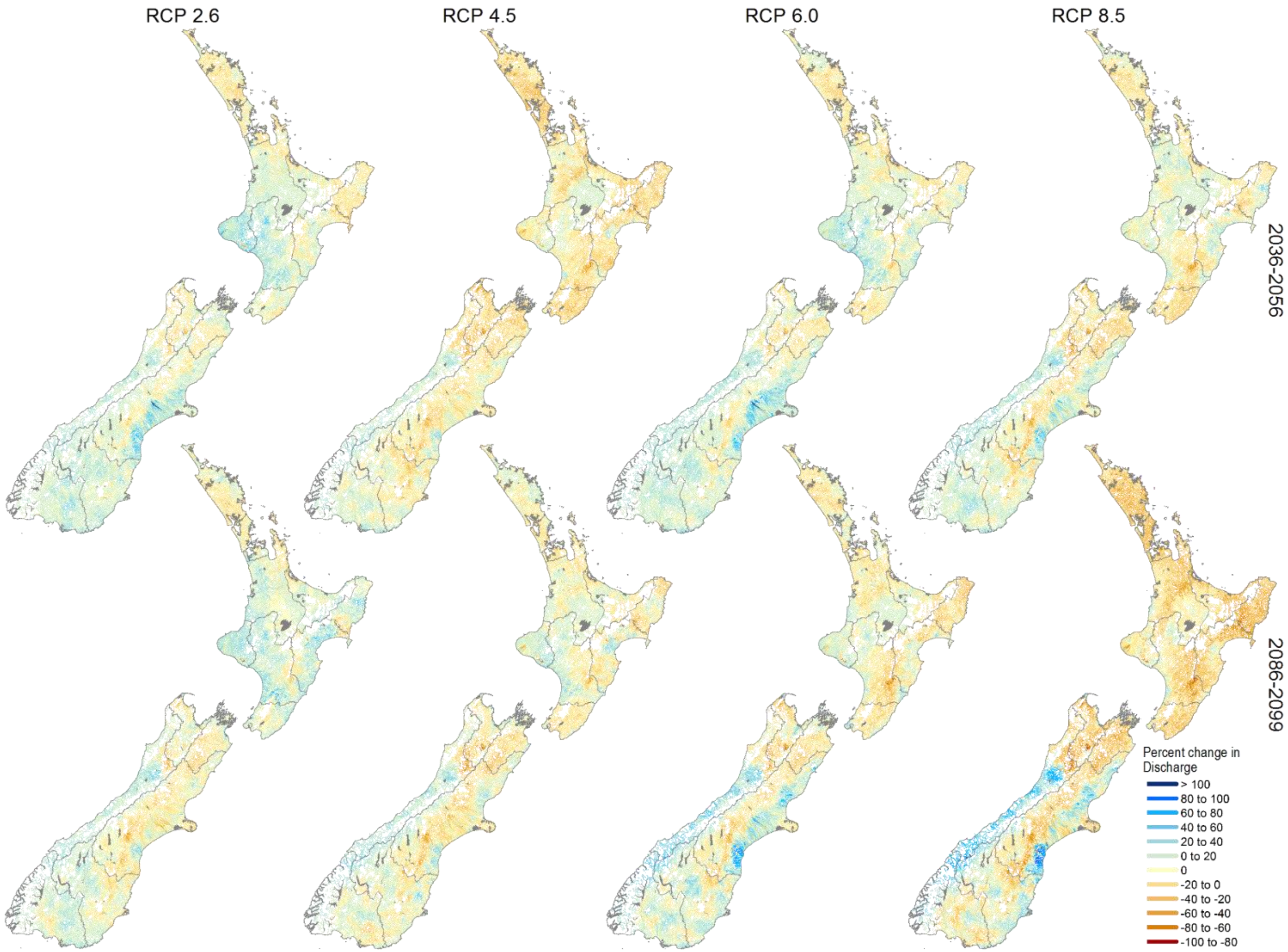


**Figure 3-6: Multi-model median changes in the Q5 discharge (%).**

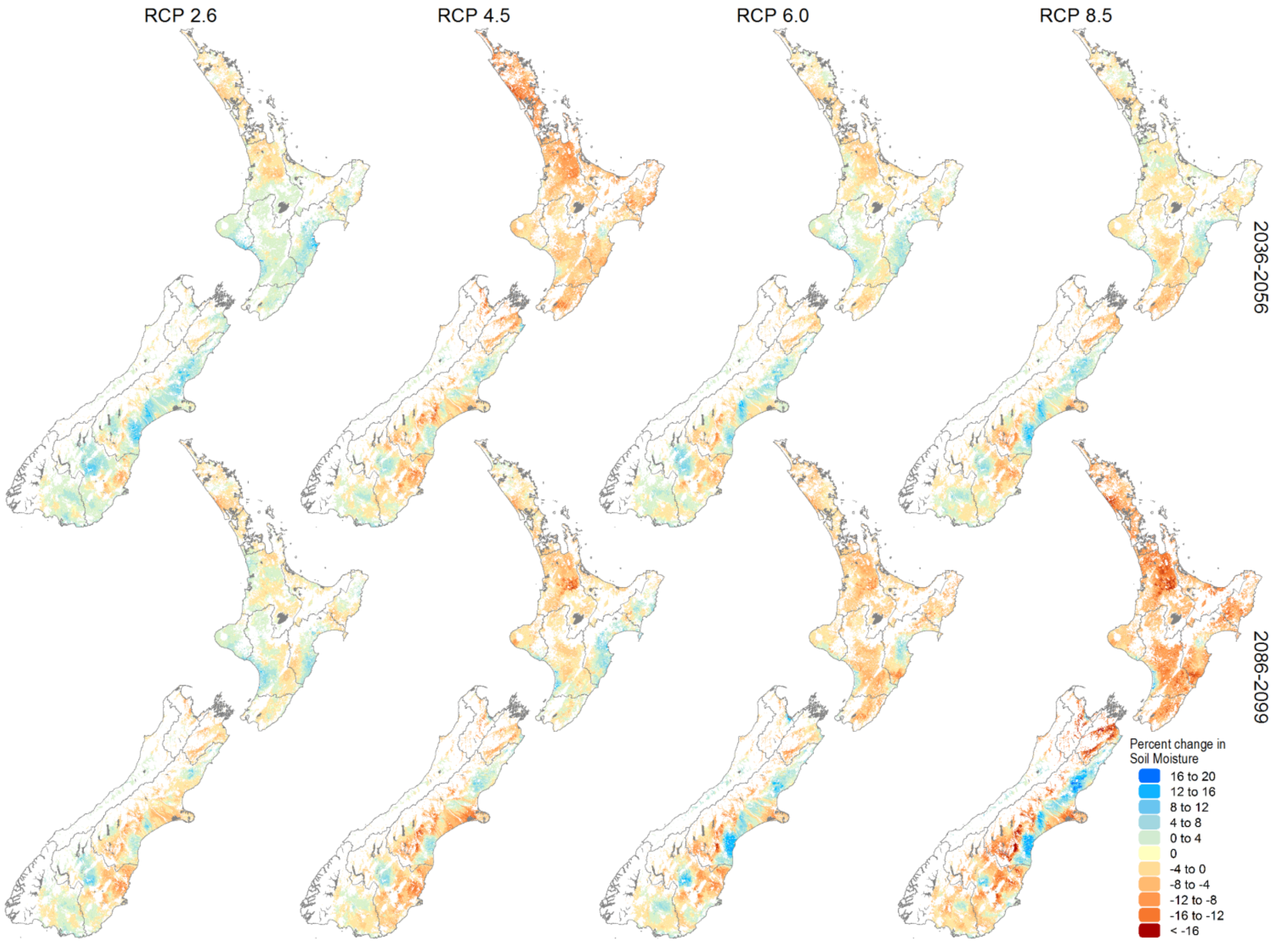


**Figure 3-7: Multi-model median changes in mean summer soil moisture (%).**

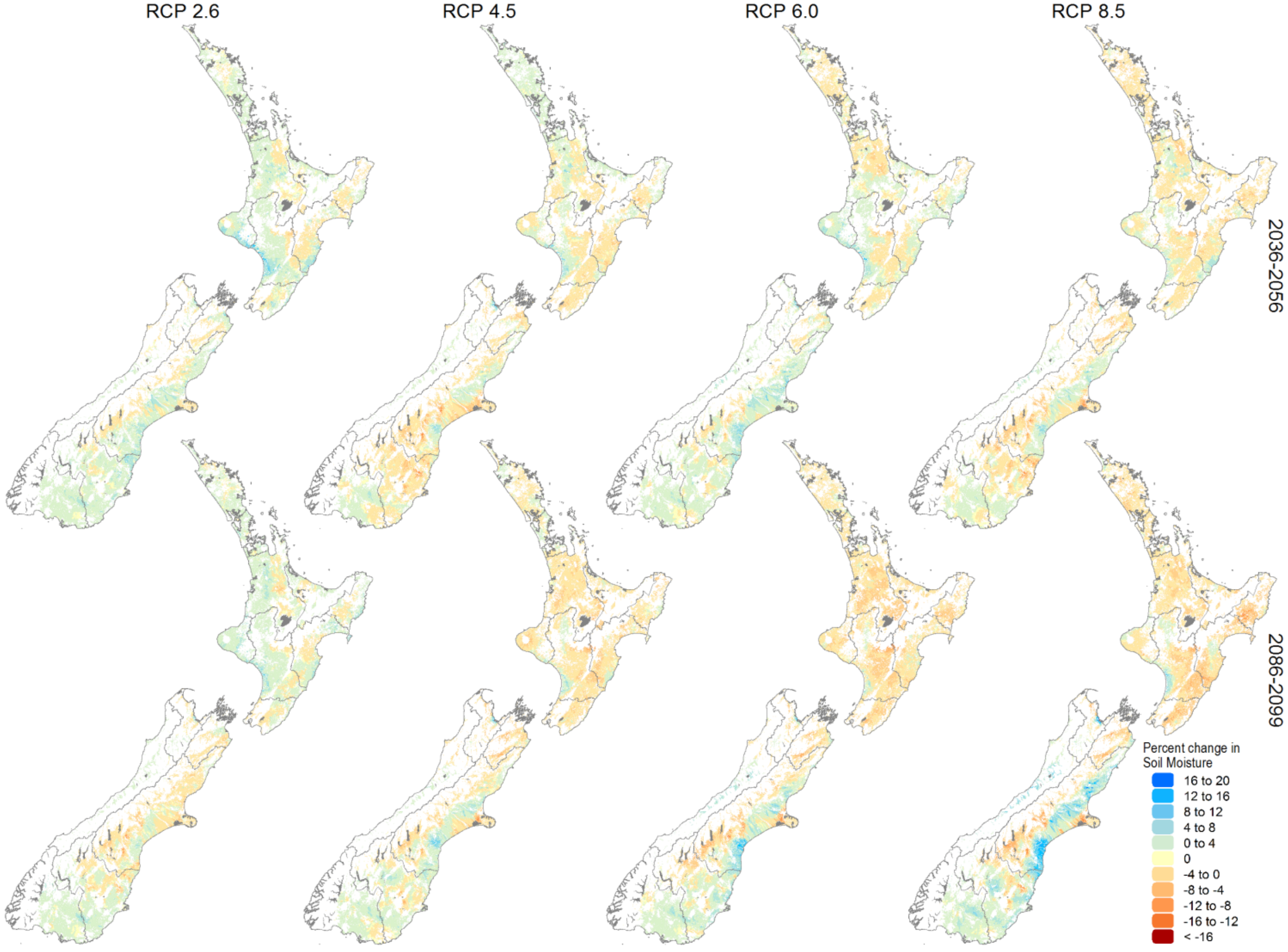


**Figure 3-8: Multi-model median changes in mean autumn soil moisture (%).**

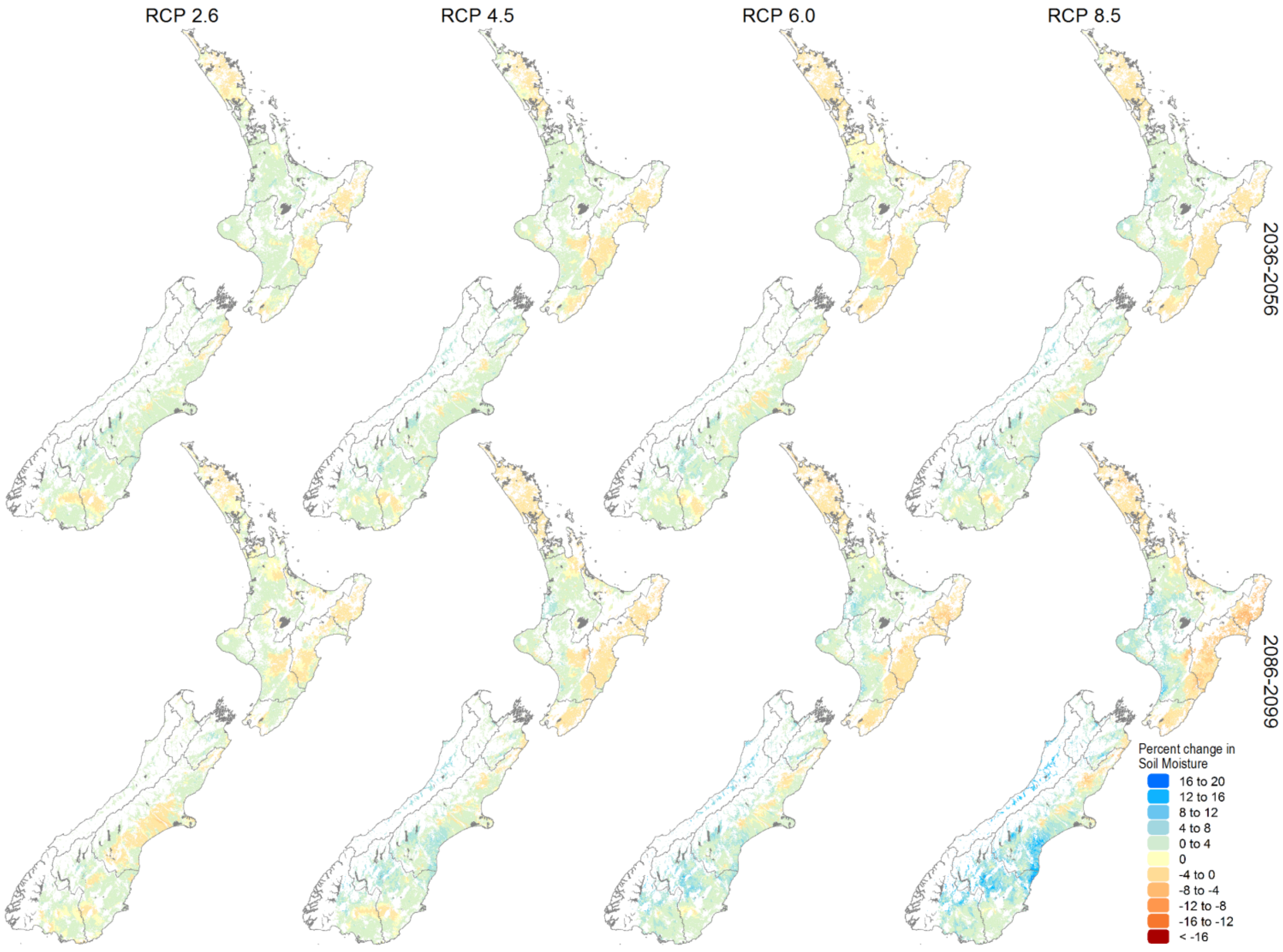


**Figure 3-9: Multi-model median changes in mean winter soil moisture (%).**

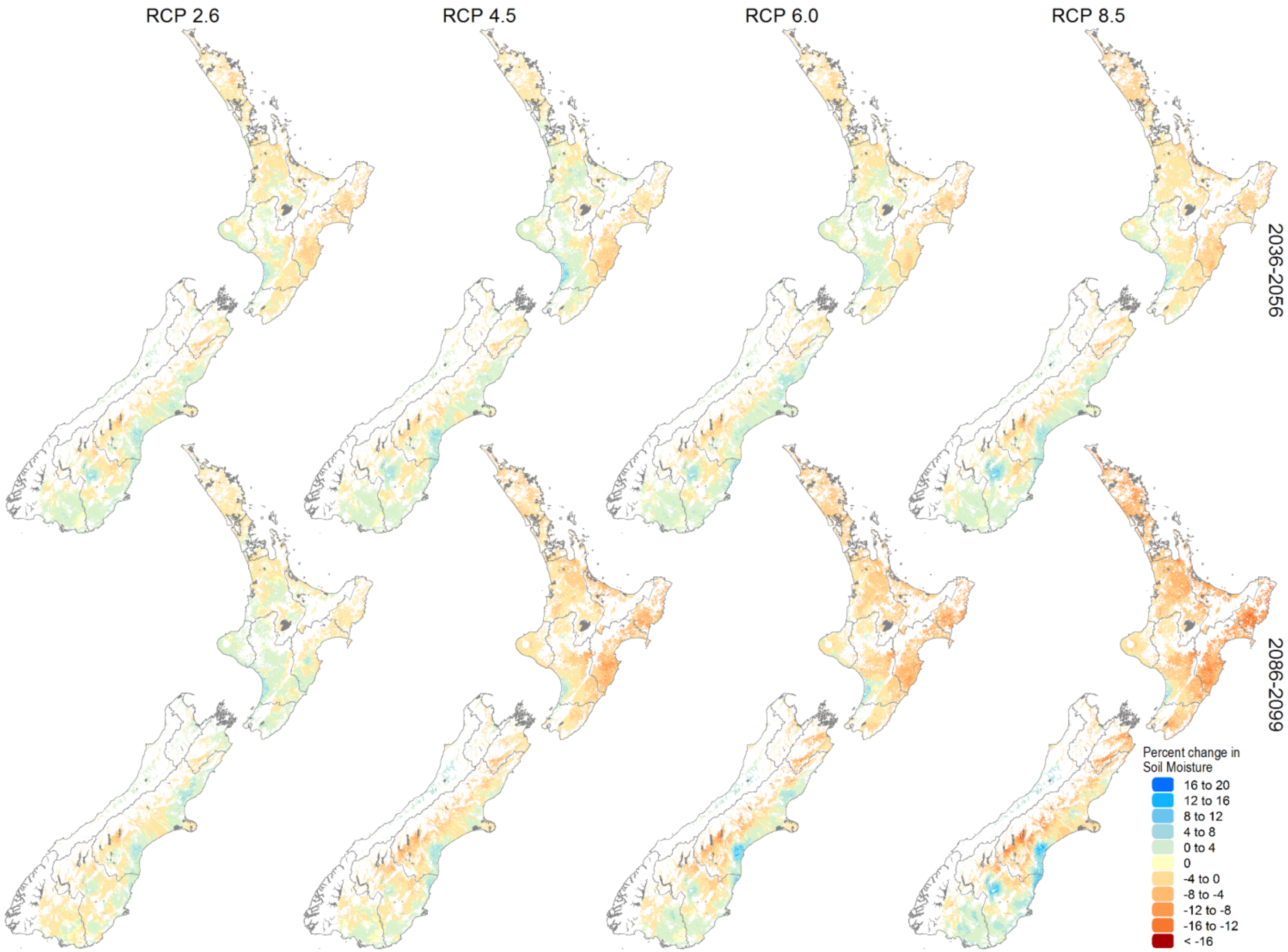


**Figure 3-10: Multi-model median changes in mean spring soil moisture (%).**

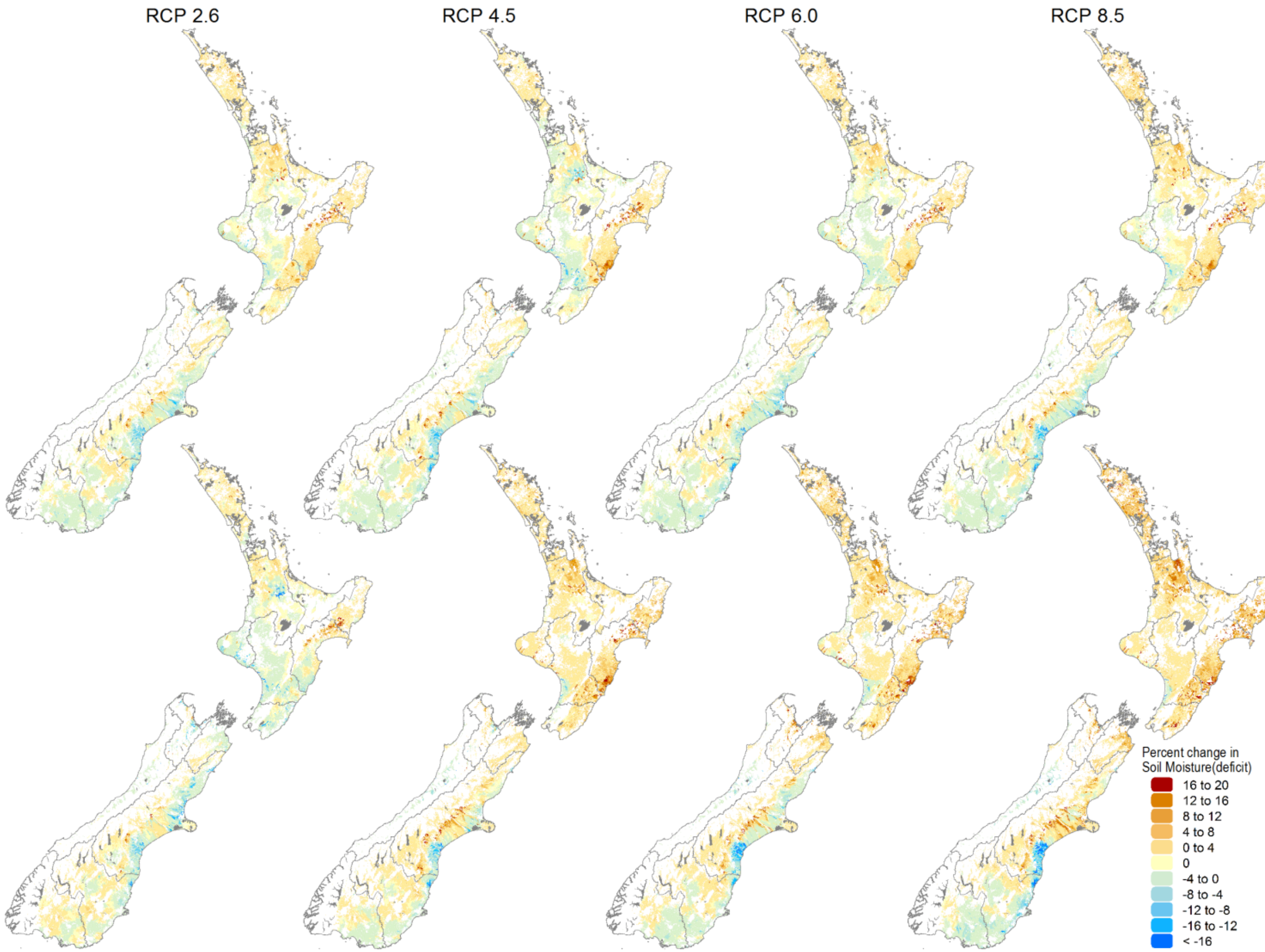


**Figure 3-11: Multi-model median changes in mean summer soil moisture deficit (%).**

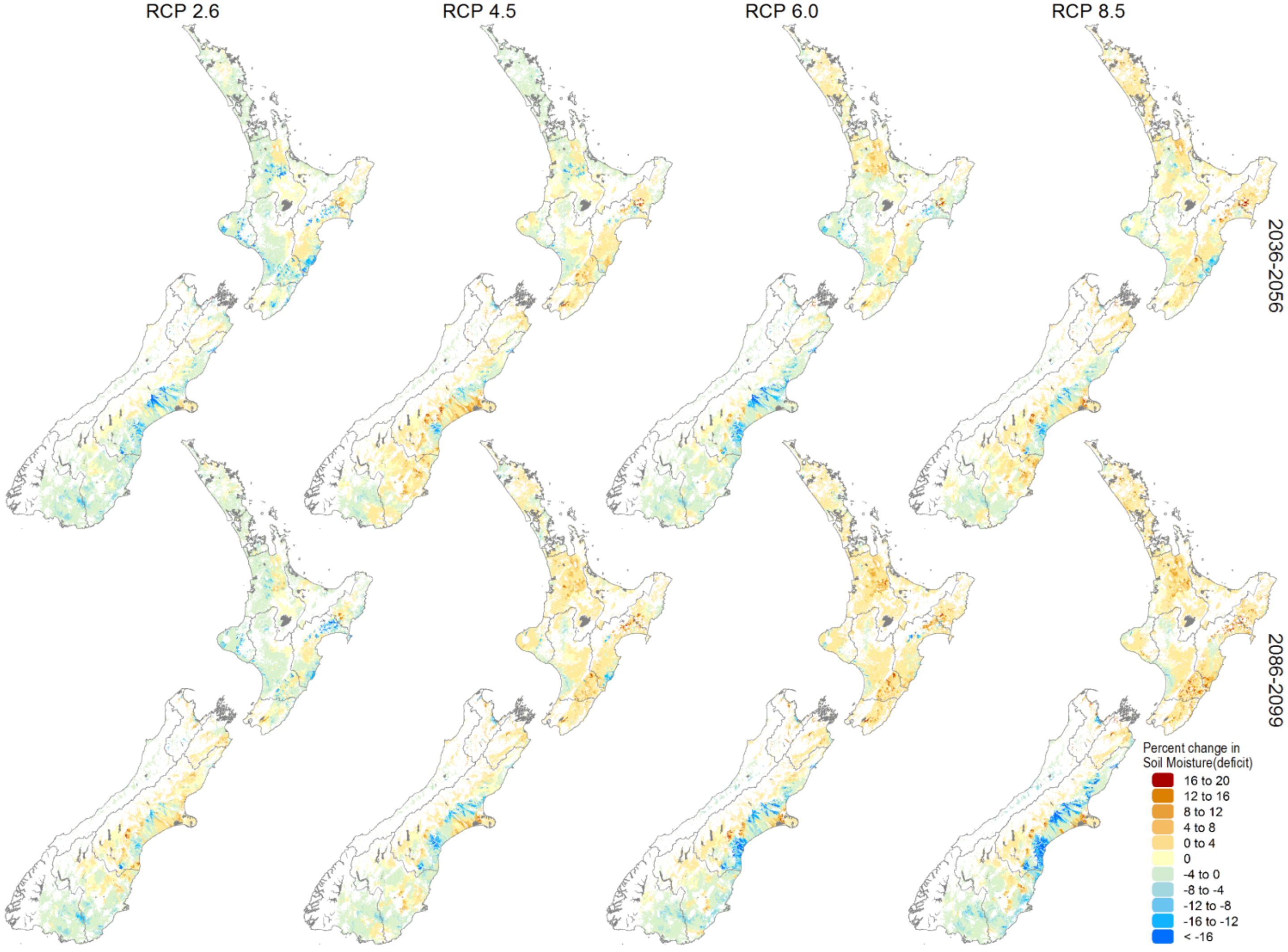


**Figure 3-12: Multi-model median changes in mean autumn soil moisture deficit (%).**

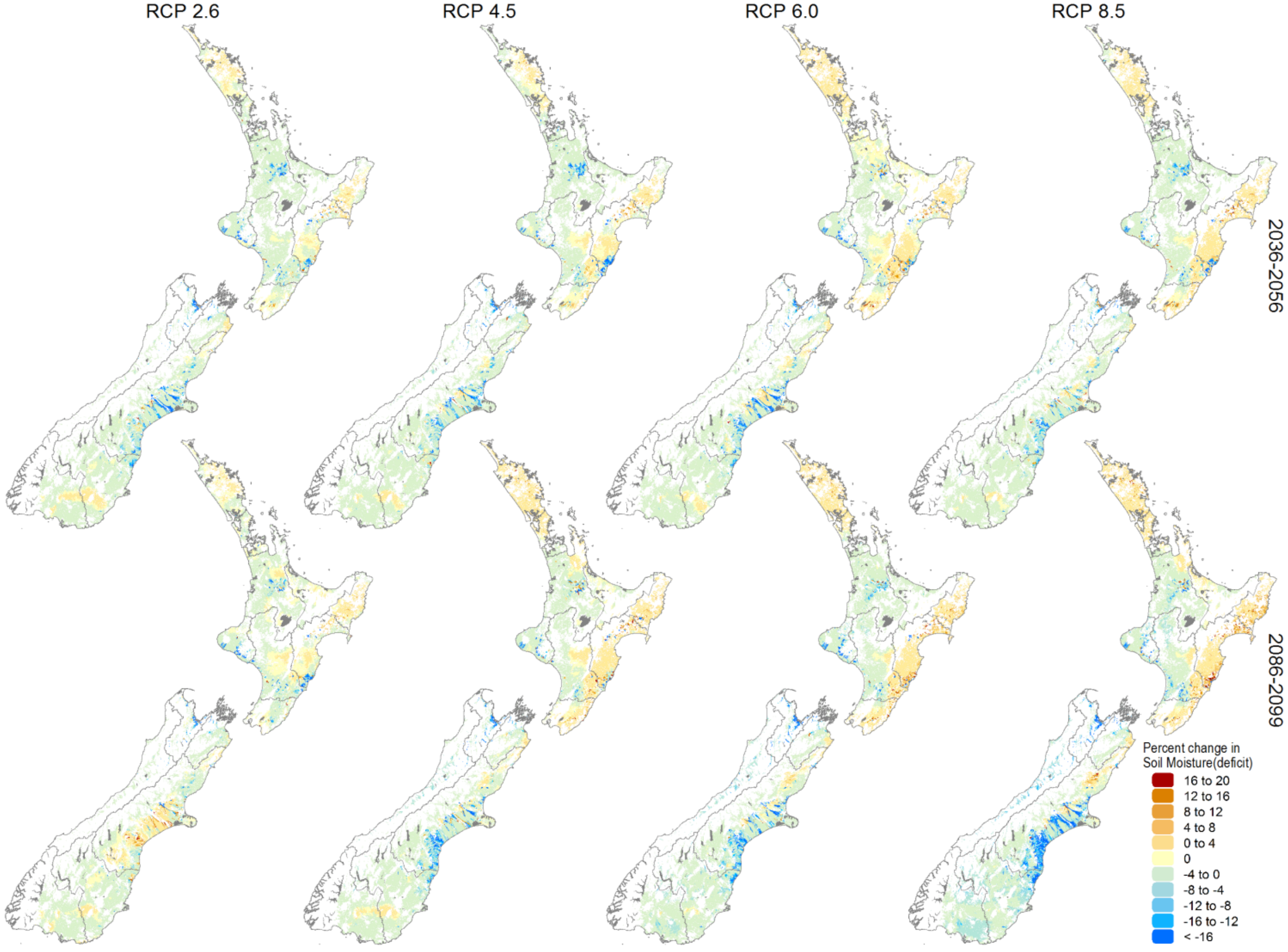


**Figure 3-13: Multi-model median changes in mean winter soil moisture deficit (%).**

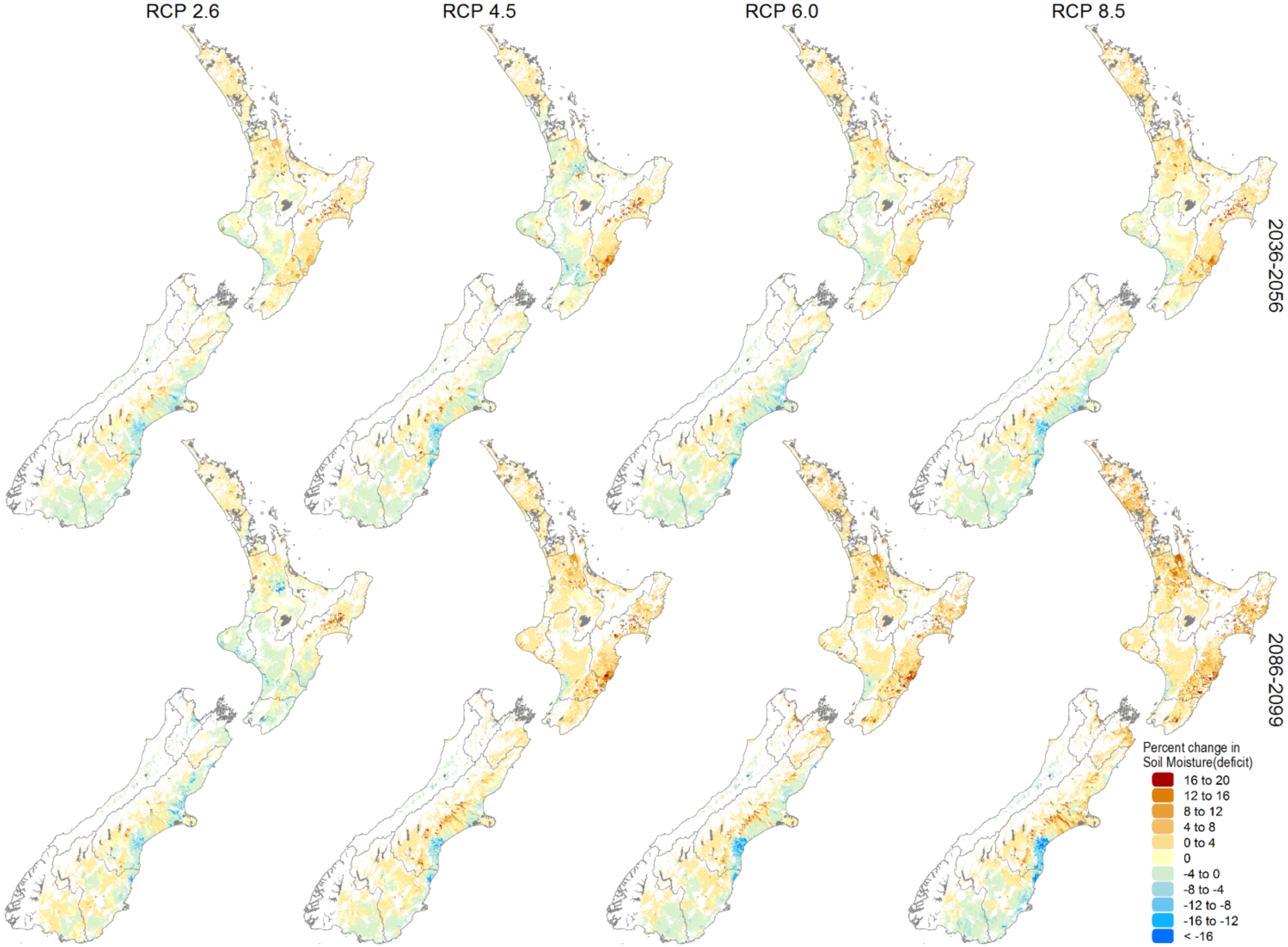


**Figure 3-14: Multi-model median changes in mean spring soil moisture deficit (%).**

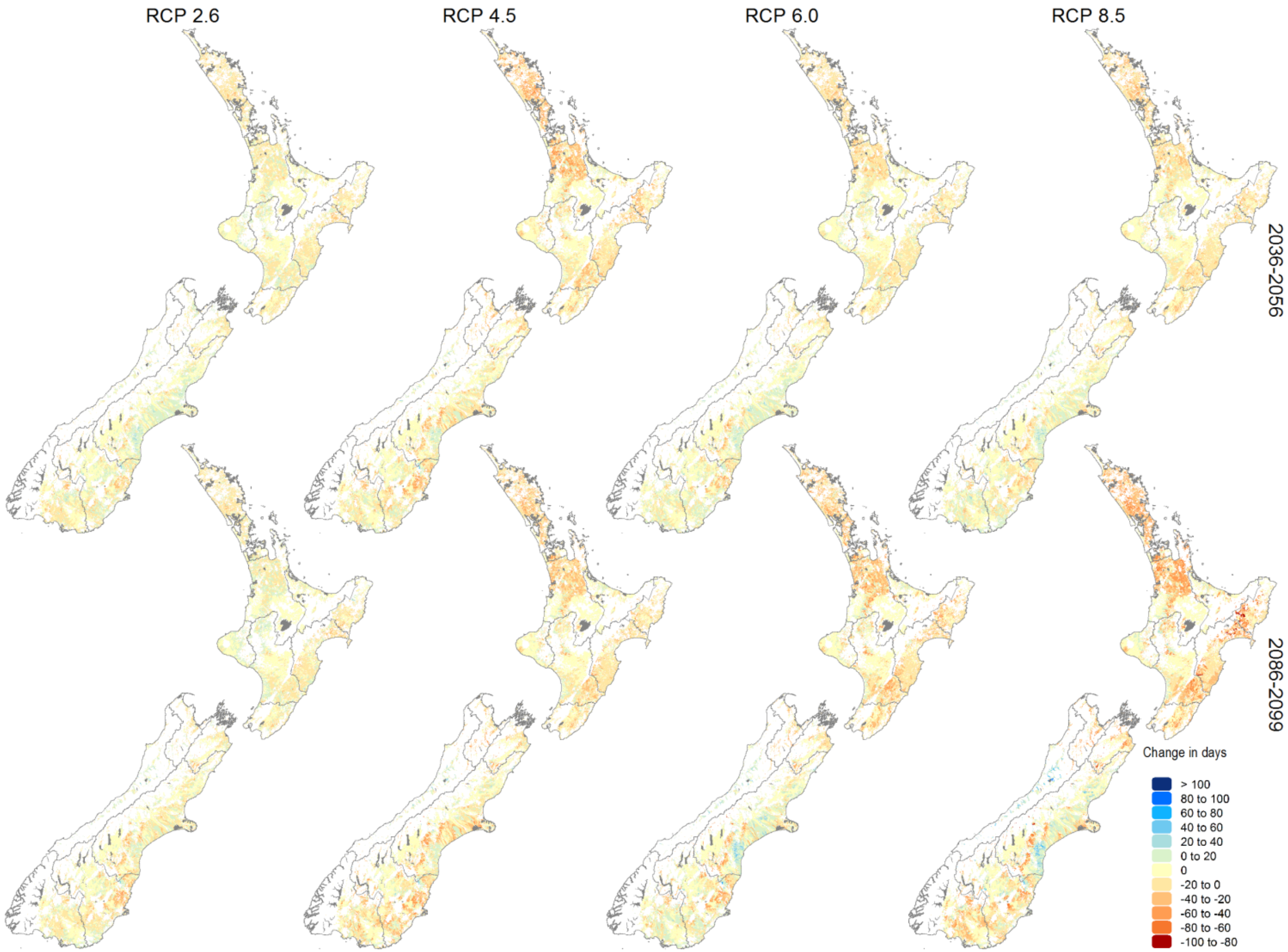


**Figure 3-15: Multi-model median change in low soil moisture timing (days).**

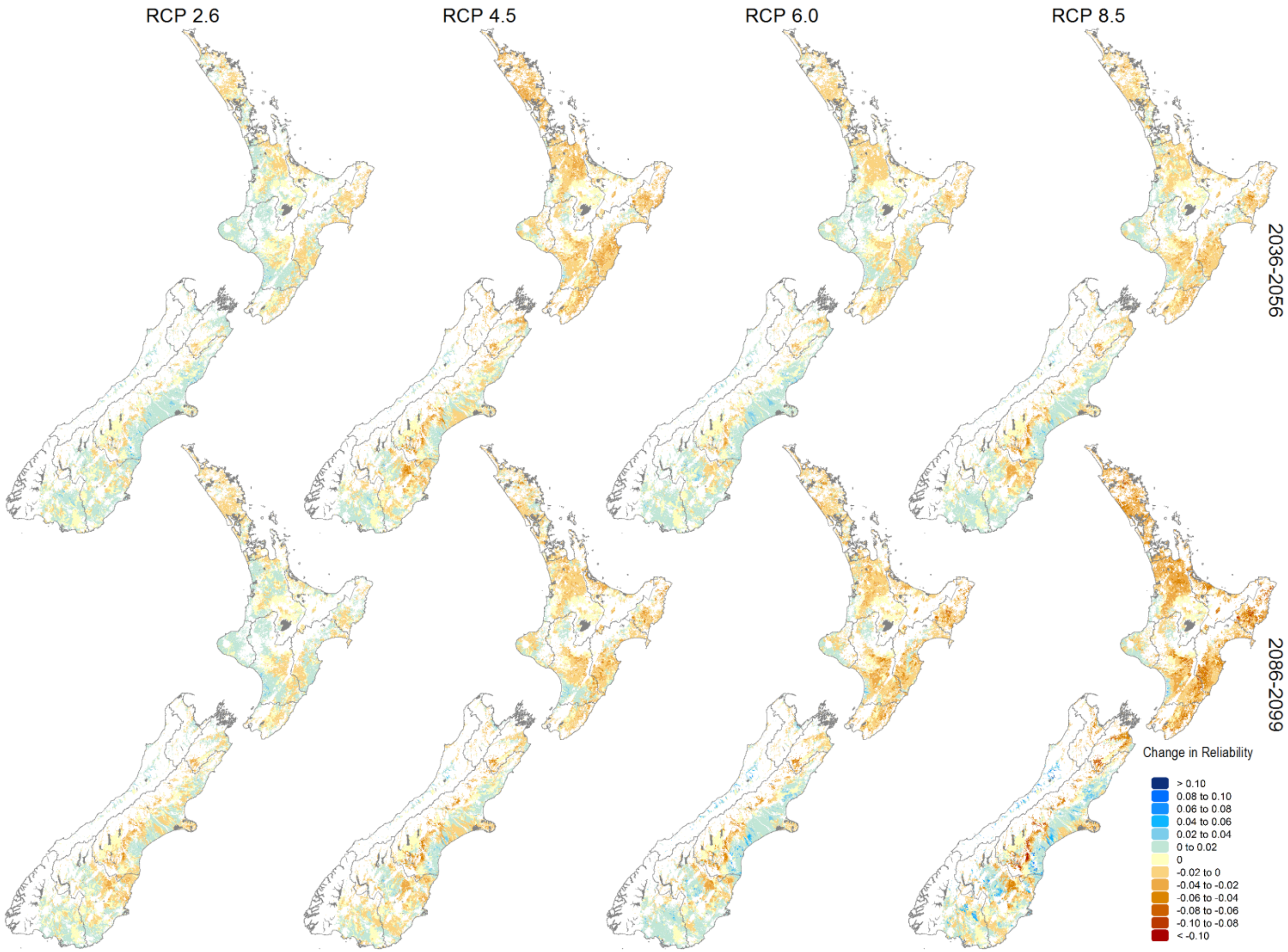


**Figure 3-16: Multi-model median change in soil moisture reliability.**

## 3.2 Northland

### 3.2.1 Mean discharge

For RCP2.6, mean discharge during both time periods increases slightly in the west and decreases along the east; for higher scenarios, the decreases extend further to the west of the region and deepen in intensity.

### 3.2.2 Mean annual low flow

MALF generally declines across Northland under all scenarios and time periods, with some minor exceptions in the north and south. Declines are slightly greater for higher scenarios and later in the century.

### 3.2.3 Low flow timing

Low flows conditions are reached earlier after winter for all scenarios and time periods. There is little difference among multi-model medians except that RCP8.5 reaches the low flow threshold even earlier.

