Potential climate change impacts on streamflow in the Manuherekia catchment

Prepared for Otago Regional Council

December 2020

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NIWA CLIENT REPORT No: 2020324CH
Report date: December 2020
NIWA Project: ORC20501

Revision	Description	Date
Version 1.0	Final Report	7 December 2020

Quality Assurance Statement		
	Reviewed by:	Roddy Henderson
	Formatting checked by:	Rachel Wright
	Approved for release by:	Helen Rouse

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Executive summary

As part of ongoing work that NIWA is carrying out to help Otago Regional Council with water management and water plan development for the Manuherekia catchment, a climate change impact assessment on natural river flows was carried out. The aim was to assess if and when climate change is likely to affect flow regimes and associated environmental flow estimation at each proposed water allocation control point within the Manuherekia catchment. This was carried out to ascertain whether the impacts of climate change on flow regime are expected to impact currently designed environmental flows across the Manuherekia catchment. If this is the case, climate change will have to be explicitly taken into account in the setting of environmental flows at all control points over the Manuherekia surface water catchment.

Climate change, through changes in precipitation patterns and increases in temperature, poses a significant challenge to water resources and users of water such as primary industry (which is an important water resource user in this catchment). Historical increases in temperature are projected to continue this century, accompanied by shifts in rainfall patterns. These could have a range of impacts on the country's water cycle and in turn on the availability of water across a wide range of users. The scale and timing of the effects depends largely on the magnitude of global efforts to curb greenhouse gas emissions (known as mitigation). Regardless of mitigation actions, the climate is already changing, and decisions need to be made to adjust to the changes in water resources (known as adaptation). In order to inform both mitigation and, particularly, adaptation decisions, it is important to understand the potential effects. This report builds upon earlier studies of the hydrology of the Manuherekia catchment (Henderson et al. 2019) by coupling a hydrological model calibrated for the Manuherekia catchment with climate projections considering when *effects may become discernible or significant*. The report considers only the effects and impacts of climate change alone and does not consider any other related changes such as land use, economic or social conditions.

Assessments of climate change impacts on the hydrological regime in the Manuherekia catchment was carried out by using climate change projections to drive a calibrated hydrological model, TopNet. Modelling considered four climate change scenarios over the period 1971-2060. Analysis was carried using 20-years periods overlapping each other by ten years, spanning from 2006 to 2060 (e.g. analysis carried out over the period 2030-2050 to represent changes in the 2040s) to represent the dynamic aspect of the climate.

Key results are as follows:

- High flows are expected to increase by over 5% by 2050;
- Median and mean flows are expected to slightly increase up to 5% by 2050;
- Low flows and Mean Annual Low Flow calculated over a running 7 day period (7-day MALF) are expected to slightly increase up to 5% by 2020 before decreasing back to their historical level by 2050, except in the Manuherekia headwaters where low flows are expected to decrease by up to 5%;
- Seasonally, mean and median discharge over Winter-Spring and Autumn are expected to increase with warming across the Manuherekia catchment, while mean and median discharge during Summer are expected to decrease from the 2020s onward;

- Low flows during the irrigation season (taken from September to March) are expected to increase in Spring, while decreasing in Summer. This behaviour is spatially variable as Summer low flows are expected to increase by the 2020s and decrease to their historical simulated levels by the 2050s for Ida Burn, while Spring flows at Falls Dam are projected to increase up to the 2020s before reducing to their historical simulated level by 2050s;
- Median number of consecutive days below hindcast 7-day MALF is not expected to change with warming, while the maximum number of events of five consecutive days is expected to increase by up to 10 occurrences. If 7-day MALF is used as a water consent threshold, this would point towards a shift in the distribution of periods where water consent will be restricted with restriction being less often but potentially lasting longer;
- Analysis of the Wilcoxon Signed Rank test[1] indicates that across the Manuherekia catchment changes in discharge are extremely likely to be associated with climate change effects (95% confidence level) for a majority of the overlapping time periods analysed over the period2006 to 2060.

[1] Wilcoxon signed-rank test is a nonparametric test that can be used to determine whether samples were selected from populations having the same distribution. In our case it is used to assess if historical and climate change driven simulations belong to the same population.

1 Introduction

To allow water management and water plan development for the Manuherekia catchment, Otago Regional Council (ORC) need to develop an understanding of catchment hydrology and water use so that policy options and rule scenarios can be assessed. To develop those policies ORC needs to explore the effects of minimum flow setting at three locations (Campground, Ophir and Dunstan Creek at Beattie Road) and below the major irrigation take points on the main stem (Omakau, Blackstone, Manuherekia and Galloway).

The Manuherekia catchment is a very challenging one for water resource assessment. Data collection of river flows has been intermittent at many sites, and most are affected by upstream water diversions or water storage. There are approximately 600 km of water races in the catchment, and three large managed reservoirs (Falls Dam, Manor Burn/Greenland reservoir and Pool Burn reservoir). This water infrastructure services more than 20,000 ha of irrigated agriculture.

Phase 1 of the minimum flow setting project aimed to explore the effects of minimum flow setting at three locations (Campground, Ophir and Dunstan Creek at Beattie Road) and below the major irrigation take points on the main stem (Omakau, Blackstone, Manuherekia and Galloway). As a result, Phase 1 of this investigation focusses on establishing those minimum flows and NIWA was in charge of developing a natural flow hydrological model (TopNet) for all the reaches within the Manuherekia catchment. TopNet has been successfully applied to the Manuherekia (Henderson et al. 2019), and simulated natural flows are thus available for the period 1972 to 2018. In combination with a GOLDSIM model (developed by Manuherekia irrigators), this will allow ORC to test alternative scenarios for minimum flow at various points in the catchment, and potentially in future to assess the potential impact of water allocation decisions.

Climate change is a major concern for water resources, hydro-electricity generation and agricultural production globally (IPCC 2014; Rosenzweig et al. 2014) and in New Zealand (Collins et al. 2012), particularly given the importance of freshwater-dependent agriculture for New Zealand's economy. The importance of reliable water resources to New Zealand's economy is highlighted by diminished economic returns during droughts (Treasury 2016). As droughts are projected to worsen as a result of increasing temperatures and changing precipitation patterns (Ministry for the Environment 2018), the potential impacts of hydrological droughts on the New Zealand economy are expected to worsen, all else being equal.

The country has warmed about 1°C over the past century (Mullan et al. 2010) and is projected to warm by a further 0.3 to 5.0°C over the next century (Ministry for the Environment 2018), largely depending on the trajectory of radiative forcing (carbon and methane emissions) followed by the global community. Precipitation patterns are also projected to change this century (Ministry for the Environment 2018), with shifts in timing and magnitude (both up and down). The changes projected for both temperature and precipitation vary spatially and seasonally, with more warming in summer/autumn and in the north, reductions in precipitation in the north and east, and increases in precipitation elsewhere. This is expected to lead to greater drought intensity in many regions, particularly in the north and east of the North Island and the east of the South Island, and correspondingly greater water demand to maintain constant levels of productivity.

The effects of changing temperature and precipitation would also translate to changes in freshwater supply, with seasonal and regional differences. A report by Collins and Zammit (2016) describes the most comprehensive study to date on the implications for New Zealand's water resources in agricultural regions. In the report they summarise projected climate change effects on river flows for the Otago region as follows:

- Change in mean flows are spatially and temporally variable. Mean annual flows are expected to increase with the increased radiative forcing in Otago with time;
- Mean annual low flows (MALF) are generally expected to decrease in Otago, however the marked downward trend is not generalisable across the entire Otago region;
- Low flow conditions are expected to be reached earlier in the water year (spanning July to June) for much of the Otago region, increasingly so with higher radiative forcing scenarios and towards the end of the century;
- 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.

Increases in drought and greater variability in river flow will have implications for agricultural water supply. However, current climate change projections (Collins and Zammit 2016) indicate that changes in river flows for the South Island of New Zealand are more variable, resulting in variable supply of irrigation water in those areas (Srinivasan et al. 2011). Under the National Policy Statement for Freshwater Management 2020 (Ministry for the Environment 2020), councils are required to have regard to the foreseeable impacts of climate change while setting water allocation and water quality limits. How water users and water managers alike would best adapt to climate change is likely to depend on factors including how much the water supply and agricultural demands change, and when they change.

The purpose of the present report is thus to build upon previous studies and better quantify:

1. Future change in natural hydrological characteristics at annual and seasonal time scales (defined as Q25[2] (referred to hereafter as large discharge flow threshold), mean, median, Q75 (referred to as low discharge flow threshold) and 7-day MALF), and the frequency of such events in each season;
2. Future change in the magnitude of low flow events (defined as Q75) during the irrigation season;
3. Future change in the frequency of historical 7-day MALF discharge;
4. Future change in the number of consecutive events and the number of consecutive five-day events where discharge is below hindcast 7-day MALF.

[2] QX represents the river flow threshold at a specific location that is exceeded X percent of the time over the period of analysis.

2 Methods

Due to uncertainties in current estimation of leakage and return flows through the 600 km of water races servicing more than 20,000 ha of irrigated agriculture, two TopNet models representing two extreme scenarios were generated during Phase 1 of the project. The first scenario assumes set reduction factors between Falls Dam and water takes on the main stem (referred as TopNet-Red), while the second scenario (referred as TopNet-upper limit) assumes no reduction factors between Falls Dam and Manuherekia main stem water take points (Henderson et al. 2019, Table 3-1). This was developed to provide ORC with a potential range of current flow conditions and associated low flow hydrological characteristics

To assess the potential impacts of climate change on natural hydrological regimes up to 2050, we coupled the TopNet-upper limit model with climate change projections for New Zealand (Ministry for the Environment 2018). The model was run continuously from 1971 to 2060, with the spin-up year 1971 excluded from the analysis. The climate inputs were stochastically disaggregated from daily to hourly time steps.

The data analysed are the daily time-series of river flow summarised at each location of interest (presented in section 2.2). Each data set is the end result of sequential climate and hydrological modelling for combinations selected under six Global Climate Models (GCMs) and four Representative Concentration Pathways (RCPs: each RCP represents a trajectory of the evolution of the past and future climate radiative forcing- assimilated to level of CO2 in the atmosphere), from 1971 up to 2060, resulting in a 24-member ensemble of simulations. As the GCM simulations are "free-running" (based only on initial conditions, not updated with observations), comparisons between present and future hydrological conditions can be made directly (as each GCM is characterised by specific physical assumptions and parameterisation), but this also means that simulated hydrological hindcasts do not track observational records.

2.1 Climate data

Following on from the fifth Intergovernmental panel for Climate Change (IPCC) assessment report (AR5) (IPCC 2014), NIWA assessed up to 41 GCMs from the AR5 model archive (referred hereafter as Coupled Model Intercomparison Project version 5 or CMIP5) 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 2018). This analysis provided performance-based ranking based on New Zealand's historical climate. Six GCMs were chosen as being better at representing climate dynamics around New Zealand and for spanning a useful range of climate change sensitivities. The GCMs were driven by four scenarios (the RCPs) of future emissions of greenhouse gases and aerosols, as well as by natural processes including solar irradiance and historical emissions. They were otherwise free-running in that they are not constrained by historical climate observations. GCM outputs (i.e., boundary conditions and Sea Surface Temperatures or SST) were then used to drive a Regional Climate Model (RCM) to refine the variables to a more useful spatial scale for the country. The output of the regional climate modelling became the input for the hydrological modelling analysed here after rudimentary bias correction. Further details on the validation and the GCM and RCM modelling can be found in Sood (2014) and Ministry for the Environment (2018).

The downscaled climate data used here run from 1971 to 2100 (Ministry for Environment 2018). 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 the century.

It is important to note that 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 vary across combinations of RCP-RCM simulations.

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 2018)		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)

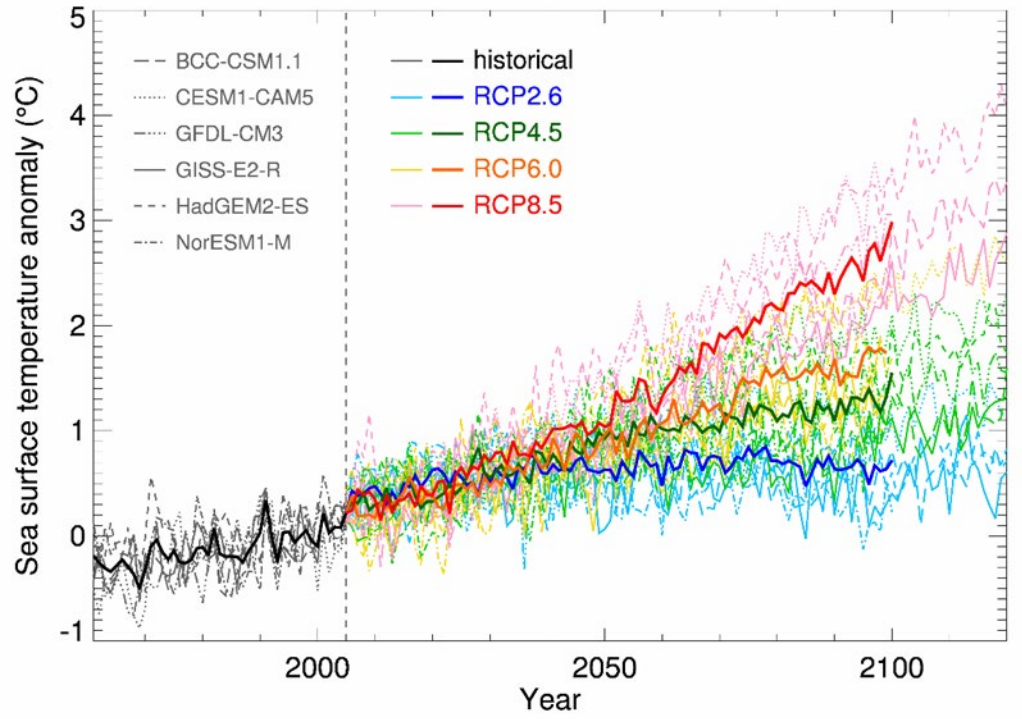

Figure 2-1: CMIP5 global climate models (2006-2120), the historical simulations. Bias-adjusted SSTs, averaged over the RCM domain, for 6 (1960-2005), and four future simulations (RCPs 2.6, 4.5, 6.0 and 8.5), relative to 1986-2005. Individual models are shown by thin dotted or dashed or solid lines (shown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

In order to understand how climate change may affect water availability it is important to consider a suite of variables characterising changes in low flow and high flow hydrological characteristics. For this application seven characteristics are chosen, calculated from the numerical output of the hydrological model. The seven variables are:

1. Static hydrological characteristics:

   1.1 7-day Mean Annual Low Flow (7-day MALF);

   1.2 Mean and Median discharge;

   1.3 Magnitude of discharge defined by Q25 and Q75 (m^3/s). Those thresholds represent the discharge event thresholds that are exceeded 25 percent (i.e., high flow threshold) and 75 percent (i.e., low flow threshold) of the time.

   1.4 Change in frequency of current 7-day MALF discharge.

2. Seasonal hydrological characteristics:

   2.1 Summer, Autumn, Winter and Spring mean and median flow;

   2.2 Magnitude of discharge defined by Q75 (m^3/s) during irrigation season (September to March).

3. Dynamic hydrological characteristics:

   3.1 Average, Median and Maximum number of consecutive days below location specific 7-day MALF;

   3.2 Average, Median and Maximum number of consecutive five-day events below the location specific 7-day MALF.

The simulations results were analysed for three time slices:

- January 1986-December 2005 being the hindcast (i.e., reference) period for climate change assessment;
- January 2006-December 2020 being the “near future” period for which climate change driven hydrological simulations can be compared with streamflow observations collected by ORC; and
- Four 20-years periods overlapping by 10 years each spanning 2010 to 2060, described in full at 2.3 below. The generation of the information over the overlapping 20-years period will enable ORC to “track” how flow characteristics are likely to change during water plan life cycle and most of the consent allocation duration.

The simulations were generated for 13 locations within the Manuherekia catchment. Those locations include:

- Existing streamflow gauging stations;
- Falls Dam inflows;
- Connection reach for Lauder, Chatto, Thomsons and Dunstan Creeks with Manuherekia main stem.

Table 2-2 provides the list of location for which the simulations are available and their associated New Zealand digital network number (nzsegment ID), while Figure 2-2 maps their locations.

Table 2-2: Simulation time series extraction locations.

Location	nzsegment	Location	nzsegment
Dunstan at Manuherekia	14218317	Ida Burn at Manuherekia	14222457
Dunstan Creek at Gorge	14205377	Chatto Creek at Matakanui Station	14223804
Falls Dam outflow	14209801	Thomsons Creek at Manuherekia	14226818
Dunstan Creek at Beattie Road	14214374	Manuherekia at Ophir	14226993
Lauder Creek at Cattle Yards	14215781	Chatto Creek at Manuherekia	14230928
Thomsons Creek at Diversion Weir	14218605	Manuherekia at Campground	14236711
Lauder Creek at Manuherekia	14221401		

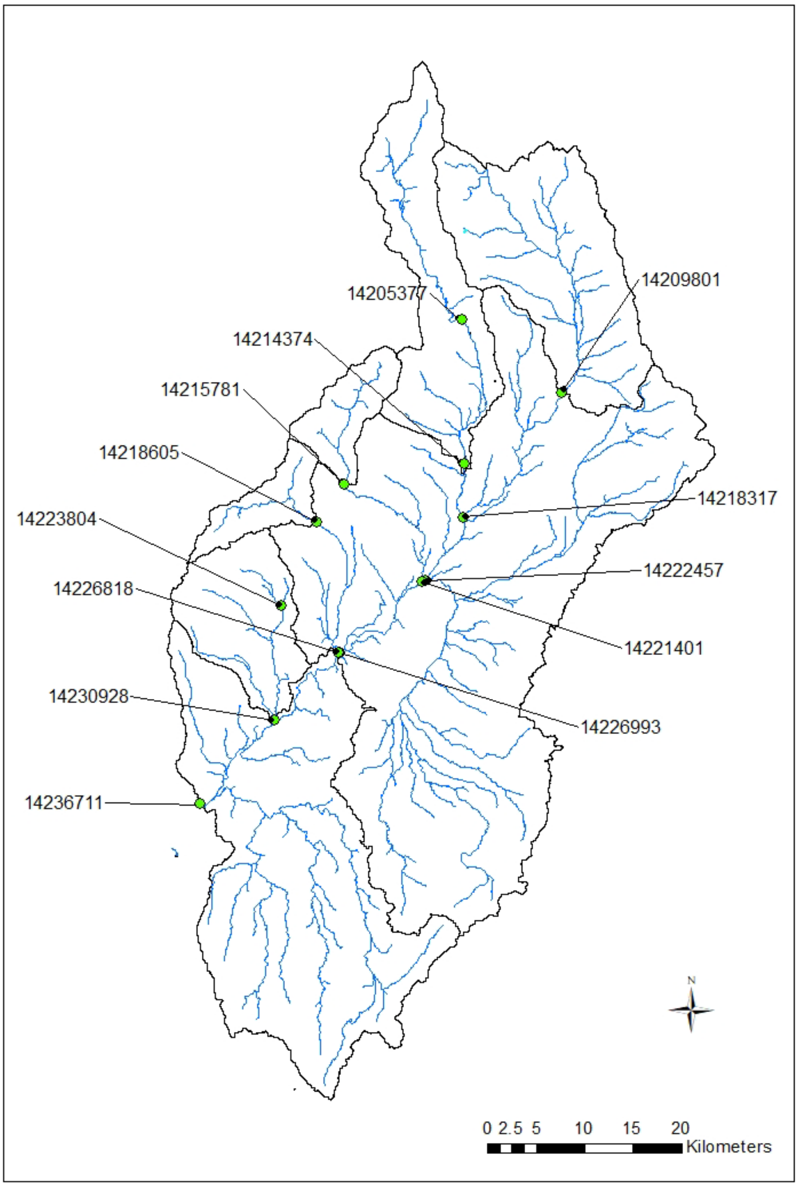

Figure 2-2: Location of analysis. Spatial location represented by green dot with nzsegment being used as identifier.

2.3 Measuring a climate change effect

To measure the effect of climate change on the chosen variable, simulated data from the baseline period from mid-1985 to mid-2006 (20-years) are compared to five centred time periods: 2006-2020 (referred as 2010s), and four 20-years periods overlapping by 10 years each: 2010-2030 (referred as 2020s); 2020-2040 (referred as 2030s); 2030-2050 (referred as 2040s); and 2040-2060 (referred as 2050s). The numbered year indicates the calendar year of the hydrological year. The first period is reduced by six years to represent the "near future period" during which observations are available. The magnitude of the effect is determined by the difference between the hydrological characteristics or thresholds calculated over the baseline and future periods.

An additional point to account for, however, is that not all numerical differences are significant. It could be that the calculated difference between two periods is small compared with the natural (modelled) variability from year to year. In this situation, while there may be a climate change effect, it would be too small to be statistically discernible. To identify the significant differences, then, the baseline and future datasets are compared using the Wilcoxon Rank Sum test using a confidence limit, α, of 0.5 and 0.66 (equivalent to a p value of 0.5 and 0.34 in T test, respectively)

Results of this analysis are presented as follows:

- Change in hydrological characteristics and their ranges across the six GCMs. Change is expressed as a percentage of the simulated hindcast hydrological characteristic;
- Median and maximum number of consecutive events and the number of consecutive five-day events below 7-day MALF. This comparison is carried out with the historical MALF estimated by Henderson et al. (2019) and provides information on the potential change in duration of those discharge "events" with time and radiative forcing (tabular results are presented in Appendices A, B and C). The change in number of consecutive five-day events is used as a proxy for change in high stress periods for freshwater ecological systems;
- Quantile of current MALF discharge as provided by Henderson et al. (2019) across time slices;
- Tables of p-value indicating the significance of the climate change effect on the simulated hydrological characteristics.

2.4 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 2018), 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). Also the median is 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

The results presented in this section are presented graphically for each variable of interest. RCM driven climate simulations (not VCSN driven simulations) were coupled to the VCSN calibrated hydrological model for each surface water catchment. Each graph is organised as follows:

1. Each colour and symbol represent a specific RCP;
2. The thick dotted line represents for each variable the annual/seasonal median of the variable calculated across the six GCMs for each RCPs (i.e., one value for each hydrological year);
3. The upper dotted thin lines represent for each variable the annual/seasonal maximum of the variable calculated across the six GCMs for each RCPs. Correspondingly the lower dotted thin lines represent for each variable the annual/seasonal minimum of the variable considered;
4. All the time slices are represented on the graph.

For the hindcast period there is no difference across the different radiative forcing scenario. As a result, analysis of the variable of interest is the same across all radiative forcing scenarios and resulting changes are set to 0. The upper and lower values represent the range of the hindcast ensemble for each variable of interest.

For clarity results in section 3 are presented only for four locations, with the results for the remaining locations being presented in Appendix A to Appendix K. The four locations in the main body of the report are:

- Manuherekia at Campground- nzsegment 14236711;
- Manuherekia at Ophir- nzsegment 14226993;
- Manuherekia at Ida Burn- nzsegment 1422257; and
- Falls Dam outflow – nzsegment 14209801.

3.1 Static hydrological characteristics

3.1.1 High flows - Q25

Figure 3-1 presents the change in high flow hydrological characteristics, as defined by Q25, across the 20-years centred time slices from the 1990s to 2050s.

Analysis of the change in high flows indicates:

- As the climate warms natural high flow characteristics are projected to slightly increase, by around 5% by 2050s, across the Manuherekia;
- Climate change simulations exhibit a large sensitivity across the different GCMs within each RCP;
- Largest changes across the catchment are not expected to be associated with the higher radiative forcing, but with the lowest;

- The near future time slice exhibits slightly higher high flow than the hindcast period. This confirms the results of the rainfall sensitivity analysis, which indicates higher flows characteristics over the period 2014-2018 than over the period 1973-2018 (Zammit 2020).

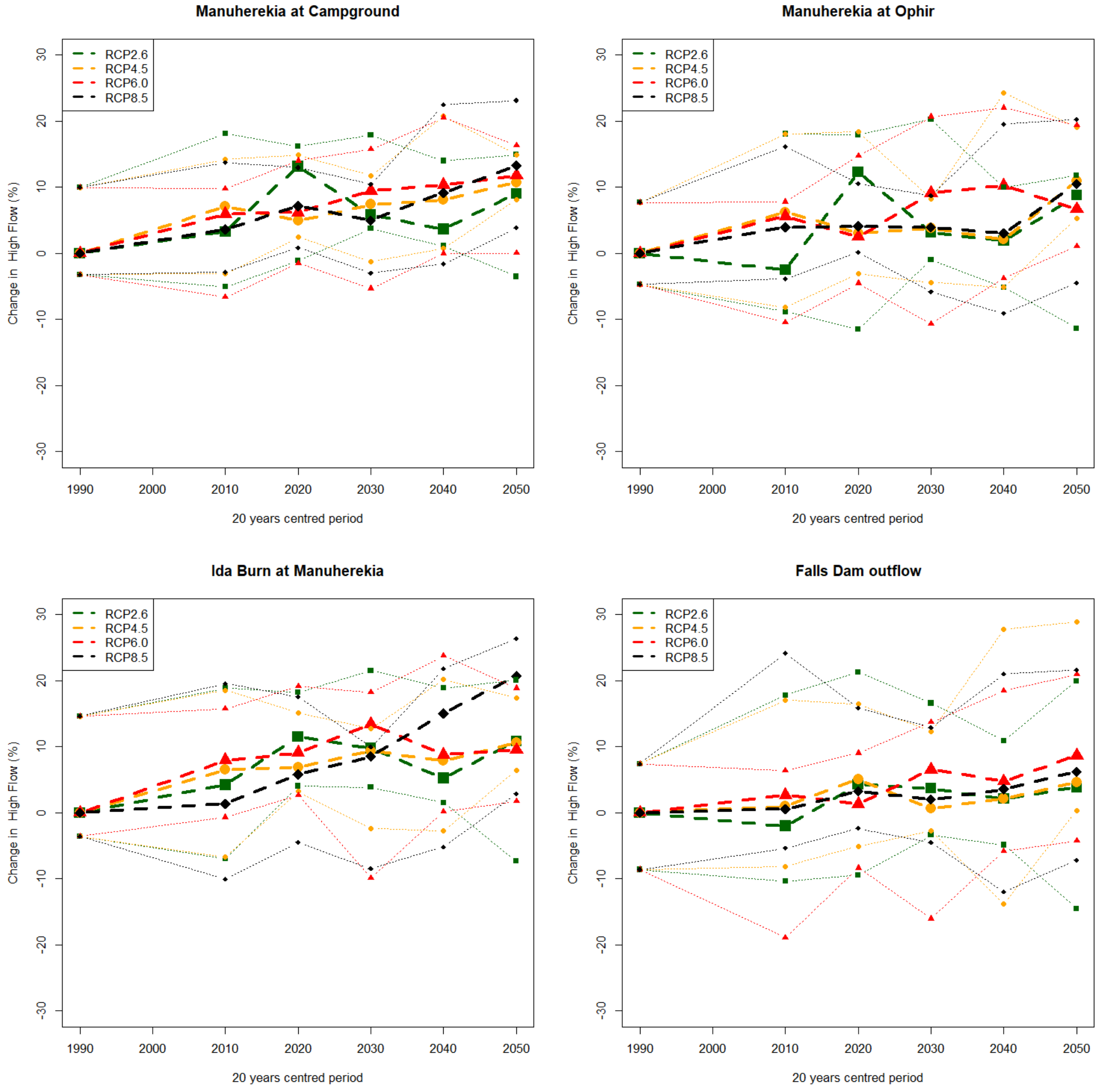

Figure 3-1: 20-years centred change in high flow (Q25) across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

3.1.2 Average and Median flows

Figure 3-2 presents the change in average flows across the 20 year centred time slices from the 1990s to 2050s, while Figure 3-3 presents the change in median flows.

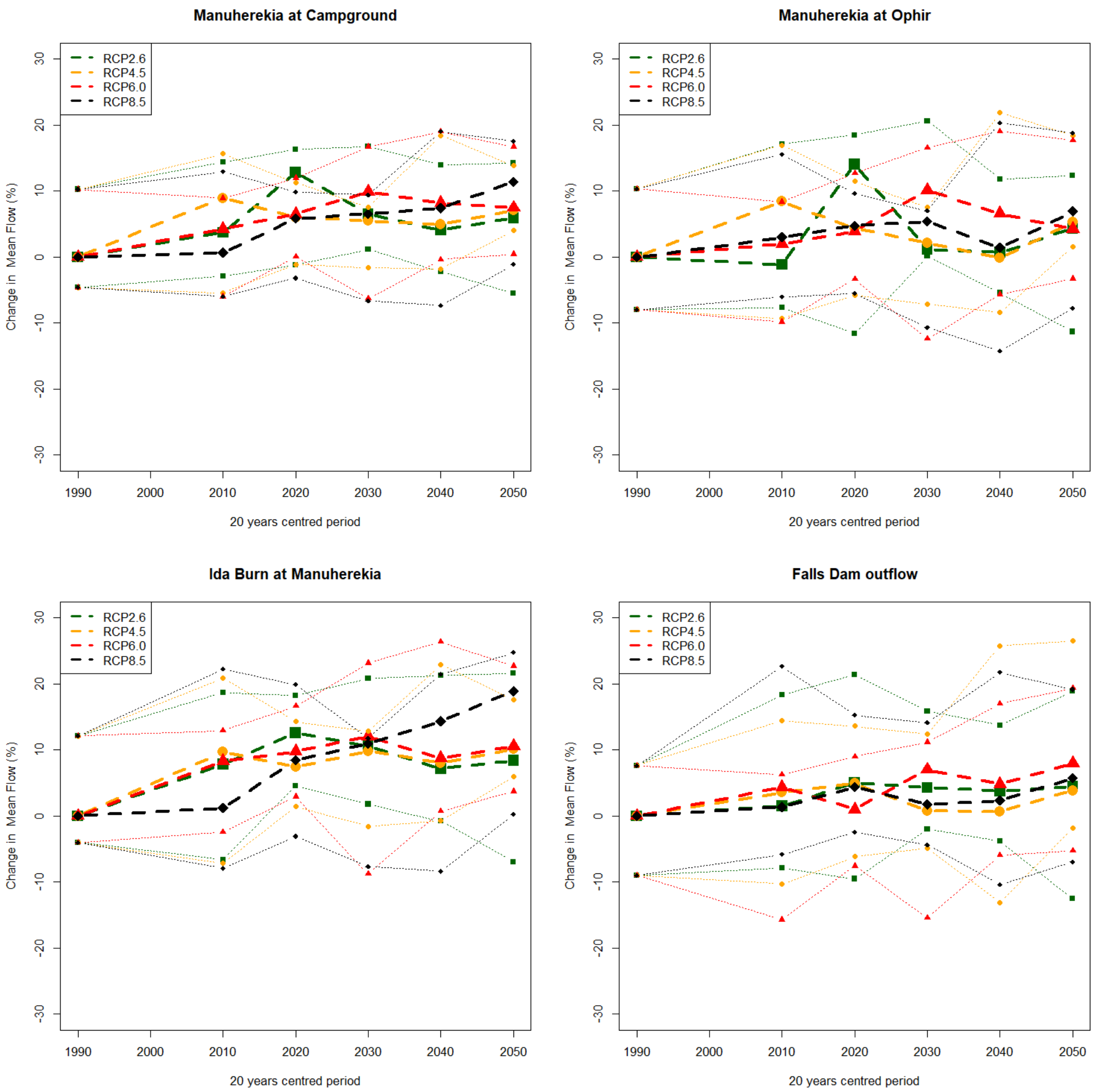

Figure 3-2: 20-years centred change in mean flow across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

Analysis of the change in mean and median flows indicates:

- As the climate warms natural mean flows are projected to slightly increase, by around 5% by 2050s, while Median flows are much more sensitive to climate warming up to the 2050s;

- Climate change simulations exhibit a large sensitivity across the different GCMs within each RCP;
- Mean flows are expected to slightly increase up to the 2050s, except for Falls Dam under RCP4.5 for the 2020-2040 time slice;
- The near future time slice exhibits slightly higher and sensitive mean and median flows than the hindcast period. This confirms the results of the rainfall sensitivity analysis, which indicates higher flow characteristics over the period 2014-2018 than over the period 1973-2018 (Zammit 2020).

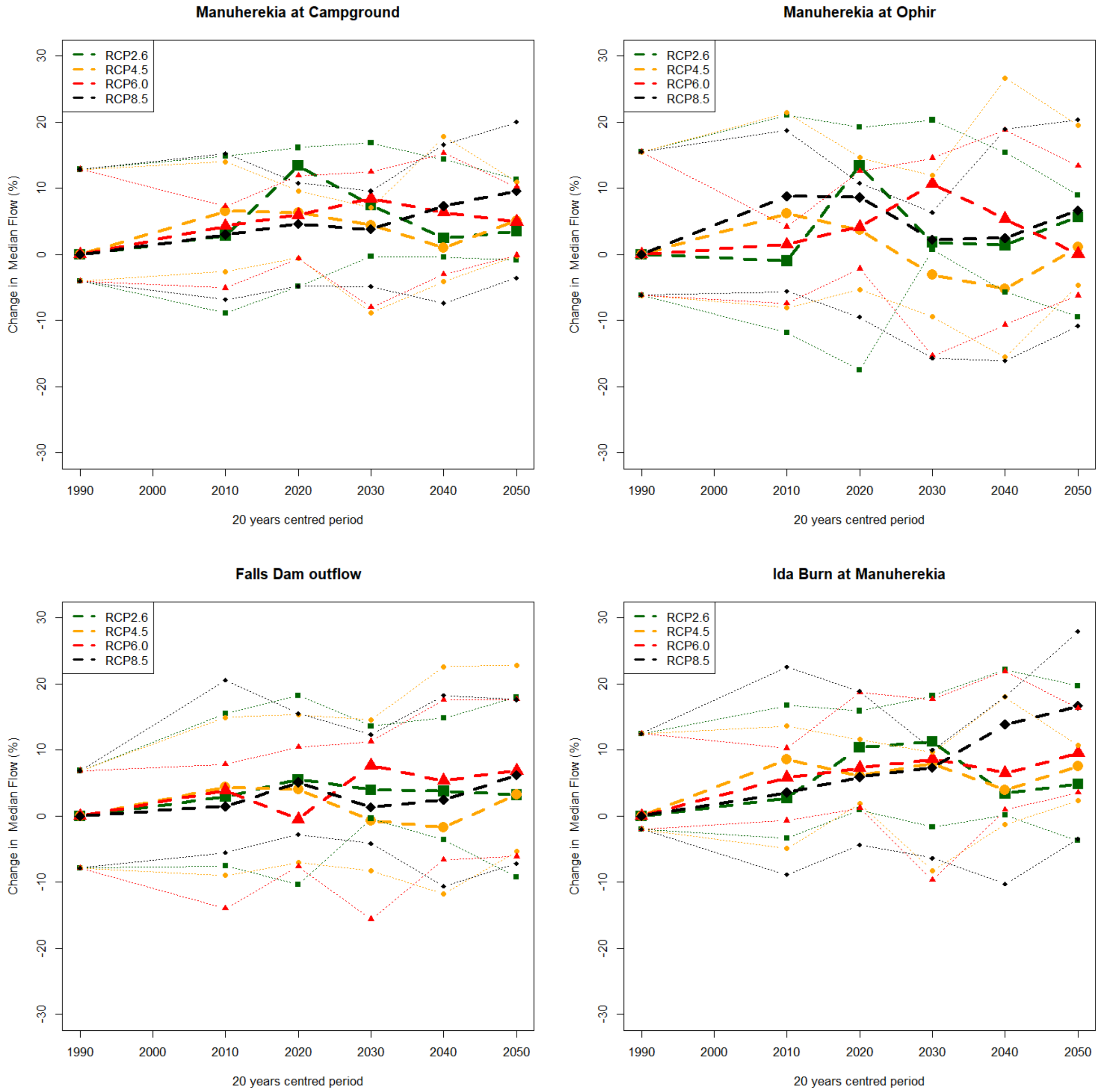

Figure 3-3: 20-years centred change in Median flow (Q50) across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

3.1.3 Low flows - Q75

Figure 3-4 presents the change in low flow hydrological characteristics, as defined by Q75, across the 20-years centred time slices from the 1990s to 2050s.