### 3.2.4 Flow reliability

Flow reliability is projected to remain the same or decrease. Decreases are more extensive and extreme by late-century and for higher scenarios.

### 3.2.5 Mean annual flood

Both increases and decreases in mean annual flood are projected for the region, with somewhat greater percentage increases in the south and under RCP8.5 late-century.

### 3.2.6 Q5 discharge

The Q5 discharge decreases for most of Northland, particularly for RCP8.5 late-century.

### 3.2.7 Mean seasonal soil moisture

Agricultural land is projected to become drier during spring, summer and winter for both mid- and late-century for all scenarios. This shift is most pronounced in summer, but late-century is only marginally drier than mid-century, and the extreme warming scenario (RCP8.5) does not necessarily result in the most extreme drying (see mean summer soil moisture for RCP4.5 and mid-century). For autumn, the higher scenarios result in drier soils while the lower scenarios result in wetter soils.

### 3.2.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with only slight differences in magnitude. Increases are greatest in spring and summer and lowest in autumn.

### 3.2.9 Low soil moisture timing

Low soil moisture conditions are reached earlier in the year under climate change, particularly for higher scenarios and late-century.

### 3.2.10 Soil moisture reliability

Northland's soil moisture reliability generally declines across the region, particularly for higher scenarios and late-century.

## 3.3 Auckland

### 3.3.1 Mean discharge

Mean discharge for most of the region increases slightly by mid-century. This changes to general decreases late-century, particularly in the north under higher scenarios.

### 3.3.2 Mean annual low flow

MALF declines under all scenarios and time periods, with some minor exceptions for the RCP2.6. Declines are slightly greater for higher scenarios and later in the century.