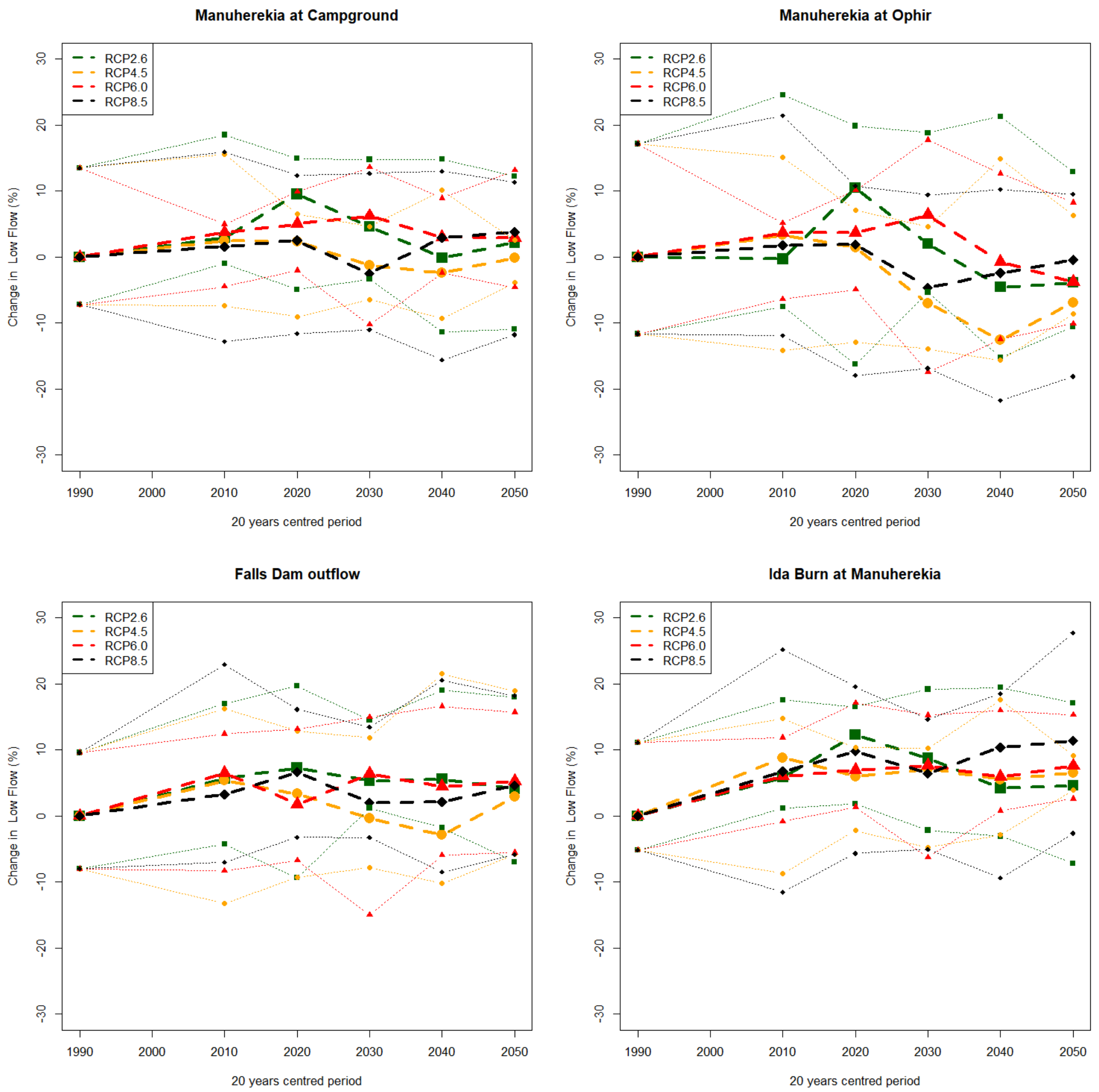

Figure 3-4: 20-years centred change in low flow (Q75) across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

Analysis of the change in low flows indicates:

- With warming change in low flow characteristics do not follow the same pattern as change in high-average and median flows;

- Low flow characteristics are expected to slightly increase for the near future and 2020s time slice (except in the catchment headwaters). The following three time slices are consistently exhibiting decreases in low flows characteristics from the 2020s time slice, with sharp decreases experienced in the 2040s and a recovery in the 2050s;
- By the 2050s time slice, low flows are expected to be at the same level as those during the hindcast period, except for the Ida Burn where low flows are expected to increase across RCPs and the headwaters for which low flow characteristics are expected to decrease;
- Climate change simulations exhibits a large sensitivity across the different GCMs within each RCP;
- The near future time slice exhibits slightly higher low flow than the hindcast period, except for the headwater catchments where low flows are expected to decrease across most of the RCPs.

3.1.4 7-day MALF

Figure 3-5 presents the changes in 7-day MALF across the 20-years centred time slices from the 1990s to 2050s.

Analysis of the changes in 7-day MALF indicates:

- With warming, changes in low flow characteristics do not follow the same pattern as changes in low flow;
- 7-day MALF is generally expected to slightly increase for the near future time slice and then consistently decrease across RCPs up to the 2040s before slightly recovering in the 2050s;
- By the 2050s time slice, 7-day MALF is expected to be at the same level or smaller than those during the hindcast period, except for the Ida Burn where 7-day MALF is expected to increase across RCPs;
- Climate change simulations exhibits a large sensitivity across the different GCMs within each RCP;
- The near future time slice exhibits slightly higher 7-day MALF than the hindcast period.

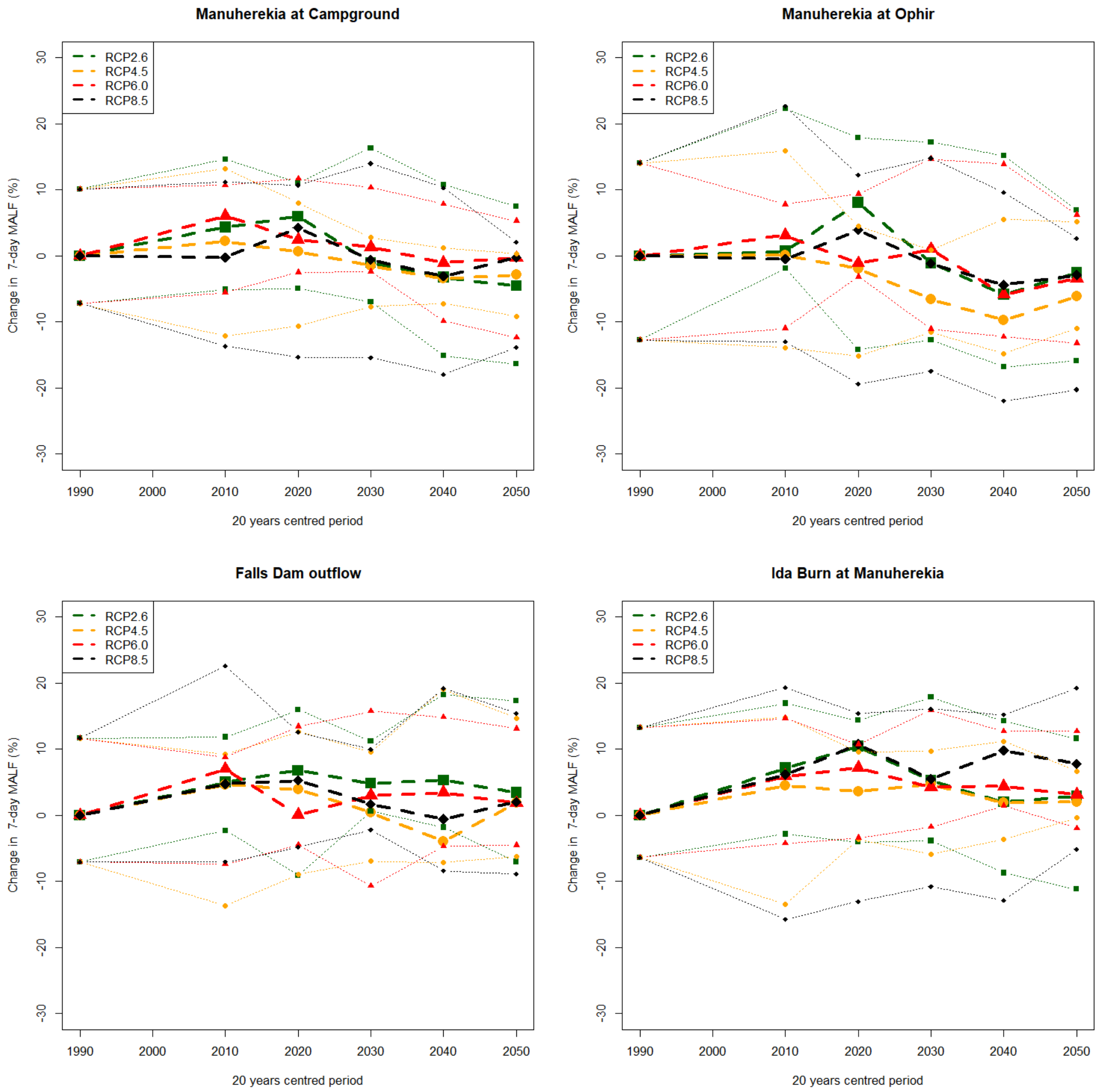

Figure 3-5: 20-years centred change in 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

3.2 Seasonal hydrological characteristics

3.2.1 Mean and Median flows

Figure 3-5 to Figure 3-9 present the change in mean flow across the 20-years centred time slices from the 1990s to 2050s across the four seasons, while Figure 3-10 to Figure 3-13 present the change in the median flows for each season.

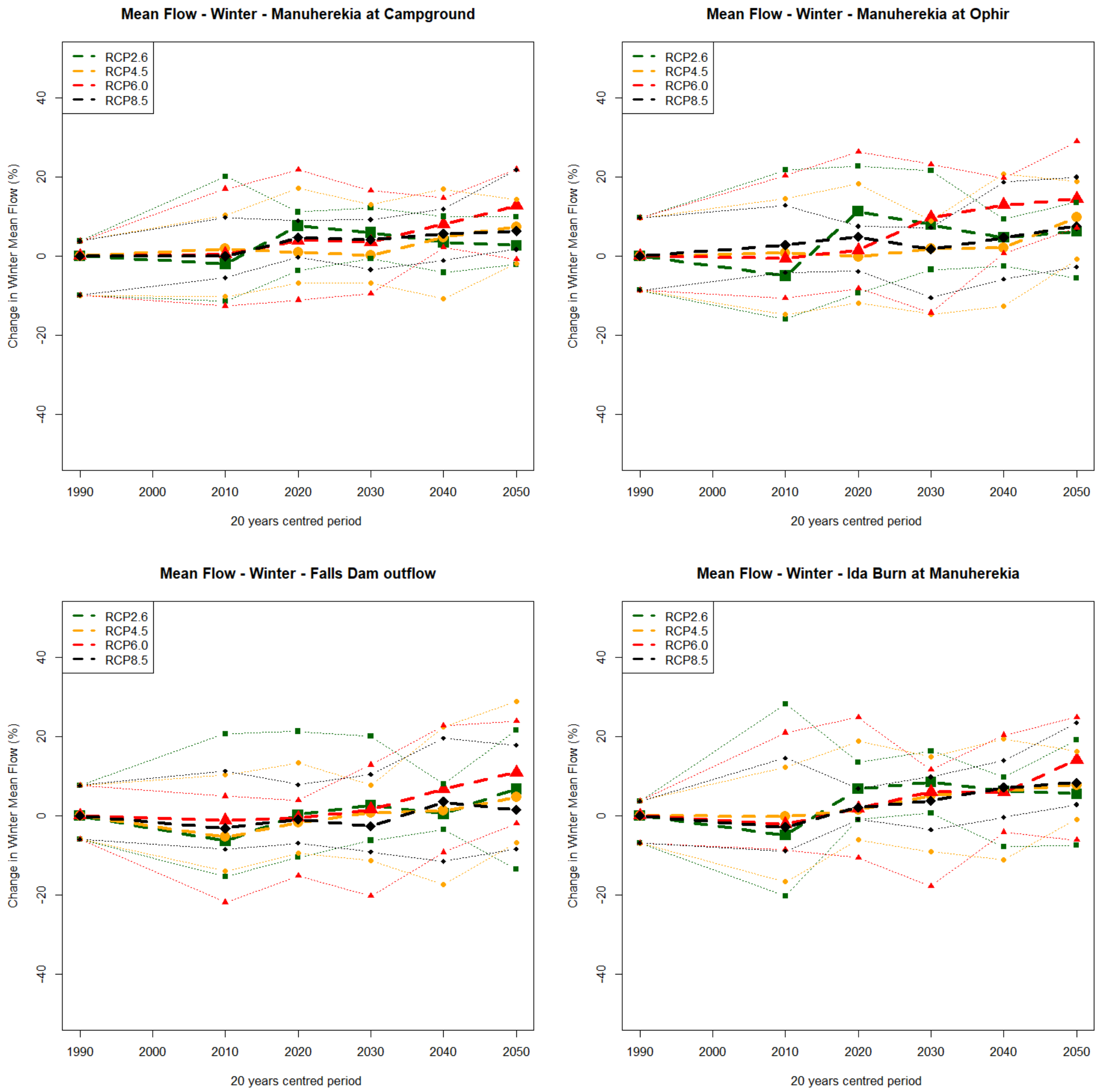

Figure 3-6: 20-years centred change in Winter Mean flow across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

Analysis of the change in mean and median seasonal flows indicates:

- Climate change simulations exhibit a large sensitivity across the different GCMs within each RCP;
- Winter mean and median flows are expected to increase with warming by around 10% by the 2050s;

- Spring mean flows are expected to increase with warming above 10% by the 2050s, except for Falls Dam where changes are expected to be negligible or less than 10%.

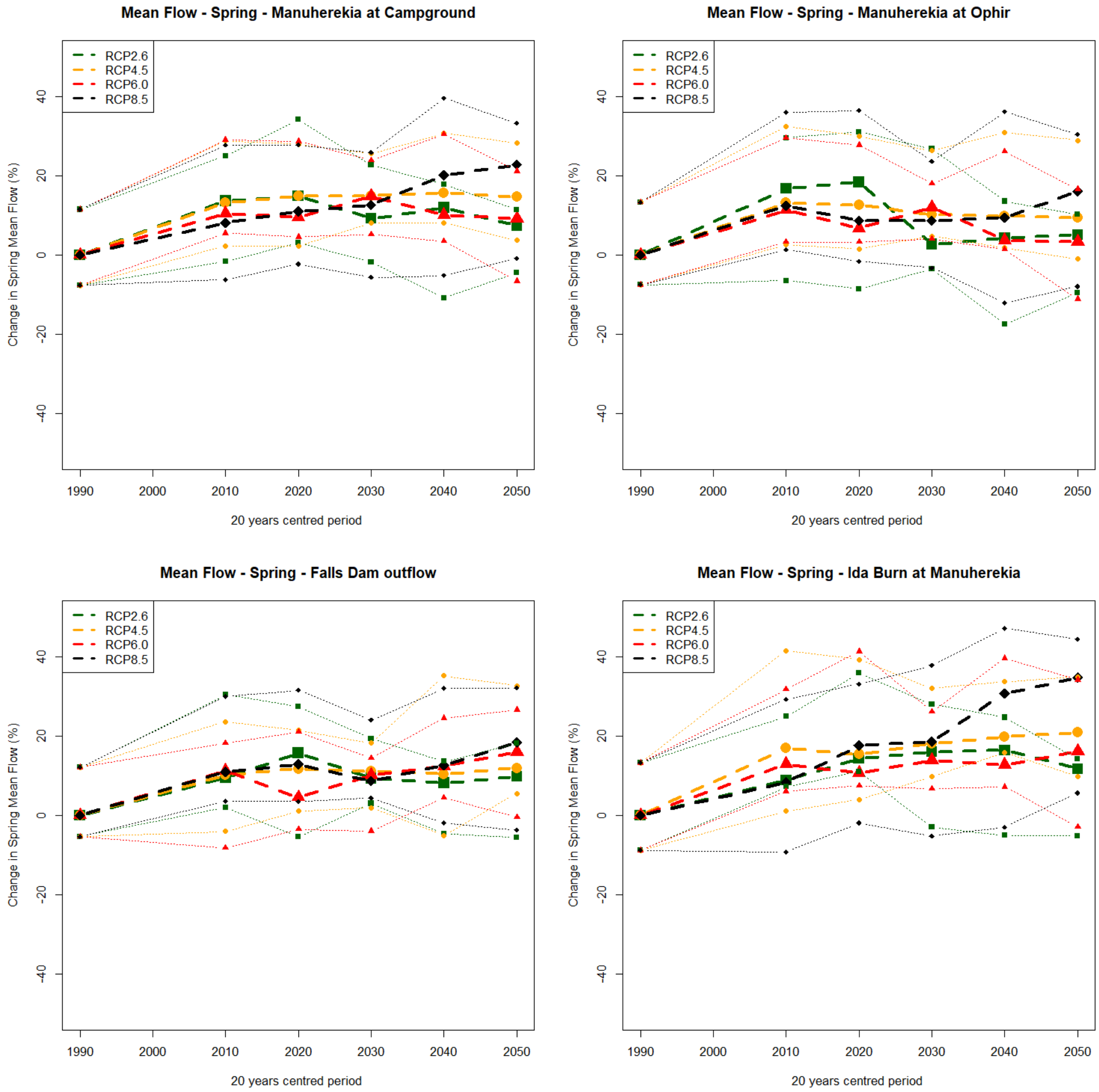

Figure 3-7: 20-years centred change in Spring mean flow across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

- Changes in Spring median flows exhibit a different behaviour over the same period. The lower Manuherekia still exhibits increases in median discharge (below 10%), but to a lower level than for the mean. However, changes in Median flows for Falls Dam indicate that median flows reach their peaks during the 2020s time slice and then decrease to their hindcast levels or lower by 2050s time slice. This behaviour is thought to be linked with an increase in high flow events during Spring;

- Summer mean and Median flows are slightly increasing or remaining similar to hindcast summer mean flow up to the 2020s time slice, before consistently decreasing to historical levels or lower by the 2050s. Change at Falls Dam exhibits a different pattern as change in Median flows indicate a sustained decrease by at least 10% (compared to historical levels) by the 2020s.

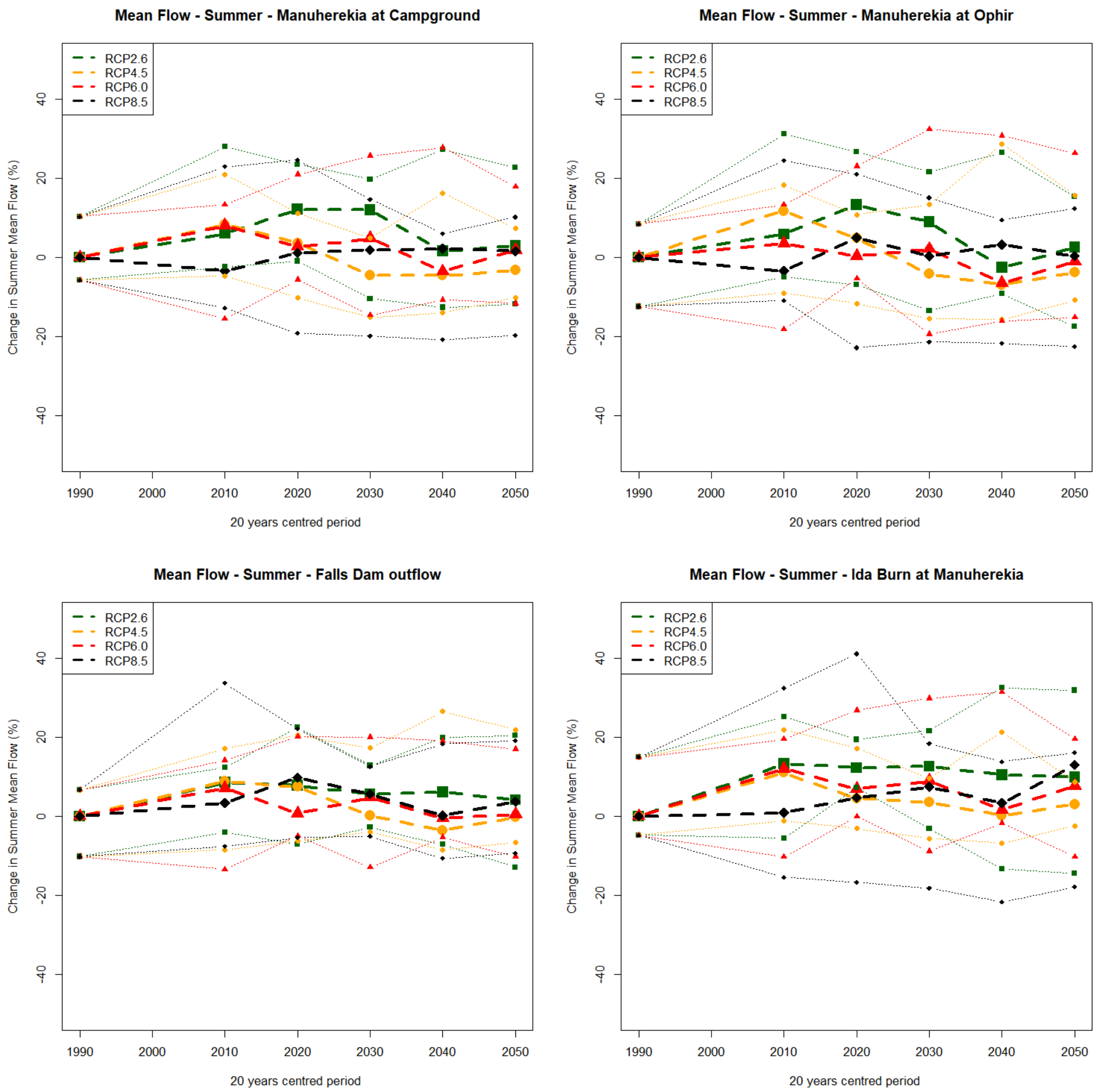

Figure 3-8: 20-years centred change in Summer mean flow across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

- Changes in Autumn mean and median discharge are consistent across the Manuherekia. Autumn discharge is expected to decrease over the 2010s time slice, before consistently increasing by up to 10% by the 2050s.

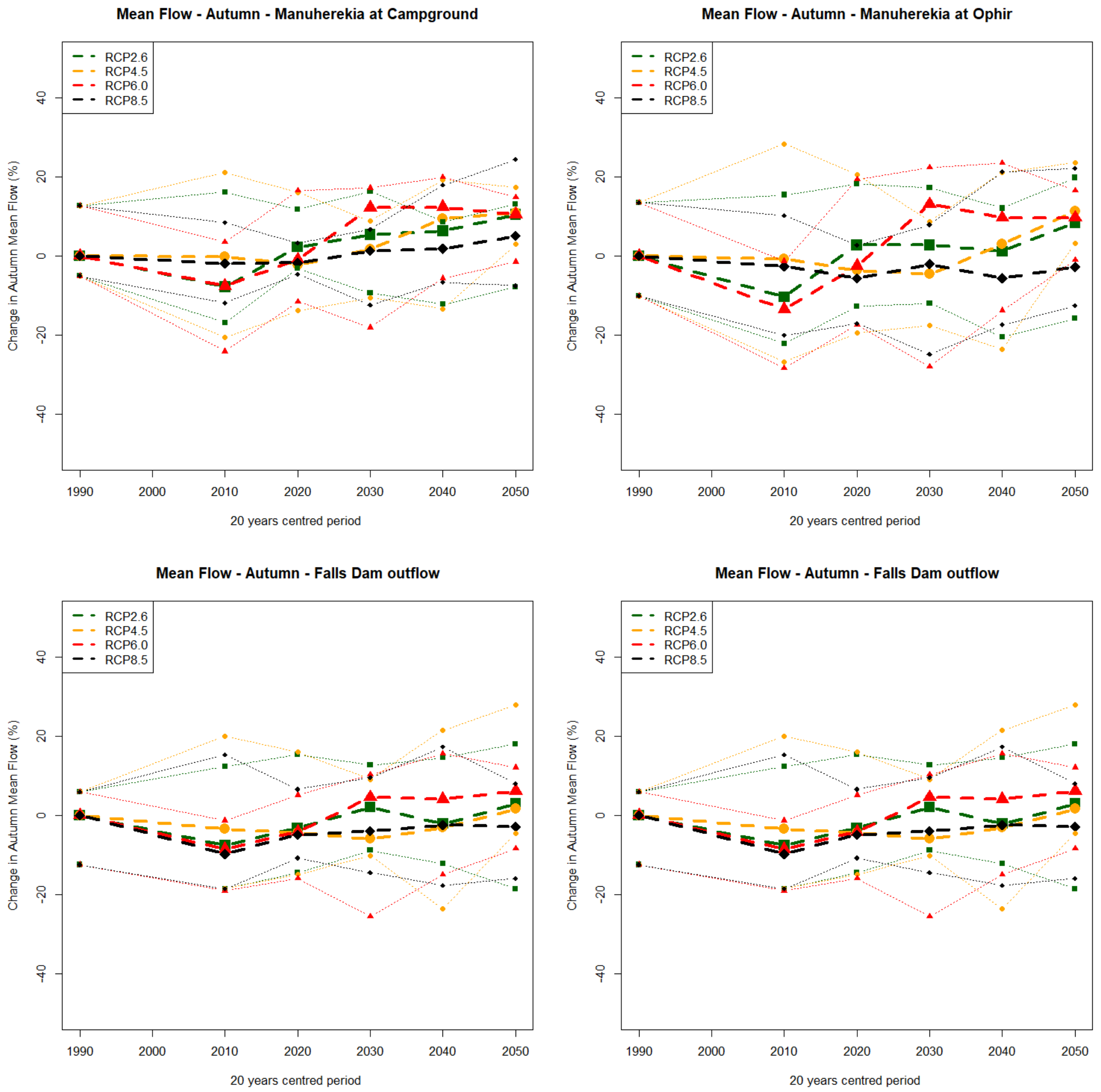

Figure 3-9: 20-years centred change in Autumn mean flow across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

- Slight changes (positive or negative) to hindcast conditions characterise the near future time slice. Campground and Ophir exhibit similar changes across the four seasons while Ida Burn and Falls Dam exhibit different behaviour depending on the warming scenario.

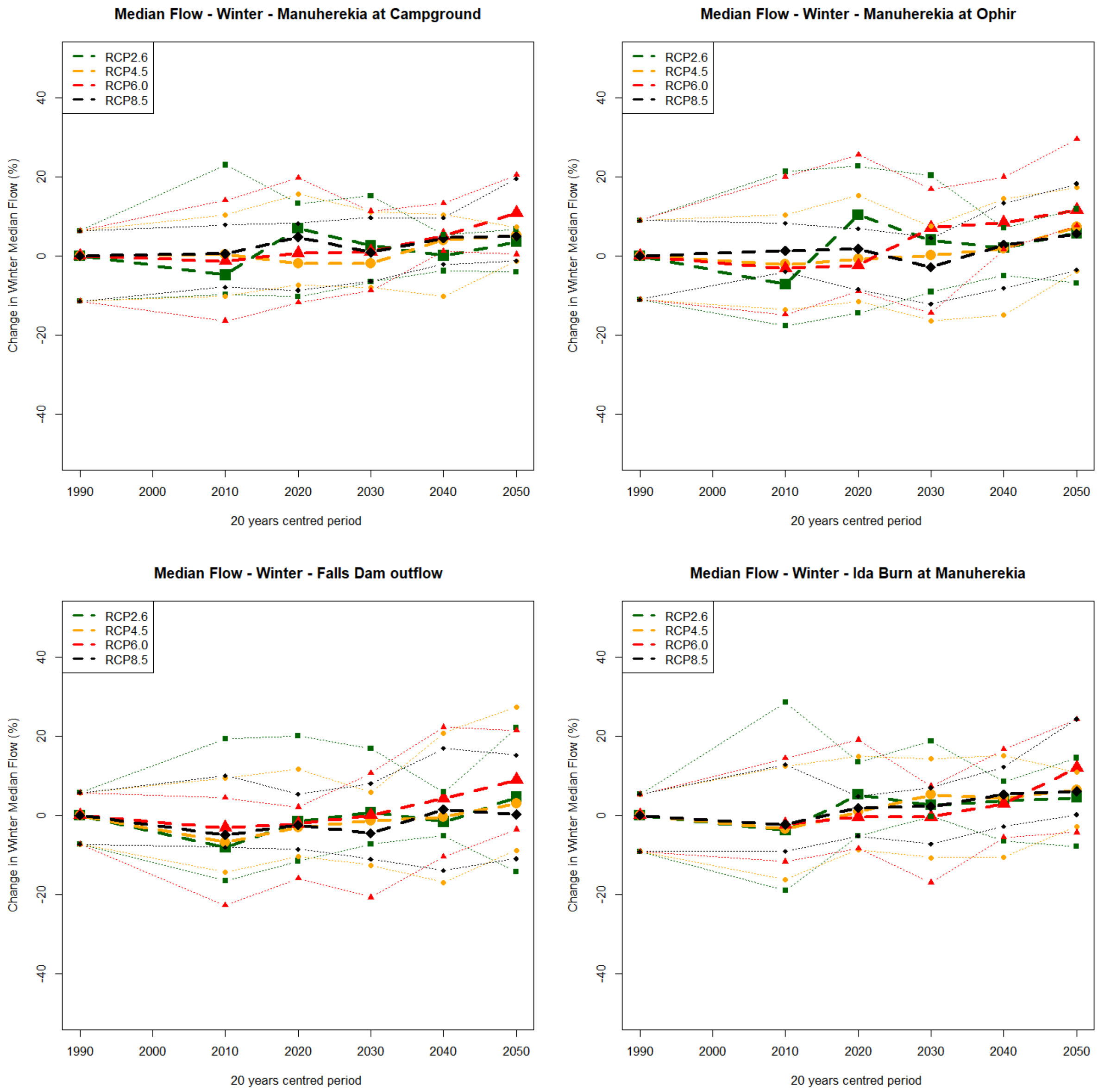

Figure 3-10: 20-years centred change in Winter Median flow across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

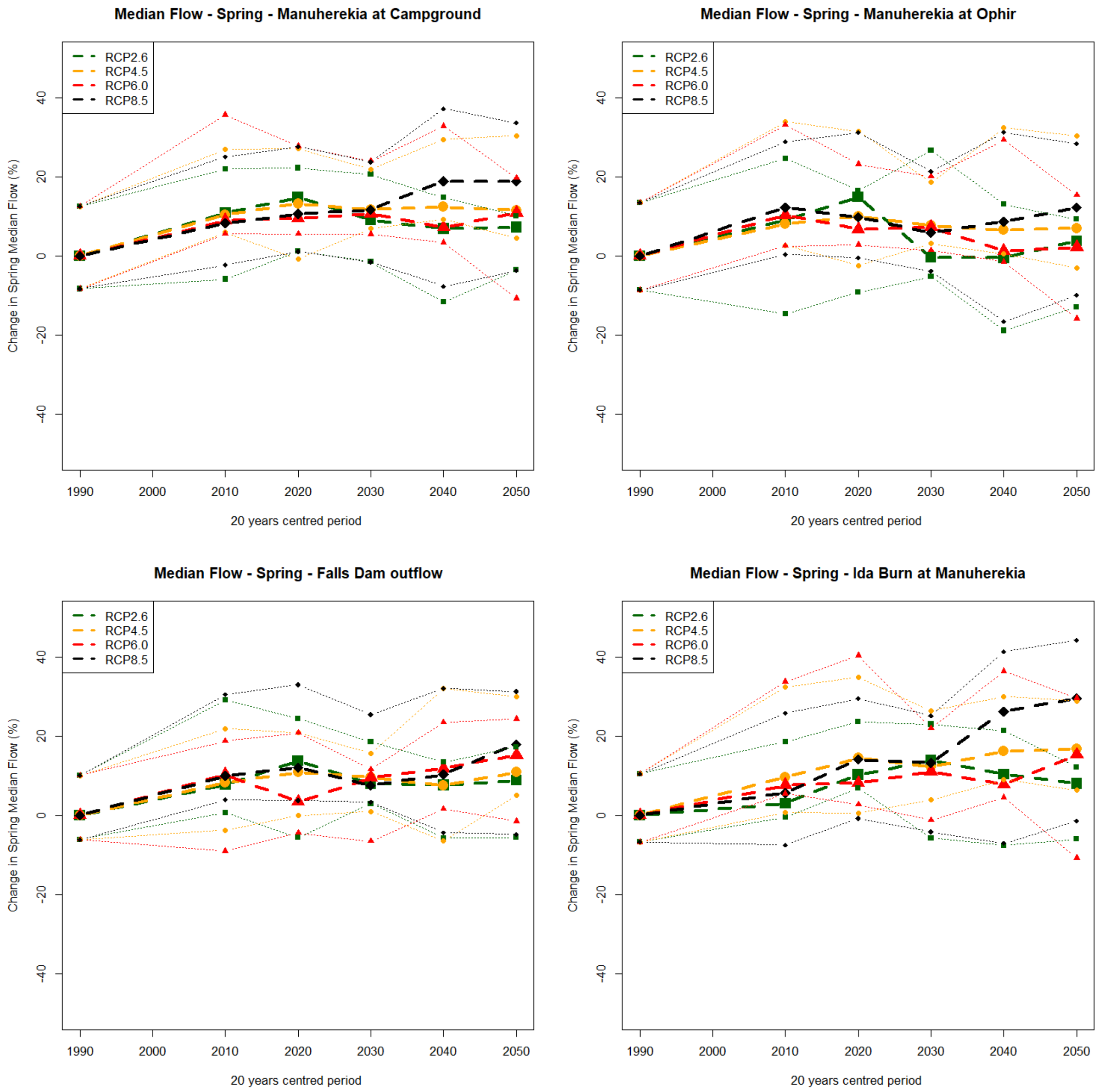

Figure 3-11: 20-years centred change in Spring Median flow across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