### 3.3.3 Low flow timing

Low flow conditions are reached earlier after winter for all scenarios and time periods. There is little difference among multi-model medians except that RCP8.5 reaches the low flow threshold even earlier.

### 3.3.4 Flow reliability

Flow reliability is projected to remain the same or decrease. Decreases are more extensive and extreme by late-century and for higher scenarios.

### 3.3.5 Mean annual flood

The mean annual flood is projected to increase or remain about the same across the region, with somewhat greater percentage increases in the south of the region, and more extensively under RCP8.5 late-century. The larger increases are particularly substantial.

### 3.3.6 Q5 discharge

The Q5 discharge decreases for most of Auckland, particularly for RCP8.5 late-century.

### 3.3.7 Mean seasonal soil moisture

Agricultural land is projected to become drier during spring and summer for both time periods and all scenarios. The shifts during spring are greater for the second period and for the more extreme RCPs, although there is no equivalent correlation for summer soil moisture (see mean soil moisture for RCP4.5 and 2040). For autumn and winter, soil are projected to wet slightly for the lower scenarios and dry for the high scenario, with little difference between the two time periods.

### 3.3.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with only slight differences in magnitude. The increases are larger in summer, and mixed for autumn and winter.

### 3.3.9 Low soil moisture timing

Low soil moisture conditions are reached earlier in the year under climate change, particularly for higher scenarios and late-century.

### 3.3.10 Soil moisture reliability

Soil moisture reliability generally declines across the region, particularly for higher scenarios and late-century although not consistently.

## 3.4 Waikato

### 3.4.1 Mean discharge

Mean discharge for most of Waikato is projected to increase slightly mid-century for all scenarios. Late-century, decreases in flow become more common, depending on scenario, but so too do some decreases become more severe.

### 3.4.2 Mean annual low flow

MALF decreases or increases in Waikato depending on location, scenario and time period. Slight increases are more widespread for RCP2.6, while decreases dominate and intensify for higher scenarios and later in the century.

### 3.4.3 Low flow timing

Most of Waikato reaches low flow conditions earlier under climate change. The exception are some inland areas in the south that in some simulations tend to reach low flow conditions later in the year. There is no compelling association with either scenario or time period.

### 3.4.4 Flow reliability

Projections of reliability change show pockets of increases, decreases, and areas of little change. The increases lie in southern Waikato but do not show a strong relationship with projection time or scenario. Late-century, however, reliability tends to decline across the region as a whole for the higher scenarios.

### 3.4.5 Mean annual flood

The mean annual flood is projected to increase or remain about the same across the region, with somewhat greater percentage increases in the west for all scenarios and time periods and also in the north for RCPs 6.0 and 8.5 for both time periods. The larger increases are particularly substantial.

### 3.4.6 Q5 discharge

For all scenarios and time periods, the Q5 discharge shows increases and decreases across the region. Western and southern areas tend to include the most consistent increases, however the decreases become more pronounced and extensive for higher scenarios late-century.

### 3.4.7 Mean seasonal soil moisture

Changes for soil moisture are spatially varied with both contemporaneous increases and decreases. Soils will tend to dry in spring, summer and autumn, with some local exceptions, and become wetter during winter. There is a tendency for these shifts to be more pronounced for the higher scenarios and late-century.

### 3.4.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, albeit with less extensive extreme changes. The remaining extreme changes are scattered across central Waikato.