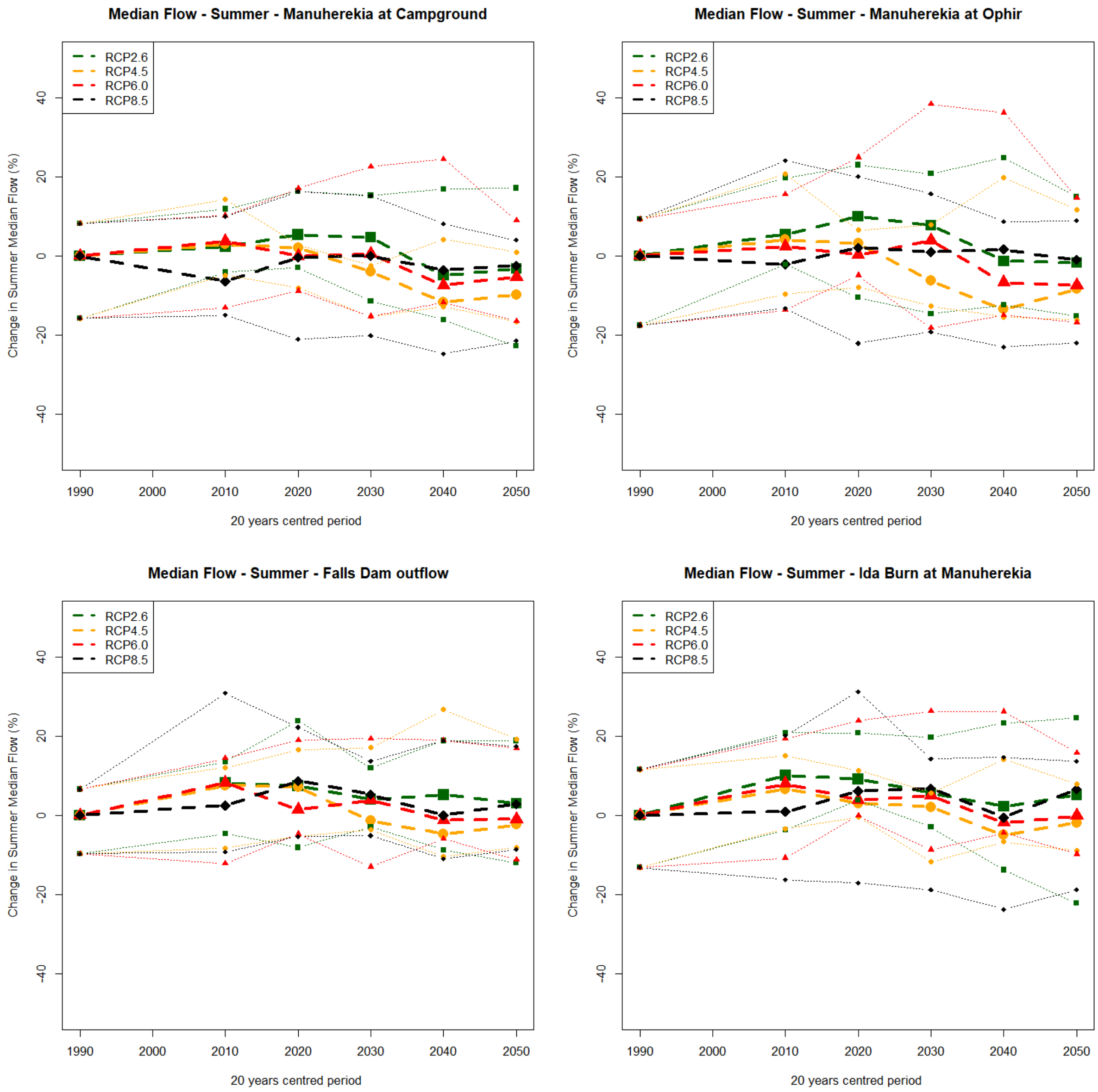

Figure 3-12: 20-years centred change in Summer Median flow across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

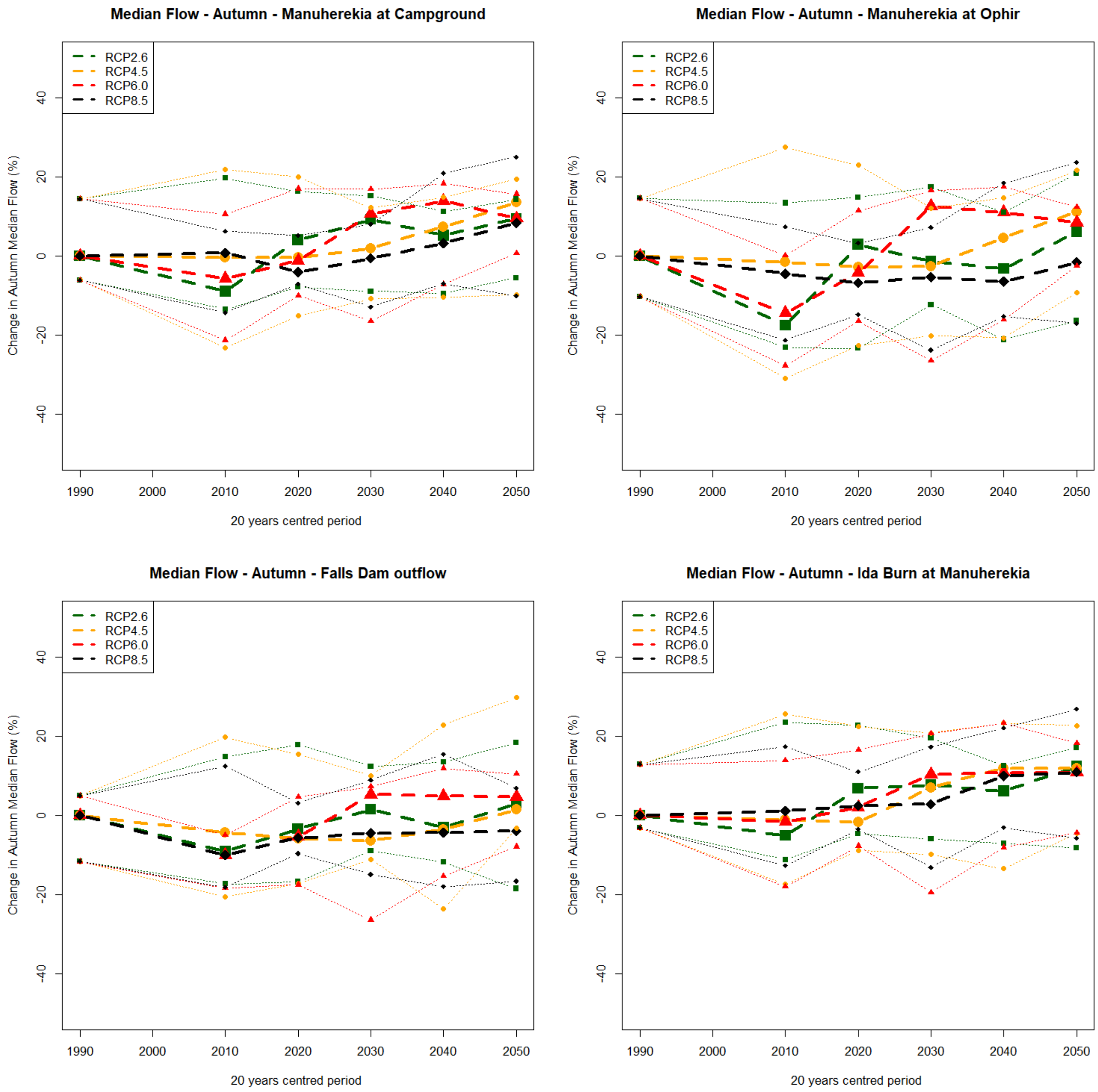

Figure 3-13: 20-years centred change in Autumn Median flow across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

3.2.2 Low flows during irrigation season

Figure 3-14 and Figure 3-15 present the change in low flow hydrological characteristics, as defined by Q75, across the 20-years centred time slices from the 1990s to 2050s.

Analysis of the change in low flows during the irrigation season indicates:

- Spring discharges are generally higher in the lower Manuherekia up to the 2050s, peaking during the 2020s and then remaining stable till the 2050s. However, Falls Dam exhibits a different pattern with low flow discharge peaking during the 2020s and then consistently decreasing. This is thought to be linked to the influence of changes in weather patterns on the eastern headwaters of the Manuherekia.

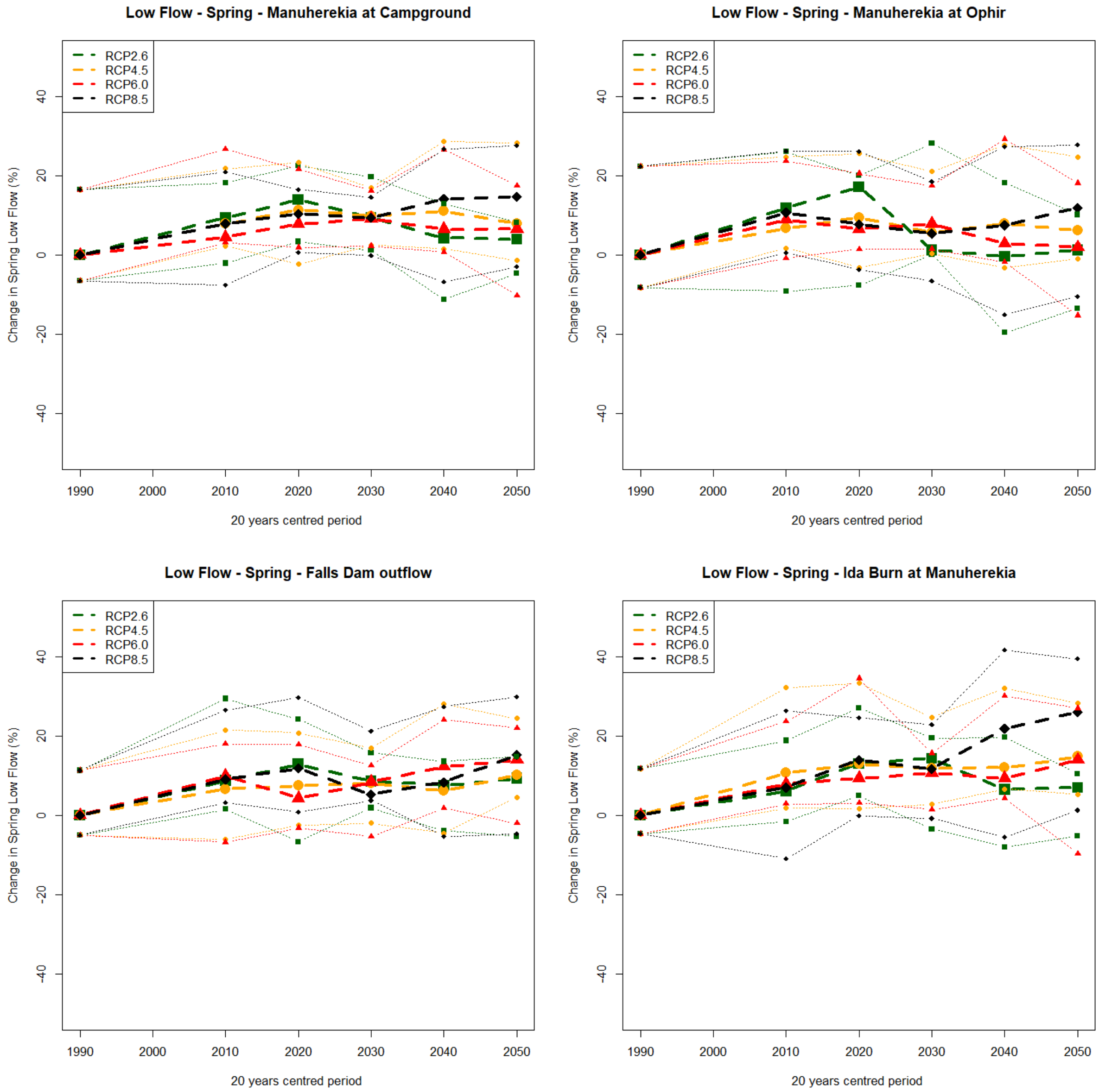

Figure 3-14: 20-years centred change in Spring low flow across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

- Summer low flows exhibit the same behaviour across the catchment. Firstly, summer low flows are expected to remain stable over the period 2006-2020 before reducing by 5 to 10% by the 2050s, except for Ida Burn which exhibits an increase of summer low flow up to 2020s before reaching hindcast summer low flows by the 2050s.

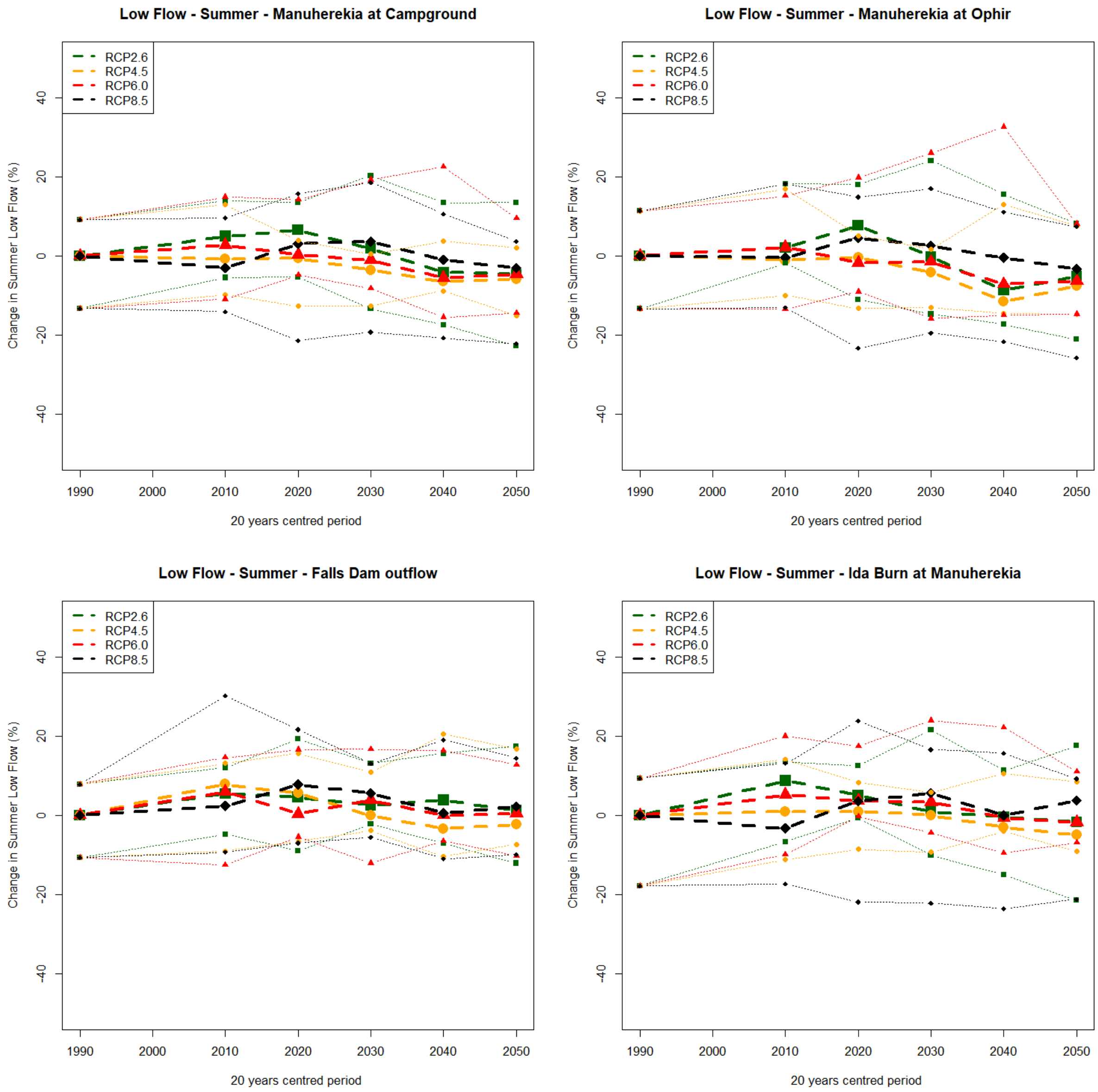

Figure 3-15: 20-years centred change in Summer low flow across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

3.3 Dynamic hydrological characteristics

Figure 3-16 presents the change in median number of consecutive events below historical 7-day MALF, while Figure 3-17 presents the change in maximum number of consecutive events below historical 7-day MALF. Figure 3-18 and Figure 3-19 present similar analyses for the number of consecutive five day below the same flow thresholds.

Analysis of the change in number of consecutive days indicate:

- No change is expected in the median ensemble of the number of consecutive events and consecutive five days events below historical 7-day MALF across the Manuherekia. This indicates that for at least three of the six GCMs no discharge is below the simulated historical 7-day MALF.

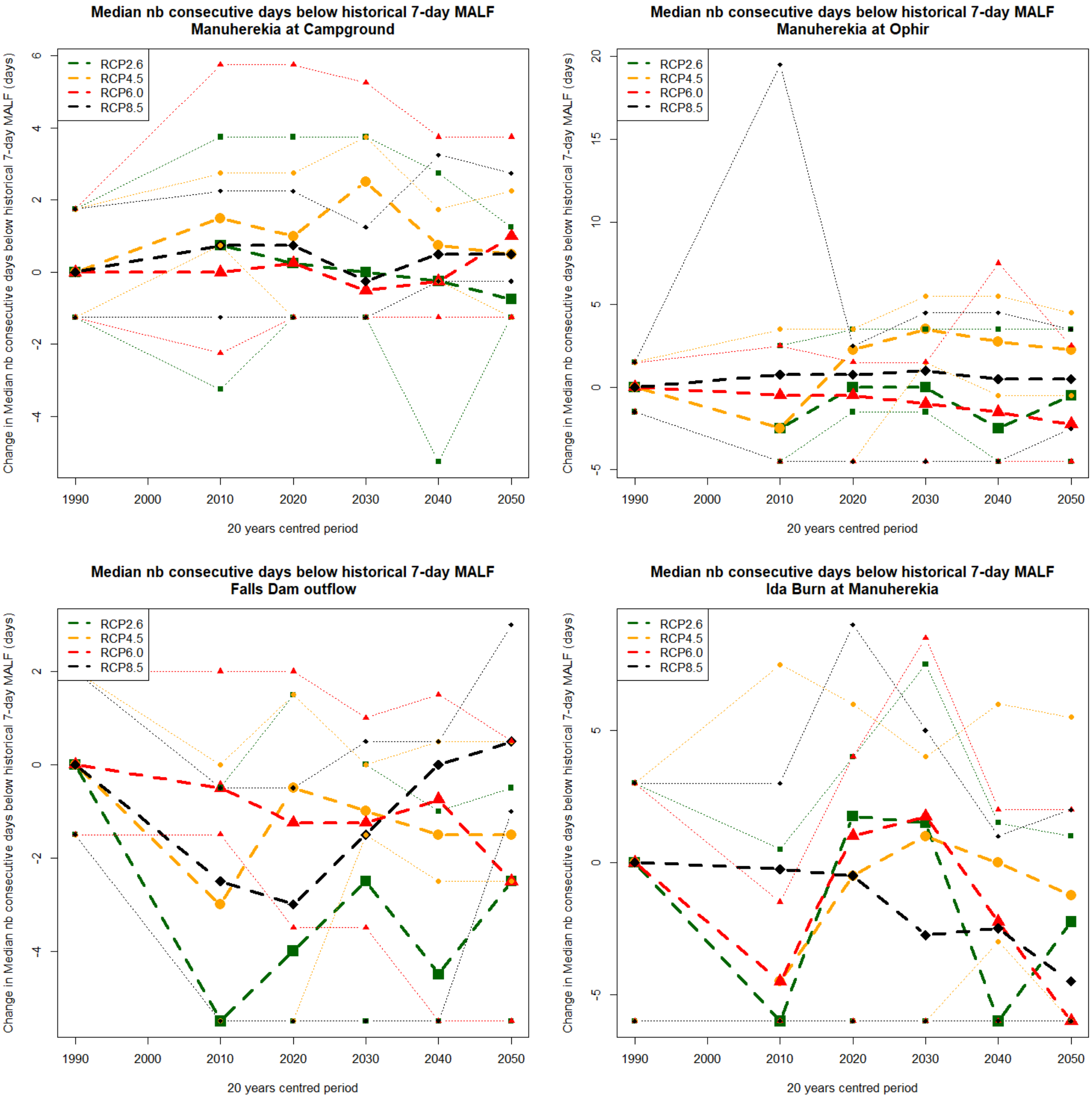

Figure 3-16: 20-years centred change in Median number of consecutive events below historical 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

- Change in the maximum number of consecutive events and the maximum number of consecutive five-day events below the historical 7-day MALF provides additional insights on the potential impact of climate change:
  - Ida Burn is expected to experience a smaller number of consecutive one day and five days below historical 7-day MALF. This is thought to be associated with the change of weather patterns expected with climate change;
  - The Manuherekia main stem is expected to experience a gradual increase in the maximum number of events below historical 7-day MALF up to an additional 10 events by the 2050s and an additional five periods of time for the number of consecutive five day events, while no change is expected for Falls Dam. This indicates that the number of dry periods, characterised as consecutive days below 7-day MALF, is expected to increase while simultaneously the median number of dry days remain unchanged. If 7-day MALF is used as a water consent threshold, this will point towards a shift in the distribution of period where water consent will be restricted with restriction being less often but potentially lasting longer.