### 3.4.9 Low soil moisture timing

Low soil moisture conditions are generally reached earlier in the year in northern Waikato, particularly for higher scenarios and late-century.

### 3.4.10 Soil moisture reliability

Soil moisture reliability in northern Waikato generally declines across the regions, particularly for higher scenarios and late-century although not consistently. The west coast shows some increases, and parts of southern Waikato show little change.

## 3.5 Bay of Plenty

### 3.5.1 Mean discharge

Mean discharge for most of Bay of Plenty is projected to increase slightly mid-century for all scenarios. Late-century, decreases in flow become more common, depending on scenario.

### 3.5.2 Mean annual low flow

Bay of Plenty shows only minor sensitivity to climate change in terms of MALF. Decreases are more likely, particularly with higher scenarios and later in the century, but increases are also observed.

### 3.5.3 Low flow timing

Low flow conditions are reached earlier after winter for all scenarios and time periods. There is little difference among multi-model medians except that RCP8.5 reaches the low flow threshold even earlier.

### 3.5.4 Flow reliability

Projections of reliability change show pockets of increases, decreases, and widespread areas of little change. The increases lie in southern Bay of Plenty but do not show a strong relationship with projection time or scenario.

### 3.5.5 Mean annual flood

The mean annual flood is projected to increase or remain about the same across the region, with the larger increases along the coast. There is little difference among the scenarios and time periods.

### 3.5.6 Q5 discharge

Bay of Plenty exhibits a mixture of increases and decreases in the Q5 discharge across the region. There is little discernible difference among scenarios and time periods, except for substantially more extensive decrease for RCP8.5 late-century.

### 3.5.7 Mean seasonal soil moisture

Soils are projected to become drier in spring and summer, particularly late-century and the higher RCPs. Autumn and winter soil moisture conditions are more likely to become wetter, although there is no substantial difference among scenarios or time periods.

### 3.5.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with only slight differences in magnitude.

### 3.5.9 Low soil moisture timing

Low soil moisture conditions are mostly reached around the same time of year.

### 3.5.10 Soil moisture reliability

Soil moisture reliability remains about the same in some parts of the region; elsewhere it declines, particularly for higher scenarios and late-century although not consistently.

## 3.6 Gisborne

### 3.6.1 Mean discharge

Mean discharge is projected to decline for most of Gisborne, with greater decreases during late-century compared with mid-century, and for the higher scenarios.

### 3.6.2 Mean annual low flow

Both increases and decreases in MALF are reported for Gisborne, with a preponderance of decreases. These decreases tend to become larger for higher scenarios, but occur by mid-century.

### 3.6.3 Low flow timing

Low flows conditions are reached earlier after winter for all scenarios and time periods. There is little difference among multi-model medians except that RCP8.5 reaches the low flow threshold even earlier.

### 3.6.4 Flow reliability

Flow reliability is projected to remain the same or decrease. Decreases are more extensive and extreme by late-century and for higher scenarios.

### 3.6.5 Mean annual flood

The mean annual flood is projected to increase or remain about the same across the region, with somewhat greater percentage increases inland or more generally under the higher scenarios. An area north of Gisborne shows decreases under most scenarios however.

### 3.6.6 Q5 discharge

Gisborne exhibits a mixture of increases and decreases in the Q5 discharge across the region. There is little discernible difference among scenarios and time periods, except for substantially more extensive decrease for RCP8.5 late-century.

### 3.6.7 Mean seasonal soil moisture

Soils are projected to become drier in general for all seasons, time periods and scenarios. Autumn shows the least change and summer the most. Changes are more pronounced late-century and the higher scenarios.

### 3.6.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with only slight differences in magnitude.

### 3.6.9 Low soil moisture timing

Low soil moisture conditions are reached earlier in the year under climate change, particularly for higher scenarios and late-century. Some areas in the west of Gisborne district reach this point much earlier.

### 3.6.10 Soil moisture reliability

Soil moisture reliability generally declines across the region, particularly for higher scenarios and late-century.

## 3.7 Taranaki

### 3.7.1 Mean discharge

Mean discharge is projected to increase over most of Taranaki, with small areas of decreasing flow developing late-century for the higher scenarios.

### 3.7.2 Mean annual low flow

Under RCP2.6, MALF has a slight tendency to increase for both time periods, but for higher scenarios MALF then generally decreases.

### 3.7.3 Low flow timing

Most of Taranaki reaches low flow conditions slightly sooner after winter for all scenarios and both time periods, but there is no compelling trend with scenario or time period. A small portion of rivers arrive at low flow conditions later.

### 3.7.4 Flow reliability

Flow reliability is projected to increase, decrease, or remain about the same depending on the time period, RCP and area within Taranaki. There is a tendency for higher scenarios and the latter time period to see more decreases, however northern coastal Taranaki is less sensitive to change.

### 3.7.5 Mean annual flood

The mean annual flood is projected to increase across most of the region. There is a slight increase in severity with higher scenarios.

### 3.7.6 Q5 discharge

Taranaki shows moderate increases in the Q5 discharge under RCP2.6, but for other scenarios the region exhibits a mix of increases and decreases with no apparent trend with either RCP or time period.

### 3.7.7 Mean seasonal soil moisture

Changes in soil moisture vary spatially, depending on exposure to westerly air flow. Winter conditions are consistently wetter for both time periods and all scenarios, and this shift is more pronounced late-century and higher scenarios. Soils are also wetter in the other three seasons for RCP2.6, but for late-century and higher scenarios there is a tendency for the soils instead to become drier.

### 3.7.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, mostly with only slight differences in magnitude. There are several isolated pockets of substantially decreased soil moisture deficit.

### 3.7.9 Low soil moisture timing

Low soil moisture conditions are generally reached slightly earlier in the year under climate change, particularly for higher scenarios and late-century, with minor exceptions.

### 3.7.10 Soil moisture reliability

Soil moisture reliability generally remains about the same across the region, although some areas show declines, particularly east of Mt Taranaki for higher scenarios and late-century although not consistently.

## 3.8 Hawke’s Bay

### 3.8.1 Mean discharge

Mean discharge is projected to decrease over most of the region, except for RCP2.6 mid-century. The decreases tend to be more pronounced late-century.

### 3.8.2 Mean annual low flow

While small pockets of Hawke’s Bay show slight increases in MALF, generally MALF is projected to decrease across the region. The decreases are the largest for RCP8.5 late-century, but otherwise there is no compelling trend with either scenarios or time period.

### 3.8.3 Low flow timing

Most of Hawkes Bay reaches low flow conditions slightly sooner after winter for all scenarios and both time periods, but there is no compelling trend with RCP or time period. A small portion of rivers arrive at low flow conditions later.

### 3.8.4 Flow reliability

Projections of reliability change show pockets of increases, decreases, and areas of little change. The increases lie in a portion of southern Hawke’s Bay but do not show a strong relationship with projection time or scenarios. Late-century, however, the region as a whole does appear to see a decline in reliability.

### 3.8.5 Mean annual flood

The mean annual flood is projected to increase or remain about the same across the region, with the larger increases in the central and southern parts of the region. There is no consistent trend across scenarios or between time periods. Varying areas in each scenario show some decreases however.

### 3.8.6 Q5 discharge

Much of Hawke's Bay exhibits a decrease in the Q5 discharge, depending on the scenarios and time period. When there are increases, they tend to cluster around central-eastern Hawke's Bay.

### 3.8.7 Mean seasonal soil moisture

Soils are projected to become drier during spring, particularly late-century and higher scenarios. During summer, both moderate drying and moderate wetting is projected, but there is no consistency with time period or scenarios. Autumn and winter experience slight drying for both time periods and scenarios, and more so for the higher scenarios.

### 3.8.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and RCPs, with only slight differences in magnitude.

### 3.8.9 Low soil moisture timing

Low soil moisture conditions are reached earlier in the year under climate change, particularly for higher scenarios and late-century.

### 3.8.10 Soil moisture reliability

Soil moisture reliability remains about the same in some part of the region; elsewhere it declines, particularly for higher scenarios and late-century although not consistently.

## 3.9 Manawatu-Wanganui

### 3.9.1 Mean discharge

Changes in mean discharge show an overall west-east gradient, with increases on the west and decreases on the east. The point at which increases give way to decreases shifts westward for higher scenarios and later in the century.

### 3.9.2 Mean annual low flow

Both slight increases and slight decreases in MALF are projected for the region. Increases are most widespread for RCP2.6 and tend to give way to decreases with higher scenarios. There is also a slight tendency towards decreases in MALF late-century.

### 3.9.3 Low flow timing

Low flow conditions tend to be reached sooner after winter across the simulations, with some local exceptions near Lake Taupō where they are reached later.

### 3.9.4 Flow reliability

Projections of reliability change show pockets of increases, decreases, and areas of little change. The increases lie in the west and north. There is a tendency for reliability to increase under higher scenarios in late-century.

### 3.9.5 Mean annual flood

The mean annual flood is projected to increase or remain about the same across the region, with the larger increases typically along the coast, and in certain simulations also centrally. RCP8.5 stands out as having more severe MAF increases than under other scenarios. Many scenarios except the most extreme mid-century show some areas of decrease however.

### 3.9.6 Q5 discharge

The Q5 discharge both increases and decreases across the region, with a tendency for more decreases late-century. Within the region, the west tends to exhibit the increases while decreases lie towards the east.

### 3.9.7 Mean seasonal soil moisture

Winter soil moisture tends to be wetter for all scenarios, with some local exceptions. Spring and autumn soils are wetter for RCP2.6 but become progressively drier for higher scenarios and late-century. Summer is projected to experience substantial changes in both directions, but there is no consistency with either time period or scenarios.

### 3.9.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with generally smaller differences in magnitude.

### 3.9.9 Low soil moisture timing

Low soil moisture conditions are reached about the same time or earlier in the year under climate change, particularly for higher scenarios and late-century, with minor exceptions.

### 3.9.10 Soil moisture reliability

Soil moisture reliability remains about the same in some part of the region; elsewhere it declines, particularly for higher scenarios and late-century although not consistently.

## 3.10 Wellington

### 3.10.1 Mean discharge

Mean discharge shows increases and decreases across the region depending on scenario and time period.

### 3.10.2 Mean annual low flow

MALF generally decreases across the region, from slight to moderate decreases. This is consistent across scenarios and time periods.

### 3.10.3 Low flow timing

Low flow conditions tend to be reached sooner after winter across the simulations.

### 3.10.4 Flow reliability

Flow reliability is projected to remain the same or decrease. Decreases are more extensive and extreme by late-century and for higher scenarios.

### 3.10.5 Mean annual flood

The mean annual flood is projected to increase or remain about the same across the region. There is no clear spatial pattern nor trend with scenarios or time period, although percentage increases are substantial in certain locations and simulations.

### 3.10.6 Q5 discharge

The Q5 discharge tends to decrease across the Wellington region, but shows no strong relationship with time period. There is also little discernible difference among scenarios, with the exception of RCP2.6 which tends to exhibit more increases.

### 3.10.7 Mean seasonal soil moisture

Soil moisture is generally projected to become drier, a trend that is most apparent for spring and summer, late-century, and for the higher scenarios. RCP2.6, however, does demonstrate slightly wetter conditions.

### 3.10.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with generally smaller differences in magnitude.

### 3.10.9 Low soil moisture timing

Low soil moisture conditions are generally reached earlier in the year under climate change, particularly for higher scenarios and late-century, with minor exceptions.

### 3.10.10 Soil moisture reliability

Soil moisture reliability generally decreases, especially in the east and particularly for higher scenarios and late-century. However some areas show little change or even some increases, particularly in the north-west.

## 3.11 Tasman

### 3.11.1 Mean discharge

Mean discharge tends to increase across Tasman for all scenarios and time periods, with increases becoming larger late-century and under higher scenarios.

### 3.11.2 Mean annual low flow

MALF generally decreases across the region, from slight to moderate decreases. This is consistent across scenarios and time periods.

### 3.11.3 Low flow timing

Low flow conditions tend to be reached sooner after winter across Tasman with the exception of the upper Buller which reaches the same conditions later. These changes are largely insensitive to scenario and time period.

### 3.11.4 Flow reliability

Flow reliability is projected to remain the same or decrease. Decreases are more extensive and extreme late-century and higher scenarios.