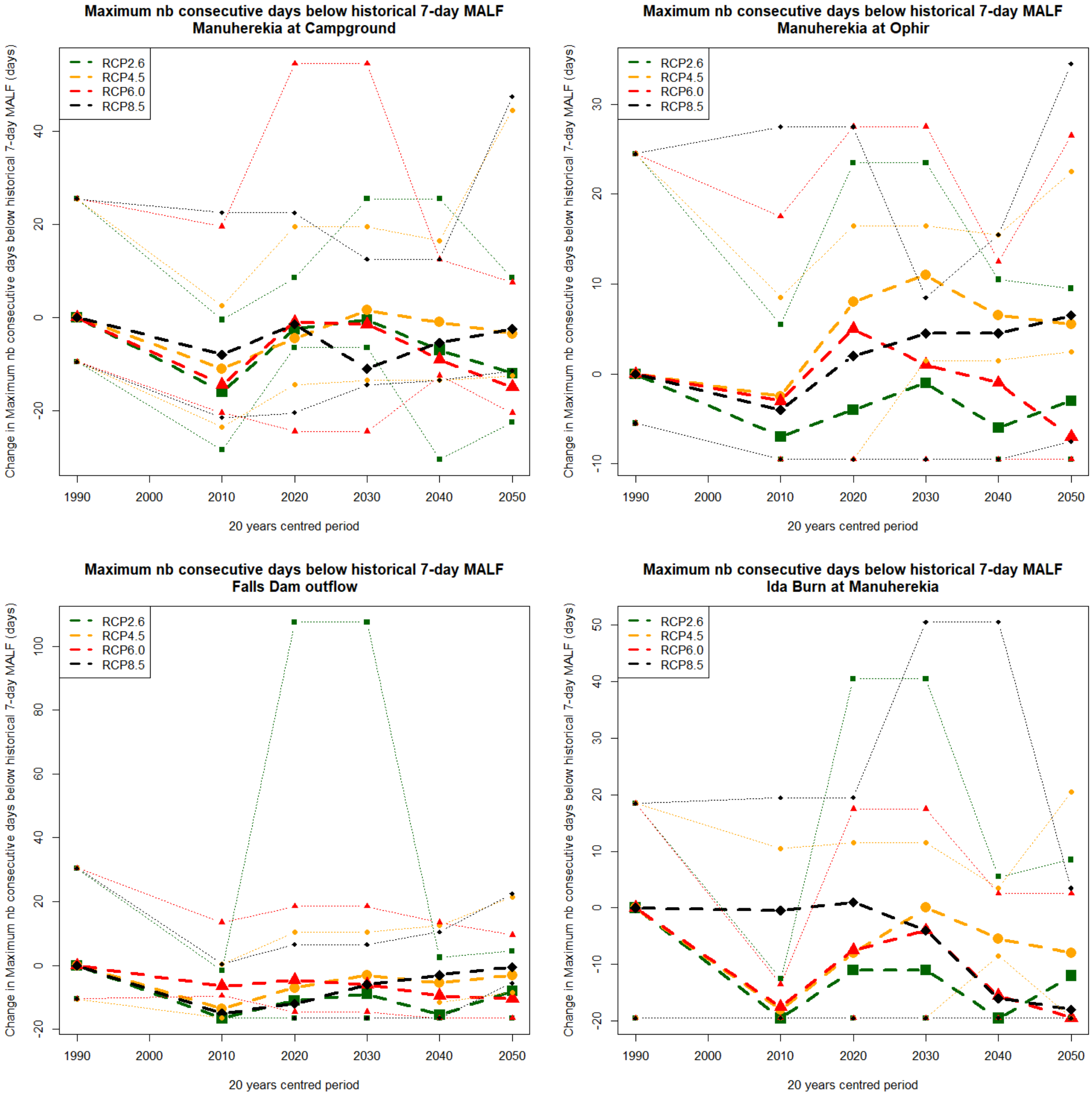

Figure 3-17: 20-years centred change in Maximum number of consecutive events below historical 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

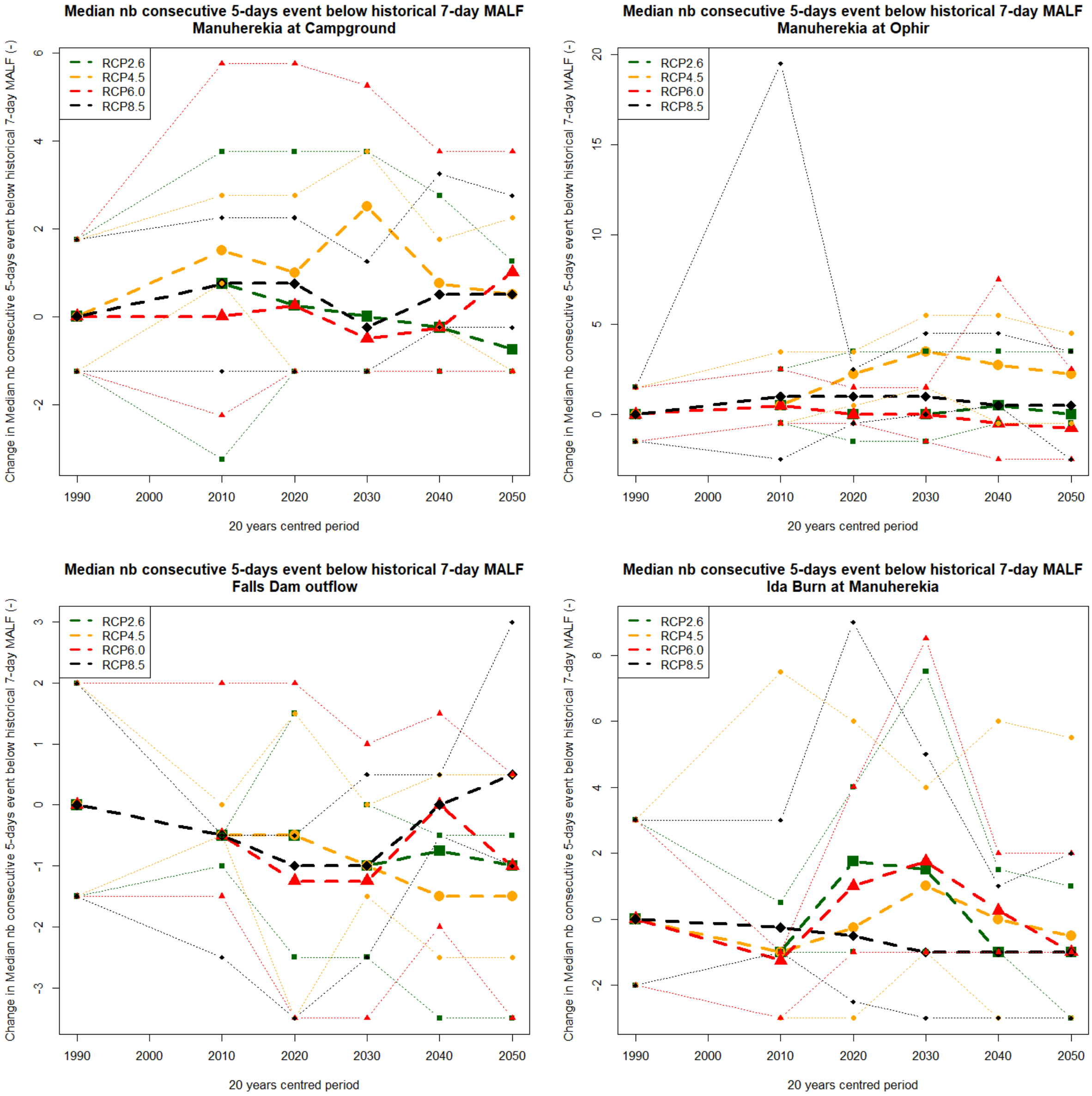

Figure 3-18: 20-years centred change in Median number of consecutive five day events below historical 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

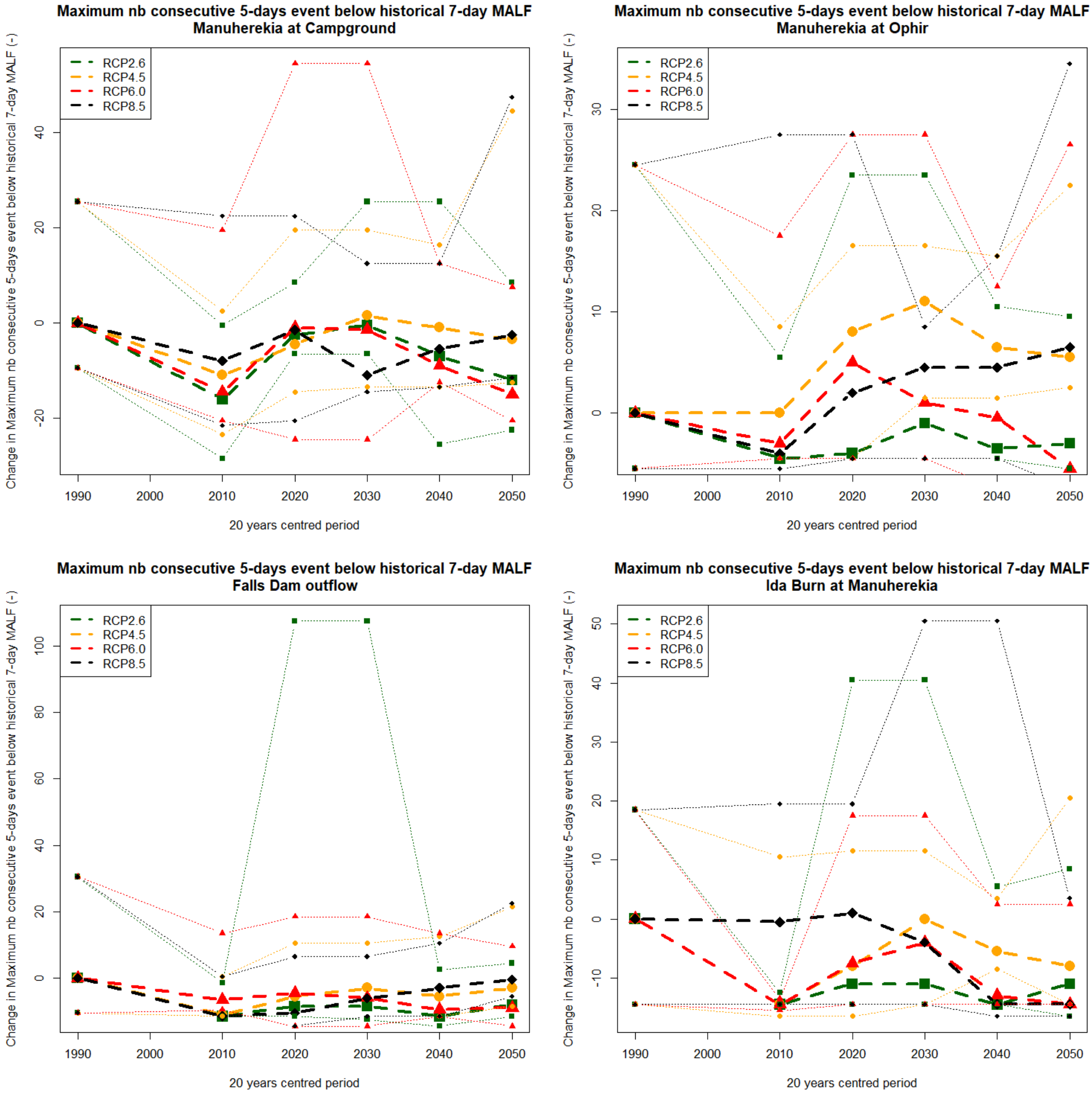

Figure 3-19: 20-years centred change in Maximum number of consecutive five day events below historical 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

3.4 Change in frequency of current 7-day MALF

Figure 3-20 represents the quantile associated with the historical 7-day MALF across the different time slices.

Analysis of the quantiles associated with historical 7-day MALF across the running time slices indicates:

- Hindcast simulations at Campground-Ophir and Falls Dam generate discharges higher than historical 7-day MALF, except for Ida Burn where historical 7-day MALF is represent the 1 percent quantile of the hindcast simulations;
- Future discharge simulations indicate that future discharges are expected to be higher than historical 7-day MALF across the Manuherekia.

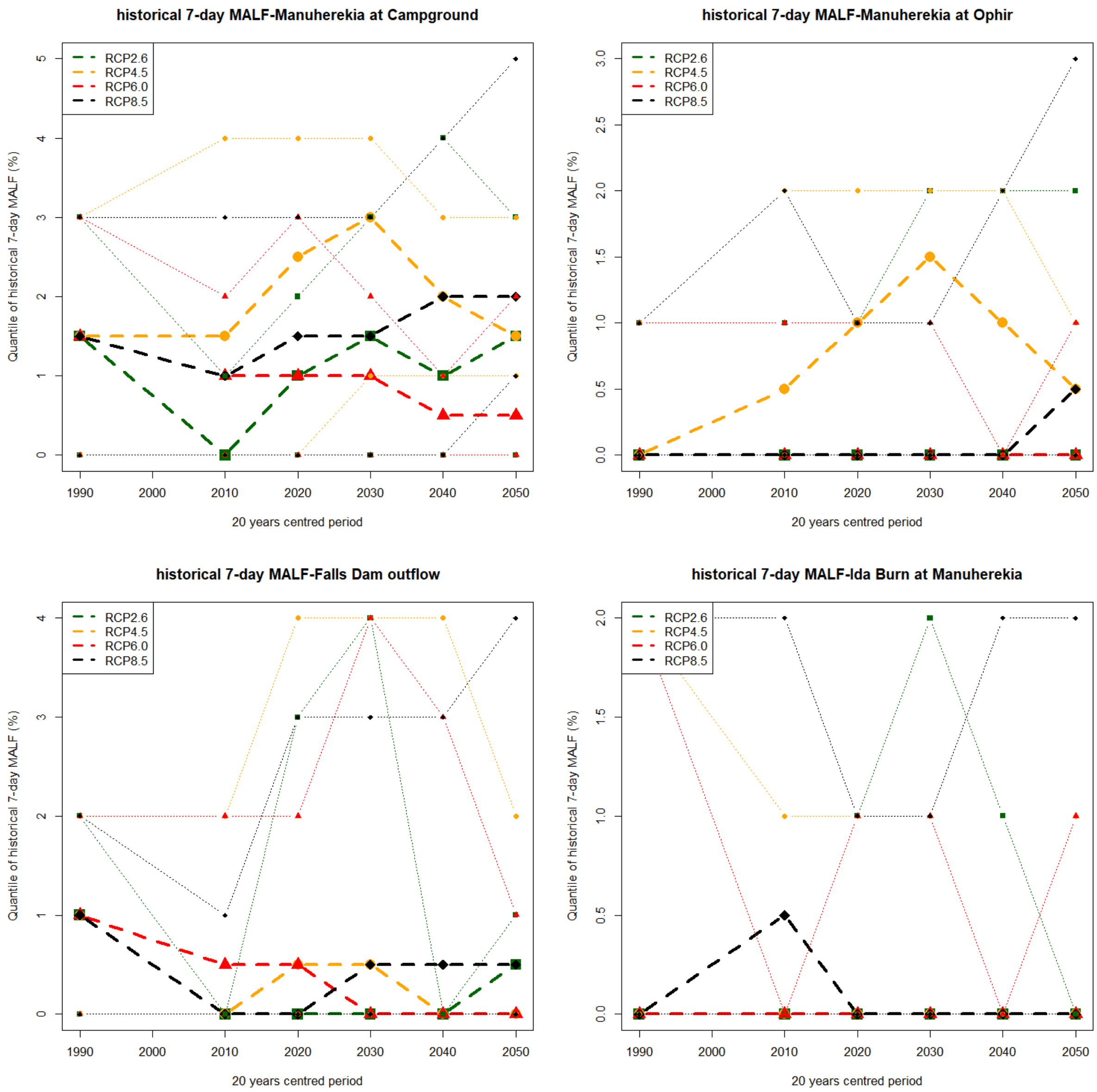

Figure 3-20: 20-years centred change in quantile of the historical 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Manuherekia at Campground, the top right plot shows the changes for Manuherekia at Ophir, the bottom right plot shows the changes for Ida Burn at Manuherekia, bottom left plot shows the changes for Falls Dam outflow. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

3.5 Significance of climate change effects

The Wilcoxon Signed Rank test is used to assess the significance of climate change effects on discharge. The test enables the comparison of two time series to assess if they are from the same distribution. If the p-value returned by the analysis is less than an agreed confidence level, the null assumption of the test (in our case that the two time series are part of the same distribution) is rejected. Uncertainty of the significance of the climate change signal compared to natural variability is to be reported at a confidence interval of 50% - 66% and 95% corresponding to pmax-value (in a T-test) of 0.5- 0.34 and 0.05 (respectively).

Table 3-1 to Table 3-4 present the result of the p-value resulting from the comparison of the ensemble of modelled discharge (merged by RCPs) with the corresponding historic-hindcast. Any p-value smaller than pmax-value indicates that the historical discharge distribution is different from the future discharge distribution at each location, hence that the climate change effect is statistically significant. Non-significant differences are outlined in bold in Table 3-1 to Table 3-4 with the confidence interval level provided in parentheses if the analysis is valid only for one of the confidence intervals.

Table 3-1: Significance of climate change effect (p-value) on streamflow discharge for RCP 2.6 over running 20-years period from 2020 to 2060. Comparison of the 20-years running period with historic hindcast using GCM inputs.

RCP	Time period	Campground	Ophir	Ida Burn	Falls Dam
RCP2.6	2010-2030	< 0.005	<0.05	<0.05	<0.05
RCP2.6	2020-2040	< 0.005	<0.05	<0.05	**0.717**
RCP2.6	2030-2050	**0.681**	0.174	0.207	<0.05
RCP2.6	2040-2060	< 0.005	<0.05	<0.05	**0.554 (66%)**

Table 3-2: Significance of climate change effect (p-value) on streamflow discharge for RCP 4.5 over running 20-years period from 2020 to 2060. Comparison of the 20-years running period with historic hindcast using GCM inputs.

RCP	Time period	Campground	Ophir	Ida Burn	Falls Dam
RCP4.5	2010-2030	< 0.005	<0.05	<0.05	**0.512** (66%)
RCP4.5	2020-2040	**0.810**	0.077	<0.05	<0.05
RCP4.5	2030-2050	0.254	<0.05	<0.05	<0.05
RCP4.5	2040-2060	< 0.005	<0.05	<0.05	<0.05

Table 3-3: Significance of climate change effect (p-value) on streamflow discharge for RCP 6.0 over running 20-years period from 2020 to 2060. Comparison of the 20-years running period with historic hindcast using GCM inputs.

RCP	Time period	Campground	Ophir	Ida Burn	Falls Dam
RCP6.0	2010-2030	< 0.005	<0.05	0.078	0.054
RCP6.0	2020-2040	< 0.005	<0.05	<0.05	<0.05
RCP6.0	2030-2050	< 0.005	<0.05	<0.05	**0.611 (66%)**
RCP6.0	2040-2060	< 0.005	<0.05	<0.05	<0.05

Table 3-4: Significance of climate change effect (p-value) on streamflow discharge for RCP 8.5 over running 20-years period from 2020 to 2060. Comparison of the 20-years running period with historic hindcast using GCM inputs.

RCP	Time period	Campground	Ophir	Ida Burn	Falls Dam
RCP8.5	2010-2030	< 0.005	<0.05	<0.05	0.006
RCP8.5	2020-2040	< 0.005	<0.05	<0.05	**0.742**
RCP8.5	2030-2050	< 0.005	<0.05	<0.05	<0.05
RCP8.5	2040-2060	< 0.005	<0.05	<0.05	**0.389 (66%)**

Analysis of the Wilcoxon Signed Rank test indicates that changes in inflows can be associated with climate change effects at confidence levels of 50% and 66%. For a majority of the time slices analysed, calculated changes in hydrological characteristics are extremely likely to be associated with climate change rather than climate variability (95% confidence level) .

4 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 (2018).

4.1 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 Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) 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 conditions 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 masks 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 4-1 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 (from Collins et al. 2018). 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).

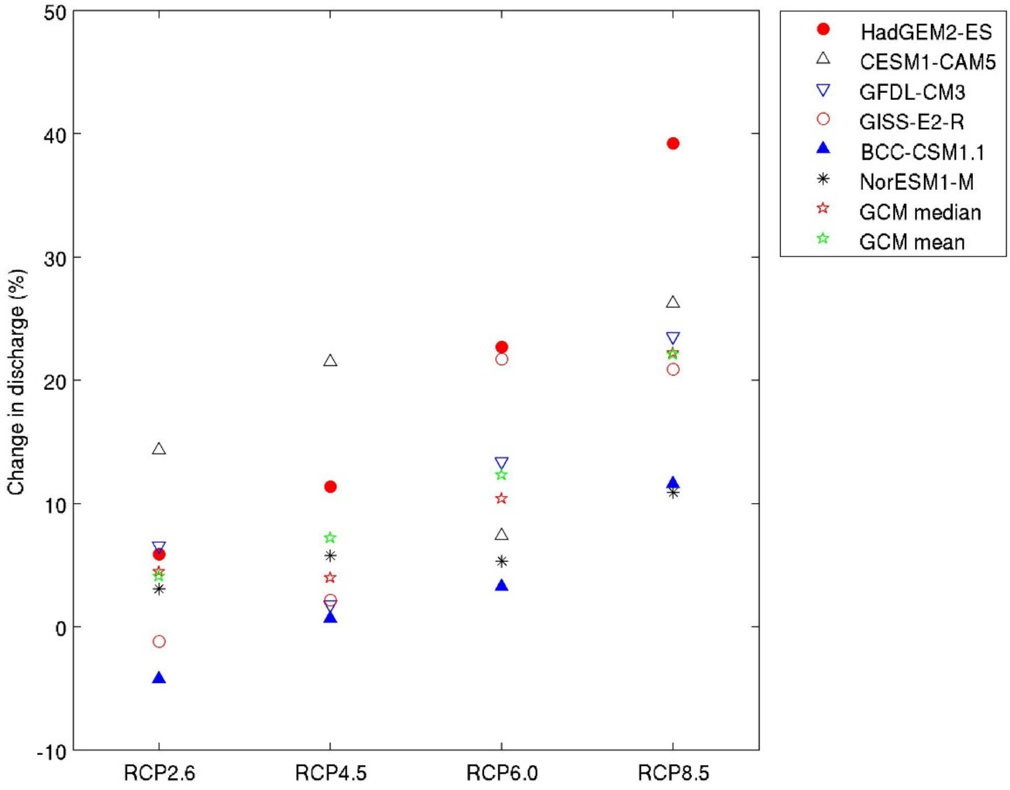

Figure 4-1: Change in mean discharge by end of the century at the outlet of the Waikato River for individual GCMs and RCPs, including GCM means and medians. (Collins et al. 2018)

4.2 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. 2010). 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.

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 deterministic calibration and neither of these uncertainties is addressed.

4.3 Distinguishing climate change from climate variability

The GCMs used to drive the hydrological modelling are unable 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 end-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.

4.4 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.

5 Conclusions

Climate change, through changes in precipitation patterns and increases in temperature, poses a significant challenge to water resources and users of water such as primary industry (which is an important water resource user in this catchment). Historical increases in temperature are projected to continue this century, accompanied by shifts in rainfall patterns. These could have a range of impacts on the country's water cycle and in turn on the availability of water across a wide range of users. The scale and timing of the effects depends largely on the magnitude of global efforts to curb greenhouse gas emissions (known as mitigation). Regardless of mitigation actions, the climate is already changing and decisions need to be made to adjust to the changes in water resources (known as adaptation). In order to inform both mitigation and, particularly, adaptation decisions, it is important to understand the potential effects. This report builds upon earlier studies of the hydrology of the Manuherekia catchment (Henderson et al. 2019) by coupling a hydrological model calibrated for the Manuherekia catchment with climate projections considering when *effects may become discernible or significant*. The report considers only the effects and impacts of climate change alone and does not consider any other related changes such as land use, economic or social conditions.

Assessments of climate change impacts on the hydrological regime in the Manuherekia catchment was carried out by using climate change projections to drive a calibrated hydrological model, TopNet. Modelling considered four climate change scenarios over the period 1971-2060. Analysis was carried using a 20-years centred overlappping time slice (e.g. analysis carried out over the period 2030-2050 to represent changes in the 2040s) over the period of interest to represent the dynamic aspect of the climate.

Key results are as follows:

- High flows are expected to increase by over 5% by 2050;
- Median and Average flows are expected to slightly increase up to 5% by 2050;
- Low flows and 7-day MALF are expected to slightly increase up to 5% by 2020 before decreasing back to their historical level by 2050, except in the Manuherekia headwaters where low flows are expected to decrease by up to 5%;
- Seasonally, mean and median discharge over Winter-Spring and Autumn is expected to increase with warming across Manuherekia catchment, while mean and median discharge during Summer are expected to decrease from 2020 onward;
- Low flows during irrigation season (taken from September to March) are expected to increase in Spring, while decreasing in Summer. This behaviour is spatially variable as Summer low flows are expected to increase by the 2020s and decrease to their hindcast levels by then 2050s for Ida Burn, while Spring flows at Falls Dam increase up to the 2020s before reducing to their hindcast level by 2050's.
- Median number of consecutive events below hindcast 7-day MALF is not expected to change with warming, while the maximum number of consecutive five day events below hindcast 7-day MALF is expected to increase by up to 10 occurrences. If 7-day MALF is used as a water consent threshold, this will point towards a shift in the

distribution of period where water consent will be restricted with restriction being less often but potentially lasting longer;

- Analysis of the Wilcoxon Signed Rank test[3] indicates that across the Manuherekia catchment changes in discharge are extremely likely to be associated with climate change effects (95% confidence level) for a majority of the overlapping time periods analysed over the period 2006 and 2060.

[3] Wilcoxon signed-rank test is a nonparametric test that can be used to determine whether samples were selected from populations having the same distribution. In our case it is used to assess if historical and climate change driven simulation belongs to the same population.

6 Glossary of abbreviations and terms

AR5	Assessment Report IPCC 5th assessment round
DEM	Digital Elevation Model
GCM	Global Climate Model
IPCC	Intergovernmental Panel on Climate Change
LCDB2	Land Cover Database version 2
7-day MALF	Mean Annual Low Flow calculated over a moving window of 7 days duration
Q25	The flow exceeded 25% of the time; the upper quartile; a high flow
Q75	The flow exceeded 75% of the time; the lower quartile; a low flow
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SST	Sea Surface Temperatures
VCSN	Virtual Climate Station Network

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Appendix A Changes in high flow

In the following figures, the green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

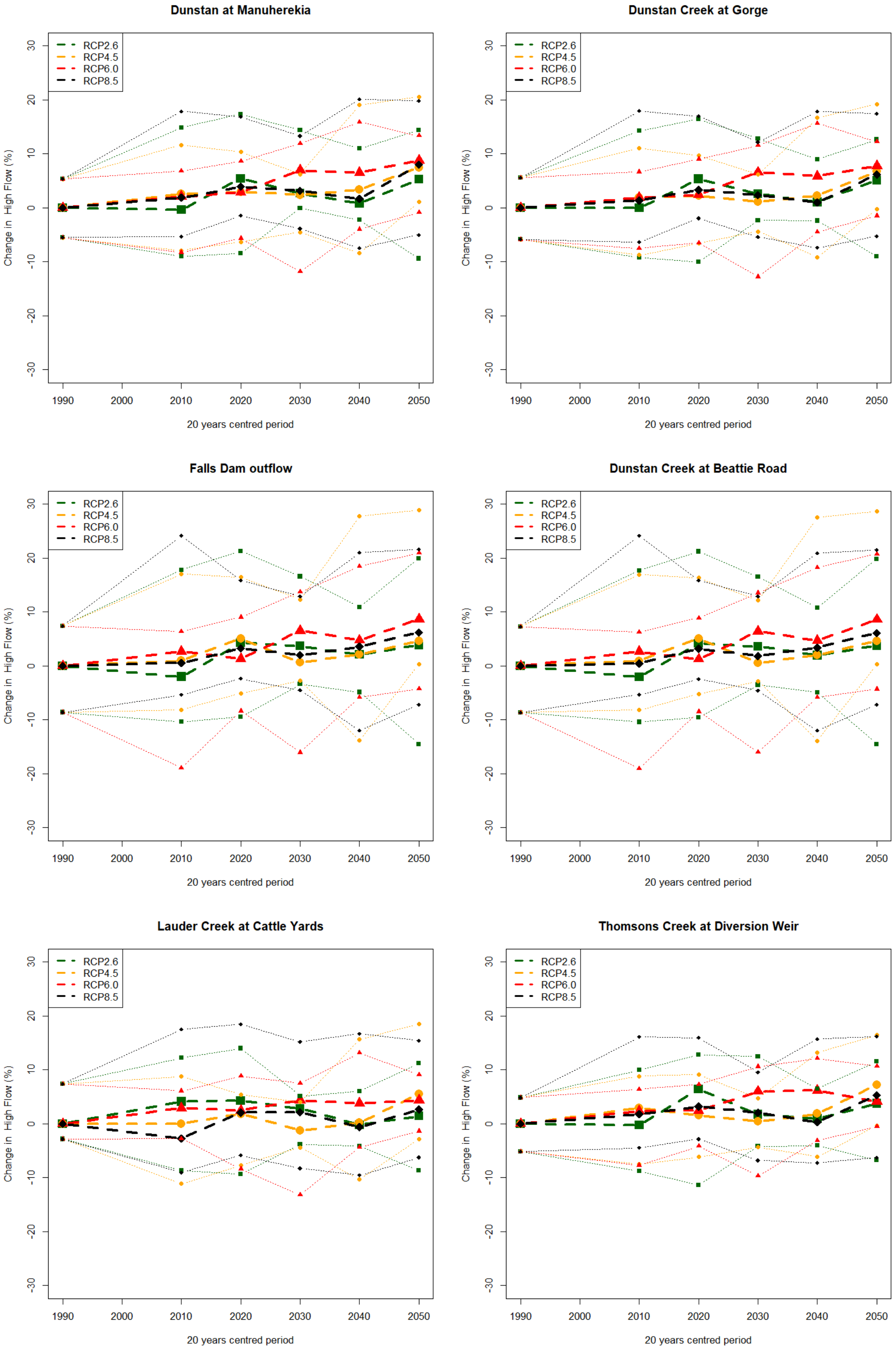

Figure A-1: 20-years centred change in high flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

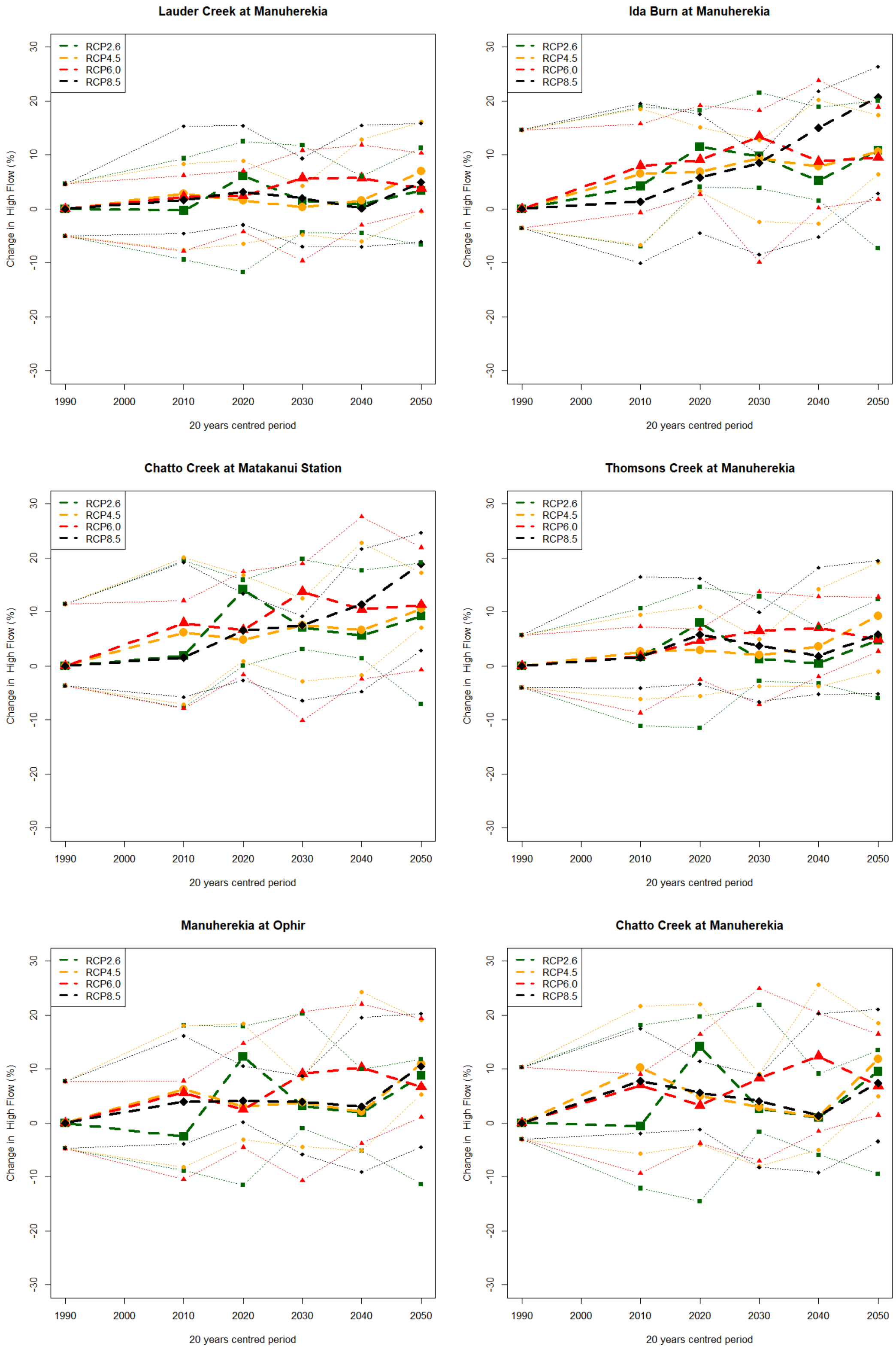

Figure A-2: 20-years centred change in high flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