### 3.11.5 Mean annual flood

The mean annual flood is projected to increase especially in the north or remain about the same across the region. There is slight increase in severity with higher scenarios. Low emission scenarios show some decreases in the south.

### 3.11.6 Q5 discharge

The Q5 discharge generally decreases across Tasman, with the decreases becoming somewhat more pronounced under higher scenarios and during late-century.

### 3.11.7 Mean seasonal soil moisture

Soils in winter are projected to become wetter for both time periods and all scenarios, particularly for the highest scenarios. For all other seasons the changes are mixed (wetter and drier), although it is noteworthy that parts of Tasman are projected to become substantially drier during summer late-century under RCP8.5.

### 3.11.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with generally smaller differences in magnitude for most seasons but greater percentage reductions in soil moisture deficit in winter compared with soil moisture itself.

### 3.11.9 Low soil moisture timing

Low soil moisture conditions are generally reached slightly earlier in the year under climate change, particularly for higher RCPs and late-century, with minor exceptions.

### 3.11.10 Soil moisture reliability

Soil moisture reliability generally decreases across the region, particularly for higher scenarios and late-century although not consistently. Some areas show no change.

## 3.12 Nelson

### 3.12.1 Mean discharge

Mean discharge is projected to increase for the Nelson region for all scenarios and time periods.

### 3.12.2 Mean annual low flow

Mean annual low flow is generally projected to decrease for Nelson for all scenarios and time periods.

### 3.12.3 Low flow timing

Low flow conditions are reached earlier after winter under climate change.

### 3.12.4 Flow reliability

Flow reliability tends to decline for Nelson, particularly under the higher scenarios late-century.

### 3.12.5 Mean annual flood

Mean annual flood is generally projected to increase for the Nelson region.

### 3.12.6 Q5 discharge

The Q5 discharge shows increases and decreases across the Nelson region, depending on scenarios and time period.

### 3.12.7 Mean seasonal soil moisture

Soil moisture conditions are projected to become drier in summer and autumn, wetter in winter, and for spring the direction of change depends on the scenarios and time period.

### 3.12.8 Mean seasonal soil moisture deficit

Soil moisture deficits are projected to become larger in summer and autumn, smaller in winter, and for spring the direction of change depends on the scenarios and time period.

### 3.12.9 Low soil moisture timing

Dry soil conditions are reached slightly earlier after winter under climate change, particularly for higher scenarios.

### 3.12.10 Soil moisture reliability

Soil moisture reliability tends to decline slightly for Nelson, particularly under the higher scenarios and by late-century.

## 3.13 Marlborough

### 3.13.1 Mean discharge

Mean discharge shows increases and decreases across the region depending on the scenarios and time period. The increases tend to cluster in the north-east and the decreases in the south-west.

### 3.13.2 Mean annual low flow

MALF decreases across the region, from slight to moderate decreases. There is little influence of scenario or time period.

### 3.13.3 Low flow timing

Low flow conditions tend to be reached sooner after winter across Marlborough with the exception of an area in the south west which reaches the same conditions later. These changes are largely insensitive to scenario and time period.

### 3.13.4 Flow reliability

Flow reliability is projected to remain the same or decrease. Decreases are more extensive and extreme late-century and higher scenarios.

### 3.13.5 Mean annual flood

The mean annual flood is projected to increase or remain about the same across the region. There is no consistent pattern across scenarios or time periods, although the eastern parts of the region show smaller changes than the other agricultural areas. There is also a consistent area of decrease in the south-west.

### 3.13.6 Q5 discharge

The Q5 discharge generally decreases across Marlborough, with the decreases becoming somewhat more pronounced under higher scenarios and during late-century.

### 3.13.7 Mean seasonal soil moisture

Soils generally become wetter in winter and drier in the other seasons. Changes are more pronounced late-century and for the higher scenarios. Summer conditions late-century under RCP8.5 show among the most extreme drying for New Zealand.

### 3.13.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with generally smaller differences in magnitude. The main difference is the extreme dry soils in summer late-century and RCP8.5 are not as extreme as measured by soil moisture deficit.

### 3.13.9 Low soil moisture timing

Low soil moisture conditions are generally reached earlier in the year under climate change, particularly for higher scenarios and by late-century, with minor exceptions.

### 3.13.10 Soil moisture reliability

Soil moisture reliability generally decreases across the region, particularly for higher scenarios and by late-century although not consistently. Some areas show no change.

## 3.14 West Coast

### 3.14.1 Mean discharge

Mean discharge increases across the West Coast for almost all rivers, scenarios and time periods. These increases are larger for higher scenarios and by late-century.

### 3.14.2 Mean annual low flow

In much of the West Coast MALF is projected to increase; only in the north is MALF projected to decrease. This sub-regional pattern is largely common to all scenarios and time periods, and there appear to be slightly greater increases late-century.

### 3.14.3 Low flow timing

Low flow conditions tend to be reached later after winter for most of the West Coast, with isolated exceptions. This is most pronounced for RCP8.5 in late-century.

### 3.14.4 Flow reliability

Flow reliability is relatively insensitive to climate change on the West Coast. While small pockets indicate a decrease under some circumstances, reliability is generally expected to remain about the same or slightly increase with time and scenario forcing.

### 3.14.5 Mean annual flood

The mean annual flood is projected to increase or remain about the same across the region. The increases are larger for the higher scenarios but there is little discernible difference between time periods.

### 3.14.6 Q5 discharge

The Q5 discharge increases across most of the West Coast, with the exception of the north that sees decreases. Both decreases and increases become more pronounced under higher scenarios and during late-century.

### 3.14.7 Mean seasonal soil moisture

The West Coast generally shows signs of become wetter in winter over most of the region (with minor local exceptions). In the other seasons there is a north-south gradient with the north drying and the south becoming wetter. This shift is most pronounced in late-century, and for the higher scenarios.

### 3.14.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with generally smaller differences in magnitude.

### 3.14.9 Low soil moisture timing

Low soil moisture conditions are generally reached slightly later in the year under climate change, particularly for higher scenarios and late-century, with minor exceptions. A slight north -south gradient applies as for seasonal soil moisture.

### 3.14.10 Soil moisture reliability

Soil moisture reliability generally increases across the region, particularly for higher scenarios and late-century. A slight north -south gradient applies as for seasonal soil moisture.

## 3.15 Canterbury

### 3.15.1 Mean discharge

Canterbury exhibits a regional patchwork of increases and decreases in mean discharge, depending on scenario and time period. South coastal Canterbury tends to become wetter, particularly for higher scenarios and late-century, and inland Canterbury often becomes drier, but otherwise there is no pronounced pattern in the changes.

### 3.15.2 Mean annual low flow

Canterbury exhibits a mix of increases and decreases in MALF under climate change. The increases tend to be isolated to southern Canterbury and inland portions of mid-Canterbury, although these decline in extent late-century. Moderate to severe decreases are more extensive across Canterbury.

### 3.15.3 Low flow timing

Low flow conditions tend to be reached slightly sooner after winter across Canterbury with the exception of high alpine areas in the west, eastern areas across Canterbury Plains and Banks Peninsula, and southern Canterbury. Changes in the major alps-fed rivers tend to reflect changes in their source areas, which can differ from the surrounding rivers across the Plains. The Rangitata, for example, reaches low flow conditions later while the Waimakariri reaches them earlier. There is no strong dependency on scenario or time period.

#### 3.15.4 Flow reliability

Flow reliability is insensitive to climate change in the most alpine areas of Canterbury. Sub-alpine areas, less far west, experience decreases or no change in reliability; the decreases tend to be more extensive and extreme for higher scenarios and late-century. Portions of the Canterbury Plains show decreases, increases and no changes, with a slight tendency towards decreases late-century. South Canterbury, however, shows the largest and most consistent increases in reliability.

#### 3.15.5 Mean annual flood

The mean annual flood is projected to increase or remain about the same across the region. There is a tendency for increases to be larger for higher scenarios, particularly under RCP8.5 which sees widespread and substantial increases in MAF.

#### 3.15.6 Q5 discharge

Canterbury tends to exhibit a west-east pattern in change in Q5 discharge, with slight increases towards the very west, decreases across much of inland Canterbury from north to south as well as Banks Peninsula, and increases along much but not all of coastal and near-coastal Canterbury. Where there are increases, they tend to be larger with higher scenarios; the same trend is not apparent for the decreases.

#### 3.15.7 Mean seasonal soil moisture

Canterbury's large area includes complex patterns of contemporaneous wetting and drying across the seasons. No season demonstrates shifts in one direction for the entire region, except for the most part winter which generally experiences wetter conditions. The most inland agricultural areas tend to become drier for all seasons, time periods and scenarios, while southern coastal areas become wetter across all the simulations. The Canterbury Plains tend to be wetter during spring mid-century and drier late-century; during autumn they are generally wetter. The most pronounced changes across the region occur during summer, which sees wetter conditions in north Canterbury, inland mid-Canterbury and southern Canterbury, and drier conditions for much of the Canterbury Plains and Banks Peninsula.

#### 3.15.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with generally greater differences (negative) in magnitude.

#### 3.15.9 Low soil moisture timing

Low soil moisture conditions are reached earlier or later in the year under climate change, particularly for higher scenarios and late-century, depending on location. Portions of south Canterbury are later, as are areas across mid-Canterbury although not consistently.

#### 3.15.10 Soil moisture reliability

Soil moisture reliability generally decreases in the western inland and high country areas, and remains about the same in much of the rest, however there are scattered areas in southern and mid-Canterbury that exhibit increases.

## 3.16 Otago

### 3.16.1 Mean discharge

Mean discharge generally shows small increases and decreases across Otago by mid-century, with minor exceptions depending on scenario. The increases intensify late-century and under higher scenarios. A portion of coastal north Otago shows consistent increases under all time periods and scenarios.

### 3.16.2 Mean annual low flow

Otago experiences both increases and decreases in MALF under climate change. There is no compelling relationship between these changes and scenario or time period. The increases tend to be distributed within the western alpine portion, one part of central Otago, and areas within the south and/or east.

### 3.16.3 Low flow timing

Low flow conditions are reached earlier or later, depending largely on the location but not the scenario or time period. The highest alpine areas in the west and a swath of rivers towards the east reach dry conditions later, while the rest of Otago tends to reach them earlier.

### 3.16.4 Flow reliability

Flow reliability across much of Otago is insensitive to climate change. Other parts do show changes – both increases and decreases – but there is no strong association with time period or scenario.

### 3.16.5 Mean annual flood

The mean annual flood is projected to increase in most parts of Otago, with the remaining parts staying about the same. There is little difference among scenarios or time periods except for RCP8.5 in late-century, which sees substantial increases in MAF over much of Otago.

### 3.16.6 Q5 discharge

Otago exhibits a patchwork of slight to moderate increases and decreases across the region. There is no discernible trend with either scenario or time period.

### 3.16.7 Mean seasonal soil moisture

Soil conditions during winter generally become wetter, more so late-century and higher scenarios. For the remaining seasons there are pockets of both wetting and drying in consistent locations, including a concentrated zone of wetting in the vicinity of Alexandra. Summer sees the most pronounced drying, particularly late-century and higher scenarios.

### 3.16.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with generally smaller differences in magnitude including the vicinity around Alexandra (reduction in deficit).

### 3.16.9 Low soil moisture timing

Low soil moisture conditions are generally reached earlier in the year under climate change, particularly for higher scenarios and late-century, with minor exceptions.

### 3.16.10 Soil moisture reliability

Soil moisture reliability changes vary across the region, with some increases in central Otago and decreases in north and south coastal Otago.

## 3.17 Southland

### 3.17.1 Mean discharge

Mean discharge generally shows small increases across Southland by mid-century. The increases intensify late-century and under higher scenarios.

### 3.17.2 Mean annual low flow

Slight and moderate increases and decreases in MALF are projected for Southland. Increases tend to be more widespread during the first time period while decreases are more common late-century.

### 3.17.3 Low flow timing

Low flow conditions are reached earlier or later, depending largely on the location but not the scenario or time period. The highest alpine areas in the west and a scattering of rivers elsewhere reach dry conditions later, while the rest of Southland tends to reach them earlier.

### 3.17.4 Flow reliability

Mid-century flow reliability across Southland increases or remains about the same. In late-century, some portions show decreases in reliability, but there is no strong dependence on scenario.

### 3.17.5 Mean annual flood

The mean annual flood is projected to increase in most parts of Southland, with the remaining parts staying about the same. There is little difference among scenarios, except for RCP8.5, and late-century generally exhibits greater increases in MAF, except for RCP2.6. A persistent area east of Lake Te Anau shows a lesser effect than the rest of the region.

### 3.17.6 Q5 discharge

Southland exhibits a patchwork of slight increases and decreases in the Q5 discharge across the region, with a tendency towards more decreases late-century.

### 3.17.7 Mean seasonal soil moisture

Soil moisture conditions are generally projected to become wetter for the whole region during autumn and winter for both time periods and all scenarios; this is largely true also for spring. Summer, however, sees slightly drier conditions for higher RCPs and late-century.

### 3.17.8 Mean seasonal soil moisture deficit

Shifts in soil moisture deficit closely resemble shifts in soil moisture for all seasons, time periods and scenarios, with generally similar differences in magnitude.

### 3.17.9 Low soil moisture timing

Low soil moisture conditions are generally reached earlier in the year under climate change, particularly for higher scenarios and late-century, but less so around Te Anau.

### 3.17.10 Soil moisture reliability

Soil moisture reliability generally remains the same across the region. Where there are changes, they tend to be increases.

# 4 Comparison with changing climatic statistics

The focus of the present report has been on hydrological effects of climate change across New Zealand. The driving climatic information is the same as used by Ministry for the Environment (2016) in its study of New Zealand's changing climate. It is thus possible to compare related statistics between the two studies, putting the hydrological results into the context of changing climatic conditions. While there is no simple, one-to-one correspondence between statistics, and there is a difference in the use of either multi-model medians (present report) and multi-model means (Ministry for the Environment 2016), there are four statistics that merit comparison.

## 4.1 Mean discharge

The long-term mean discharge for any point along a river reflects a complex balance of precipitation and evaporation across the upstream catchment. It is not a direct function of precipitation totals, but to a large degree will reflect precipitation gradients across New Zealand. Comparing mean discharge reported here (Figure 3-1) with the seasonal precipitation projections of Ministry for the Environment (2016) we see very good correspondence across all RCPs: wetter along the West Coast and in the south of the South Island; drier across the North Island and on the north-east of the South Island.

## 4.2 Mean annual flood

The mean annual flood statistic reported here (Figure 3-5) may be compared with the magnitude of the 99$^{th}$ percentile of daily precipitation reported in Ministry for the Environment (2016). While extreme daily rainfall is not the sole driver of extreme flooding, the two are related. The other major contributing factors are the timing of the large precipitation event relative to antecedent conditions and the hydrological characteristics of the catchment. The results presented here generally correspond well to those in Ministry for the Environment (2016): there is little change by mid-century, but by late-century a large portion of Otago and Southland shows increases in daily storm intensity and flood magnitude, as well as a portion of the northern South Island. There is also correspondence between predicted higher daily intensities and flooding in the vicinity of Auckland.

## 4.3 Soil moisture deficit

The seasonal soil moisture deficits derived by the hydrological modelling herein (Figure 3-11 to Figure 3-14) equate to the volume of soil pore space (before field capacity) not filled by water. As the soil dries, the rate of evaporation also declines. This means that the potential evaporative demand set by atmospheric conditions is increasingly unmet, and this 'potential evapotranspiration deficit' (PED) is reported by Ministry for the Environment (2016). While Ministry for the Environment (2016) presents PED in annual terms and the present report considers soil moisture deficit in seasonal terms, a degree of correspondence between the two statistics can be seen: the North Island tends to be water-short, particularly along the east, as is the north and east of the South Island. However, there is also a noticeable discrepancy: there are areas along inland Canterbury down to south Canterbury that show declines in soil moisture deficit, instead of the increases in PED reported by Ministry for the Environment (2016). This discrepancy stems from differences in the model used by the two studies, along with their underlying environmental datasets. While both models are arguably simplistic interpretations of soil moisture dynamics and may not represent soil moisture dynamics accurately, TopNet's model likely encapsulates a somewhat more realistic representation of environmental conditions and processes.

## 4.4 Soil moisture reliability

Soil moisture reliability reflects the time that the soil moisture spends above a threshold level. Given that the residence time of soil moisture is short (on the order of days to weeks at most), and that soil moisture is a point measurement (in contrast with accumulating river flow), there can be a strong connection between soil moisture reliability and the number of days without precipitation. Ministry for the Environment (2016) shows increases in the number of dry days across the North Island and down the alpine spine of the South Island; their frequency increases along the West Coast and in a small region of southern Canterbury. This is broadly consistent with the results displayed in Figure 3-16.

# 5 Weighing model certainties and uncertainties

The hydrological projections made in this report are the most advanced and robust available for New Zealand to date. They draw on internationally vetted GCMs (CMIP5) and RCPs; New Zealand-specific bias correction and downscaling techniques (Sood 2014); and New Zealand's most tested and applied national hydrological model (TopNet). Despite the substantial knowledge encapsulated by these models and datasets, however, they are not without errors and uncertainties. A thorough interpretation of the results must thus consider these limitations. Uncertainties related to climate change fields are discussed in detail in Ministry for the Environment (2016).

## 5.1 Hydrological uncertainties due to Global Climate Model uncertainty

As stated in Section 2.1, multiple GCMs are used in order to encapsulate a plausible range of physical interpretations of the climate system given uncertainties in climate science. The IPCC assessment contains an ensemble of more than 41 GCMs. NIWA selected 41 to be used in New Zealand, but the number of simulations available varied with RCP – only 23 for RCP2.6, but the full 41 for RCP8.5 and this historical period ending 2005. Thus among those GCMs, a subset of 23 GCMS was established to be used in New Zealand for the four RCPs (Ministry for the Environment 2016). A further subset of six GCMs to be used for dynamical downscaling was established representing the wide range of potential climate condition across New Zealand for each RCP (Ministry for the Environment, 2016). To provide an indication of the central tendency of these models, the multi-model ensemble median of the hydrological results is presented. While this allows for effective communication of the main results, it clouds the uncertainty due to model error. Each GCM will invariably produce a unique and different hydrological outcome. To illustrate the potential variability of these outcomes, Figure 5-1 depicts the change in mean discharge at the outlet of the Waikato River for each individual GCM and RCP as well as the mean and median of the GCM results. For the lower three RCPs, the variation among GCMs is greater than the variability among RCPs. Differences in the distribution of the GCM results for a given RCP also affect the relative position of the GCM mean and median: while the GCM mean increases monotonically across RCPs, the GCM median does not.

The GCM hindcasts are also biased to a degree. This is addressed through the bias correction and downscaling described by Sood (2014).

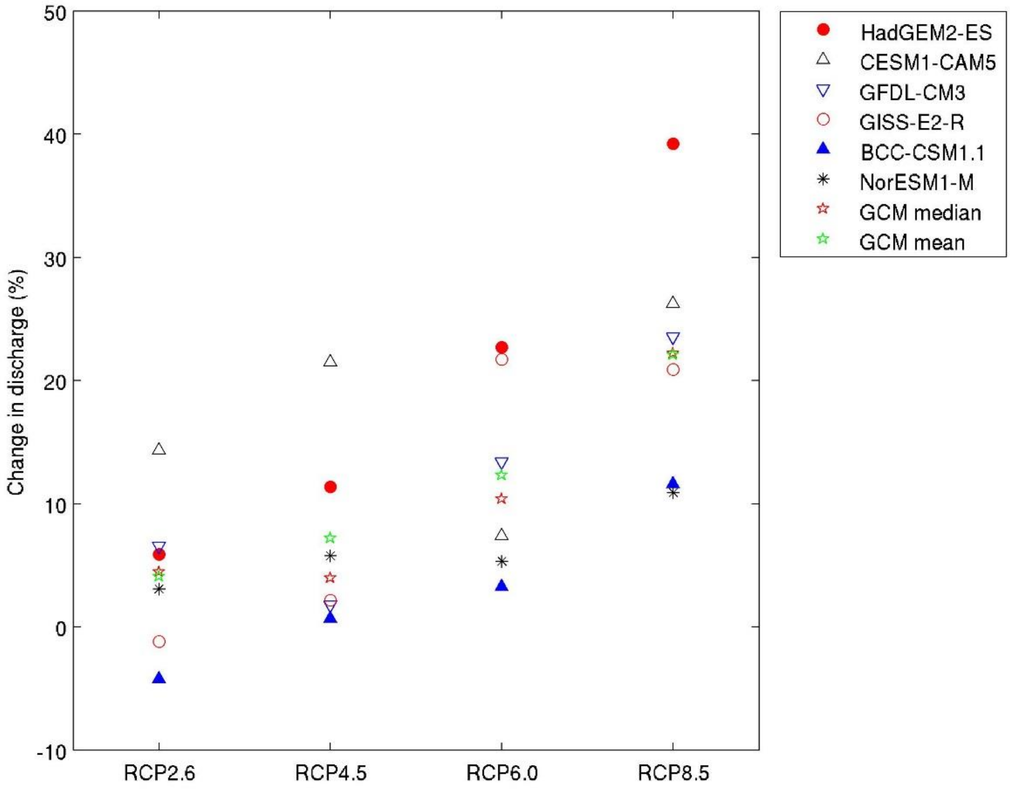


**Figure 5-1: Change in mean discharge by end of the century at the outlet of the Waikato River for individual GCMs and RCPs, including GCM means and medians.**

## 5.2 Hydrological model uncertainty

The TopNet model was designed to have a sufficiently comprehensive description of catchment hydrology to be used for the diverse range of landscapes and climate characteristics present in New Zealand. This results in a model that approximates all of the country's hydrology with the same set of hydrological process representations. TopNet is widely used in hydrological modelling applications in New Zealand; for example for operational flow forecasting (McMillan et al. 2013), to predict the hydrological impacts of climate change (Poyck et al. 2011; Zammit and Woods 2011), and for national water accounting (Collins et al. 2015).

At the start of the project the current limitations of the model include the lack of a dedicated glacier component (without coupling to a glacier energy balance model), no simulation of deep groundwater processes that transfer subsurface water between sub-catchments (Yang et al. 2016), and the use of a single ground water store in each catchment which restricts the possible recession behaviour (McMillan et al. 2011). Those limitations are currently being addressed by NIWA through improved conceptualisation and parametrisation of TopNet. The TopNet model (used in this project) was assessed against a consistent suite of test procedures aiming to quantify spatial and temporal patterns in performance of representation of various part of typical hydrological signatures within a hydrological model (McMillan et al., 2016). The authors indicate that model performance varied in space and time with better scores in larger and medium-wet catchments, and in catchments with smaller seasonal variations. The authors further acknowledge that TopNet performance was not sensitive to connectivity to large groundwater systems, making the uncalibrated model suitable for national scale assessment.

Hydrological model uncertainty is usually associated with either model parameterisation or model structure. Uncertainty associated with model parameterisation is usually estimated using an ensemble of potential model parameters, while uncertainty associated with model structure is usually addressed using an ensemble of hydrological models. In this project the hydrological model is used in an uncalibrated form and neither of these uncertainties is addressed.

## 5.3 Distinguishing climate change from climate variability

The GCMs used to drive the hydrological modelling are able to encapsulate long-term natural oscillations, such as the Interdecadal Pacific Oscillation (IPO). The IPO, as observed, has a periodicity on the order of 20 to 30 years, a period that extends beyond the time frames used to average hydrological results here. This can pose a problem in that hydrological differences between time periods (i.e., baseline, mid-century, and late-century) will reflect a combination of both gradual (but not linear) climate change as well as natural climate variation. If the simulated IPO during one projection period is out of phase from the other, then the resulting analysis would either exaggerate or downplay the effect of climate change. This effect has not been analysed, but it could be responsible for the non-monotonic trend often seen across RCPs. RCP4.5 often stands out as exhibiting more severe changes than RCP6.0, which can be traced to higher mid-century temperature increases (Ministry for the Environment 2016). This may be due to inter-annual climate variability, due to higher radiative forcing of RCP4.5 compared with RCP6.0 in the early century, or a combination of both.

## 5.4 Deterministic vs stochastic modelling

Both the GCMs and the hydrological model are deterministic and free-running. This means that the randomness that effectively pervades natural process is removed from the simulations and only one trajectory (or ‘realisation’) of hydroclimatic change is simulated for a given set of climate inputs (i.e., RCPs) or models (i.e., GCMs). Including randomness in environmental simulations is thus a good way of reflecting an important element of natural systems and could be applied in future work.

# 6 Implications for agricultural water resource and hazard management

The hydrological projections presented here paint a complex picture of changing water resource availability, water demand, and hazard exposure. There is not always a consistent trend with scenario or time period, and there is a patchwork of positive and negative changes across New Zealand and within regions, leading to a mix of opportunities and threats.

As a proxy for water demand, soil moisture deficits during spring and summer show increases for most of the country with the notable exception of portions of Canterbury. This is reflected in the projections of soil moisture reliability. The increases in deficit are most pronounced in pockets of Waikato, eastern North Island, Otago, and other portions of Canterbury. This would lead to greater water demand and pressure to abstract more water and/or store water from earlier seasons, and in extreme cases shifts to less water-demanding crops. The decreases, on the other hand, are a boon for agricultural productivity, all else being equal.

Across New Zealand, the more widespread increases in water demand generally coincide with declines in flow reliability and earlier onsets of low flow conditions. This means that run-of-river water supply would be decreasingly available where it is also increasingly in demand, prompting a need to adapt. Many areas of Canterbury and some parts of the western North Island see increases in mean discharge at the same time as water demand increases. In these areas water may be increasingly available, but not necessarily when it is demanded. The earlier onset of low flow and dry soil conditions, in many but not all regions, further highlights the changes in hydrological seasonality seen in other statistics. They also point to a potential demand for an earlier and possibly longer irrigation season.

Changing flood hazard is also nationally and regionally varied, with the greatest increases in mean annual flood in western parts of the North Island and the southern half of the South Island. This may prompt larger flood protection schemes, re-zoning, or reassessment of flood insurance. The combination of increased flood hazard and increased drought exposure emphasises that climate change can bring with it more extreme extremes, leading to combined threats for agricultural activity in these regions.

# 7 Recommendations

The research presented here encapsulates a significant step forward in analysis of the hydrological impacts of climate change. It provides a near-national assessment for two components of the water cycle of agricultural relevance (river flows and soil moisture) and a range of statistics representing these components. It is expected that these results will help shape climate change adaptation policies and interventions, but the study does not address all the information that would be of use. As requested by MPI, therefore, we make the following recommendations for future research. Aspects of some of these are contained in a new Sustainable Land Management and Climate Change (SLMACC) research project and in three research projects as part of the Deep South National Science Challenge. The list is not meant to be exhaustive and fixed, but it represents the authors' current opinions on research needed to inform agricultural policies and practices in a changing climate.

1. The analysis presented here offers a relatively coarse interpretation of the results. We recommend delving into the data further on a regional basis and for nationally important river basins.

2. Agricultural water resources include river flows, soil moisture, and aquifers. We recommend that future assessments of this nature include at least groundwater recharge if not also groundwater levels and associated lag times.

3. In addition to assessing changes to water supply, we recommend that the effects of climate change on changes to water demand be addressed as well.

4. The mean annual flood (MAF) is a benchmark flood magnitude used in flood design in New Zealand, but it is not the most pertinent variable for flood management. It is estimates of the 1-in-50 year flood or the 1-in-100 year flood, for example, that are more important. We thus recommend that future analysis includes estimates of these statistics.

5. The relevant flood statistics used in flood management (e.g., the 1-in-100 year flood) represent periods of time that far exceed the 20-year analysis windows used in the analysis reported here. This poses a problem for standard flood frequency analysis as it assumes stationary conditions (i.e., hydrological conditions that do not change over the study period). With climate change, however, this assumption is invalid. We thus recommend that a method for non-stationary flood frequency analysis be developed for New Zealand flood management applications.

6. The severity of floods and droughts not only depends on the peak flow or water shortage for individual farms or river reaches, but also on the spatial extent of coincident flooding and drought. The more extensive the disaster, the more severe the impacts on agricultural activity, on the economy, and on disaster relief efforts. More frequent disasters, which are not captured by the analysis in this report, also compromise agricultural activity. We thus recommend that a future climate change impact assessment focus on water-related disaster severity in its entirety – local and regional intensity, spatial extent, and recurrence.

7. The GCM projections used in this analysis represent single trajectories of hydrological change. This makes it difficult to assess the range of plausible hydrological outcomes due to the randomness of the climate and hydrological systems. We thus recommend that, once the data and tools are available, climate change impacts are reassessed using ensemble projections, providing a better representation of model uncertainties.

8. The GCM projections used in this analysis combine both climate warming and natural climate variability (e.g., El Nino-Southern Oscillation and Interdecadal Pacific Oscillation). This means that hydrological differences in a future window of time may reflect the effect of climate change, may reflect the effect of climate variability, or a mixture of the two, making it difficult to isolate the climate change contribution. Indeed, this may contribute to the fact that RCP4.5 often produces more extreme hydrological changes than RCP6.0 mid-century. We thus recommend that future climate change impact studies, encompassing both the climate and hydrological effects, attempt to tease out the direct climate change effect from the background climate variations.

9. The four RCPs are identified by differences in their final global radiative forcings. However climate and hydrological effects are not a linear function of these forcings, particularly mid-century when RCP4.5 is very close to RCP6.0 and may even exceed the latter in some ways. Focusing on just two reporting time periods clouds these decadal changes. We thus recommend that future reporting of climate change effects be made on the basis of moving windows instead of fixed isolated windows.

10. While it is valuable to project how hydrological conditions may change in the future it is also valuable to know when these changes become either statistically ‘significant’, or relevant in an agricultural/hydrological context. One component of smart climate change adaptation is the effective timing of adaptation actions; it is possible that climate change impacts will be too small in some locations or within some time periods to warrant adaptation. We thus recommend that climate change impact assessments estimate when ‘significant’ changes are projected to occur.

11. Quantifying and communicating uncertainties of climate change effects is complex and not thoroughly understood. We recommend that science providers and science users develop a joint understanding on how to best represent uncertainties to more accurately inform policy decisions.

12. Once the hydrological effects of climate change are understood, it would be necessary to translate them into agricultural, economic, social, environmental and other effects. For example: crop yield is liable to change, affecting farm revenue and wider labour market and other economic activities; severe droughts affect mental health; and lower river flows may affect the catchment nutrient loading limits necessary to meet environmental and social objectives. Thus we recommend that future assessment of impact of climate change include social and economic assessment.

13. Once a thorough understanding of the effects is obtained it is necessary to identify how to adapt, however it is not necessary to wait until a thorough hydrological understanding has been developed. Adaptation options to consider include: reservoirs and on-farm dams; inter-basin water transfers; changes to water allocation rules, including more explicit allocation for supply reliability; changes in crop types, crop genetics and crop management; agricultural forecasting tools (short-term and seasonal); and precision agriculture. This list is neither complete nor restricted only to climate change applications.

# 8 Conclusions

Anthropogenic climate change is projected to alter New Zealand's weather over the course of this century resulting in a range of hydrological changes with implications for agricultural water resource and hazard management. The hydrological modelling presented here shows that the changes vary across hydrological statistics, regions, scenarios, and time periods, providing both potential opportunities and costs for the industry as a whole.

- **Northland**: Drier conditions are seen across Northland for MALF, the mean and Q5 discharges, and soil moisture, resulting in lower reliability for flows and soil moisture and earlier onset of dry conditions. This contrasts with slight increases in mean annual flood. Spring and summer are the driest seasons experiencing the largest reduction in terms of soil moisture.
- **Auckland**: Drier conditions are seen across Auckland for MALF, the Q5 discharge, and soil moisture, with lower reliability for flows and soil moisture and earlier onset of dry conditions. This contrasts with slight increases in mean annual flood, and to a lesser extent mean discharge. Spring and summer are the seasons experiencing the largest reduction in terms of soil moisture.
- **Waikato**: Waikato shows a regional patchwork of increases and decreases in the various hydrological statistics. Mean and high flows increase while low flows broadly decrease, and reliability of both flow and soil moisture tend to decline. These changes indicate an increase in the variability of hydrological conditions across the region, with extremes becoming more extreme.
- **Bay of Plenty**: Bay of Plenty shows a mix of wetter and drier conditions, with a tendency towards drier for most statistics, but wetter for the mean annual flood.
- **Gisborne**: Gisborne is projected to become drier across river flow and soil moisture statistics alike. Even the mean annual flood, which is projected to increase in other regions, shows light increase here.
- **Taranaki**: Taranaki shows mixed hydrological responses to change, with general increases in flows and soil moisture conditions, but also some declines.
- **Hawke's Bay**: Across most statistics, Hawke's Bay is projected to become progressively drier, although the severity of change varies within the region. The main exception is that the high flows – Q5 and more so mean annual flood – show increases.
- **Manawatu-Wanganui**: The two overall patterns seen in the hydrological results are that the extremes become more extreme – the dry become drier and the wet become wetter – and that there is a west-east gradient in response to climate change with the west tending towards wetter conditions and the east towards drier.
- **Wellington**: While the mean annual flood is projected to increase, in general, for Wellington, most other hydrological statistics indicate a decline in the availability of water.
- **Tasman**: In general, Tasman is projected to become drier, in terms of both river flows and soil moisture. The mean annual flood flow, however, is projected to increase.

- **Nelson**: In general, Nelson is projected to become drier, in terms of both river flows and soil moisture. The mean annual flood flow, however, is projected to increase.
- **Marlborough**: Wet and dry conditions are projected to both become more extreme under climate change, particular the mean annual flood and spring and summer soil moisture conditions.
- **West Coast**: The West Coast is generally projected to become wetter under climate change, particularly for higher scenarios and the later in the century. The north of the region, however, shares some properties with the adjoining Tasman and is projected to become drier.
- **Canterbury**: Canterbury exhibits the most complicated response to climate change of all the regions, as well as among the most extreme changes. These changes include substantial decreases in water availability as well as increases, which are particularly high in south Canterbury. Mean annual flood is also projected to increase substantially in parts of the region.
- **Otago**: Otago shows a mix of increases and decreases in water availability, whether river flow or soil moisture. The mean annual flood is also projected to increase substantially in parts of the region.
- **Southland**: While portions of Southland are projected to become dry for some hydrological statistics, the region is generally projected to become wetter. This is particularly true for the mean annual flood.

As with all climate change projections there is a degree of uncertainty with the results. The largest source of uncertainty rests with the scenario – we simply do not know how the global community will continue with its greenhouse gas emissions and changes to radiative forcing. Uncertainties in the modelling itself, whether of the climate system of the hydrological cycle, add additional uncertainties, but these have not been quantified.

The implications for agricultural water resource and hazard management vary with the hydrological changes. In most cases water demand is projected to increase, but the opportunity to abstract water in these areas is generally expected to decline, putting greater pressure on water resource management and agricultural productivity. The flood hazard is projected to remain about the same or increase; in some areas the increases are substantial. Increased flood exposure is projected for areas with minimal increases in water shortage as well as severe increases, potentially compounding the challenges faced by local agricultural activities.

# 9 Glossary of abbreviations and terms

| | |
|---|---|
| AR5 | Assessment Report 5 for IPCC5 |
| CMIP5 | Coupled Model Intercomparison Project Phase 5 |
| DEM | Digital Elevation Model |
| GCM | Global Climate Model |
| IPCC4 | Intergovernmental Panel on Climate Change Fourth Assessment |
| IPCC5 | Intergovernmental Panel on Climate Change Fifth Assessment |
| IPO | Interdecadal Pacific Oscillation |
| LCDB v.2 | Land Cover Database version 2 |
| MAF | Mean Annual Flood |
| MALF | Mean Annual Low Flow |
| MPI | Ministry for Primary Industry |
| NES | Proposed National Ecological Statement for Ecological Flows |
| PED | Potential Evapotranspiration Deficit |
| Q5 | River flow that is exceeded 5 per cent of the time |
| REC1 | River Environmental Classification version 1 |
| RCP | Representative Concentration Pathway |
| SST | Sea Surface Temperature |

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