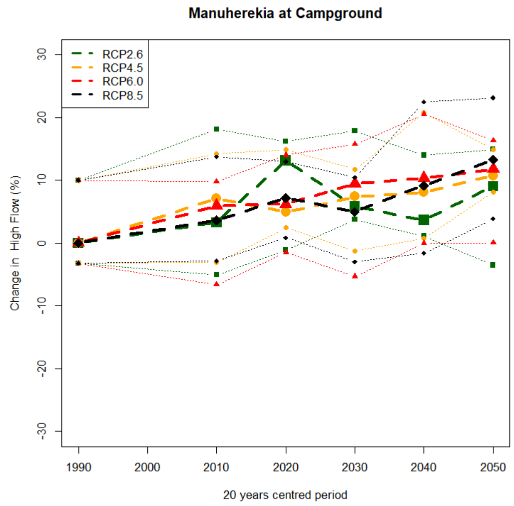

Figure A-3: 20-years centred change in high flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Appendix B Changes in mean Flows

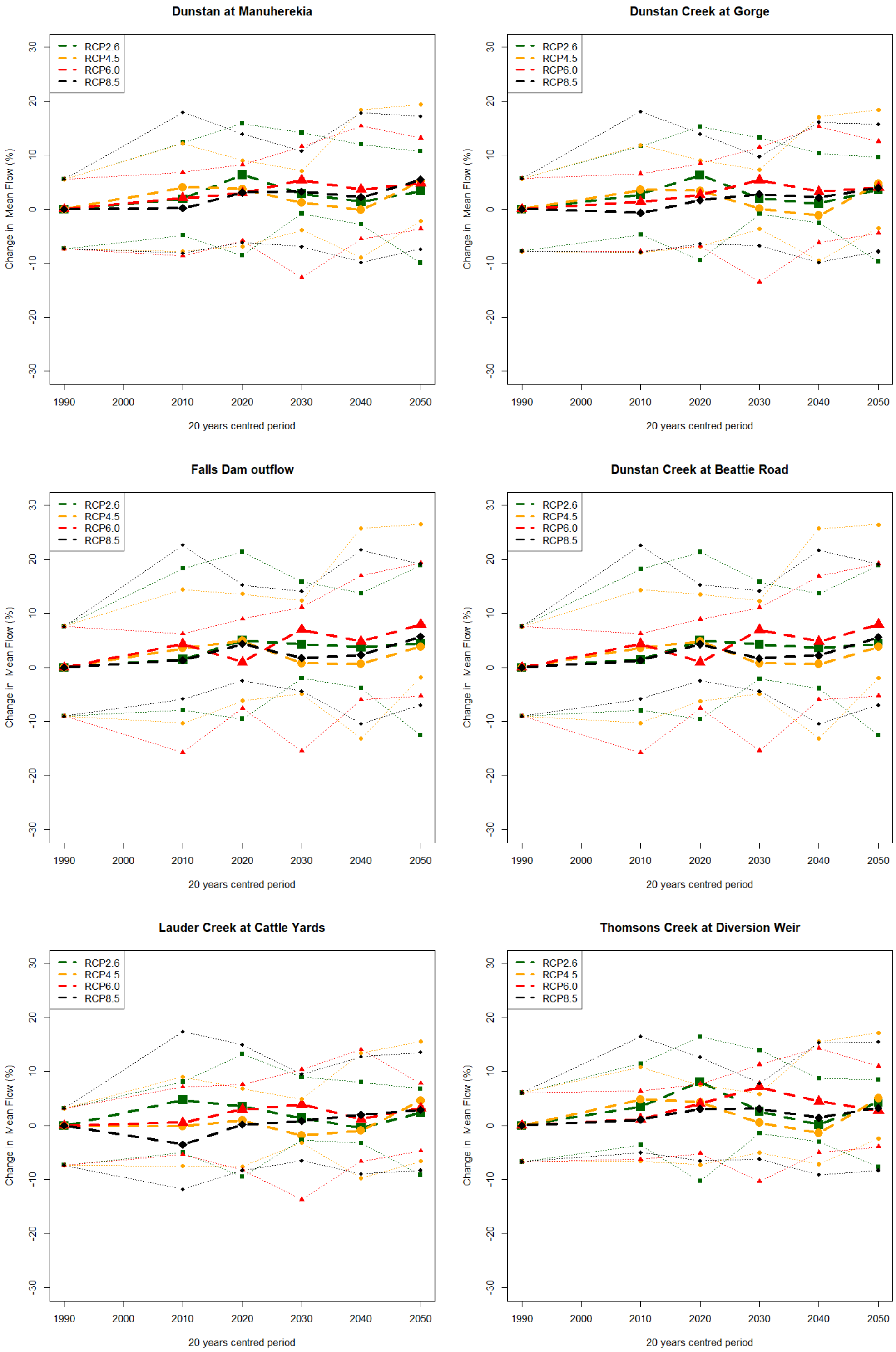

Figure B-1: 20-years centred change in mean flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

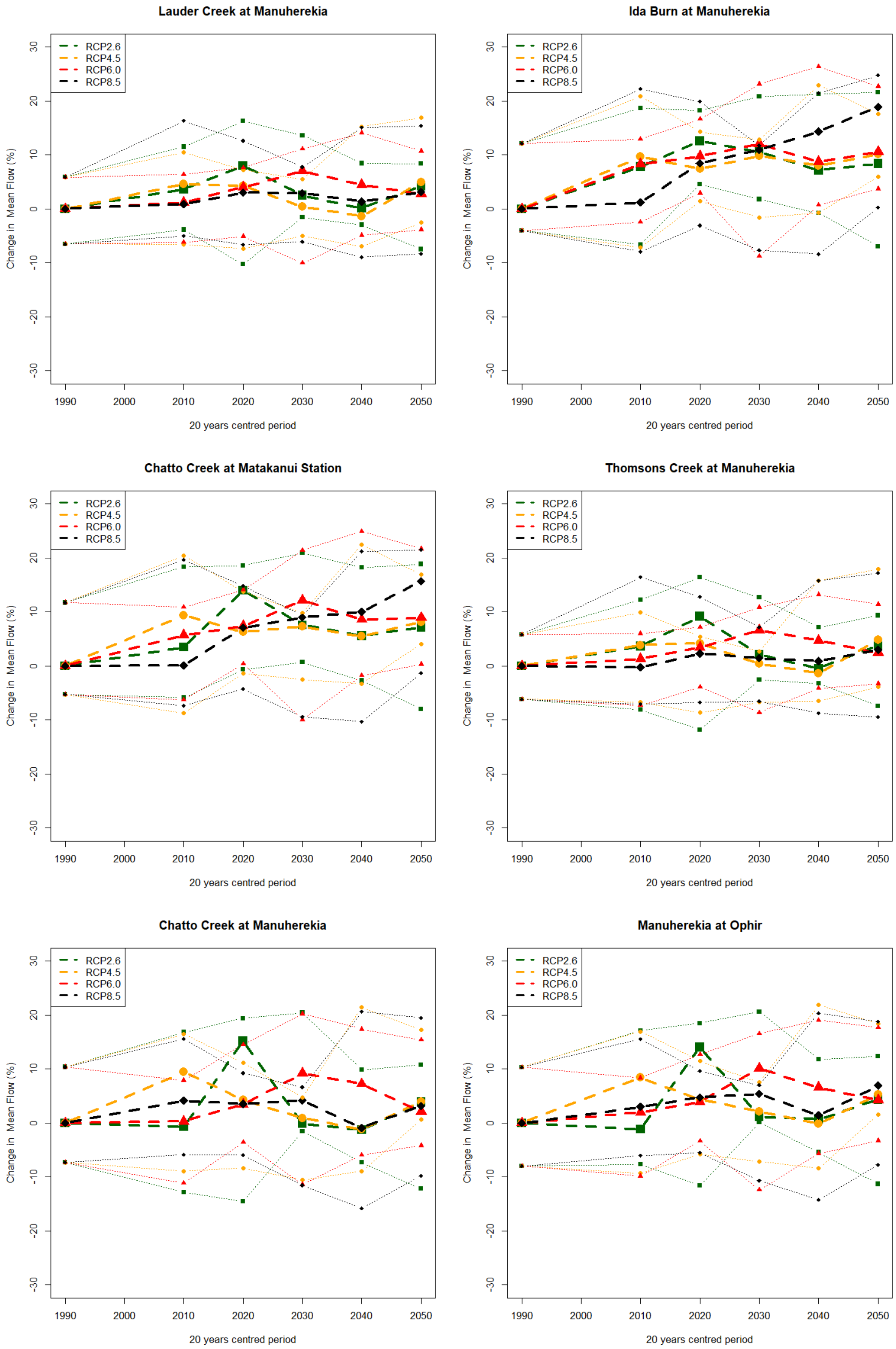

Figure B-2: 20-years centred change in mean flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

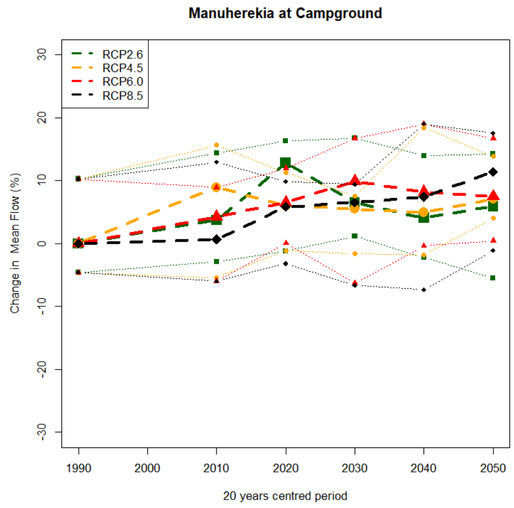

Figure B-3: 20-years centred change in mean flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Appendix C Changes in median flow

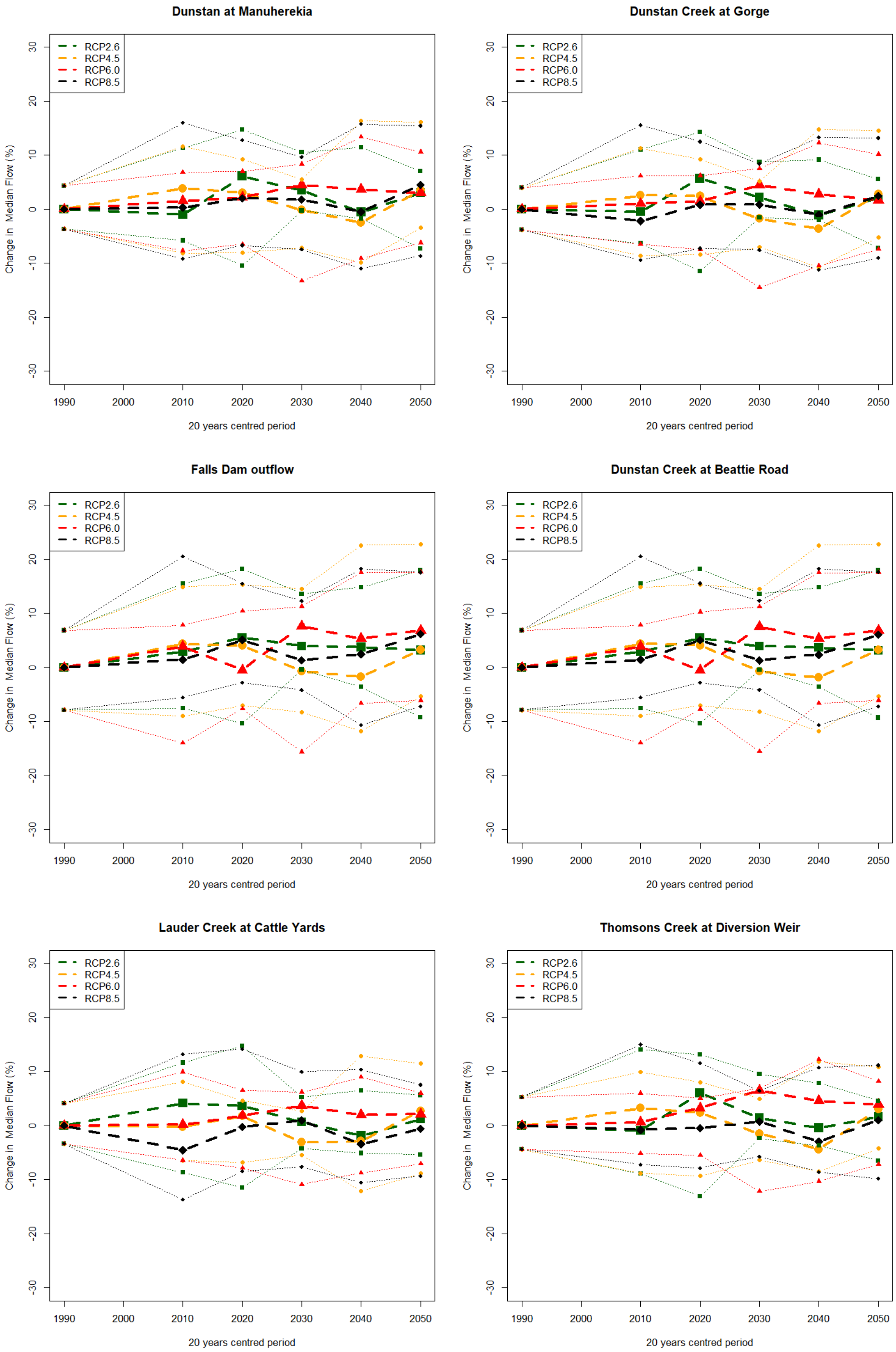

Figure C-1: 20-years centred change in median flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

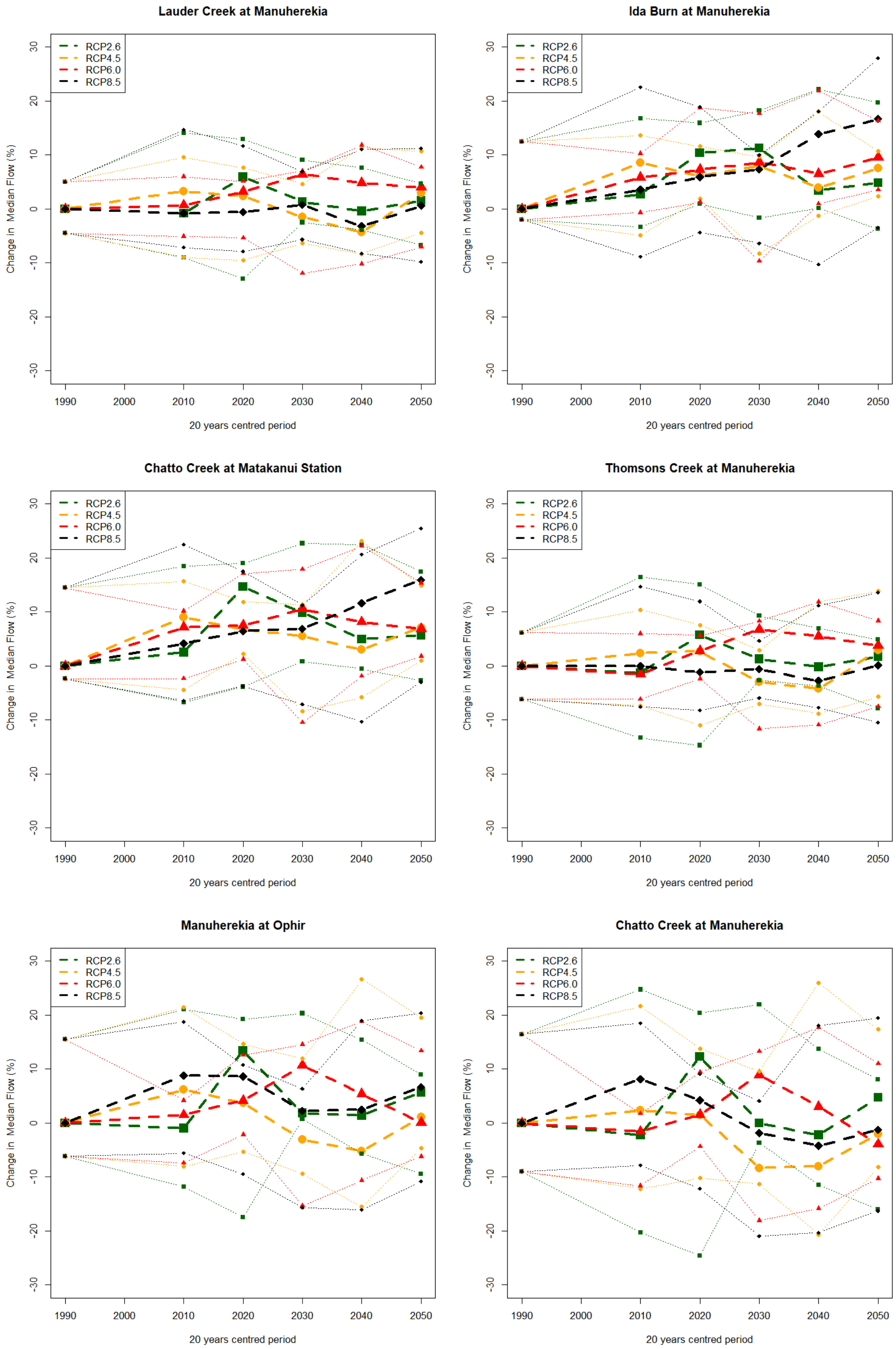

Figure C-2: 20-years centred change in median flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

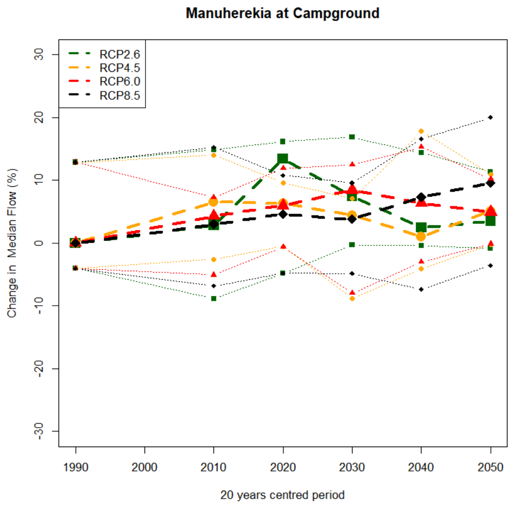

Figure C-3: 20-years centred change in median flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Appendix D Changes in low flow

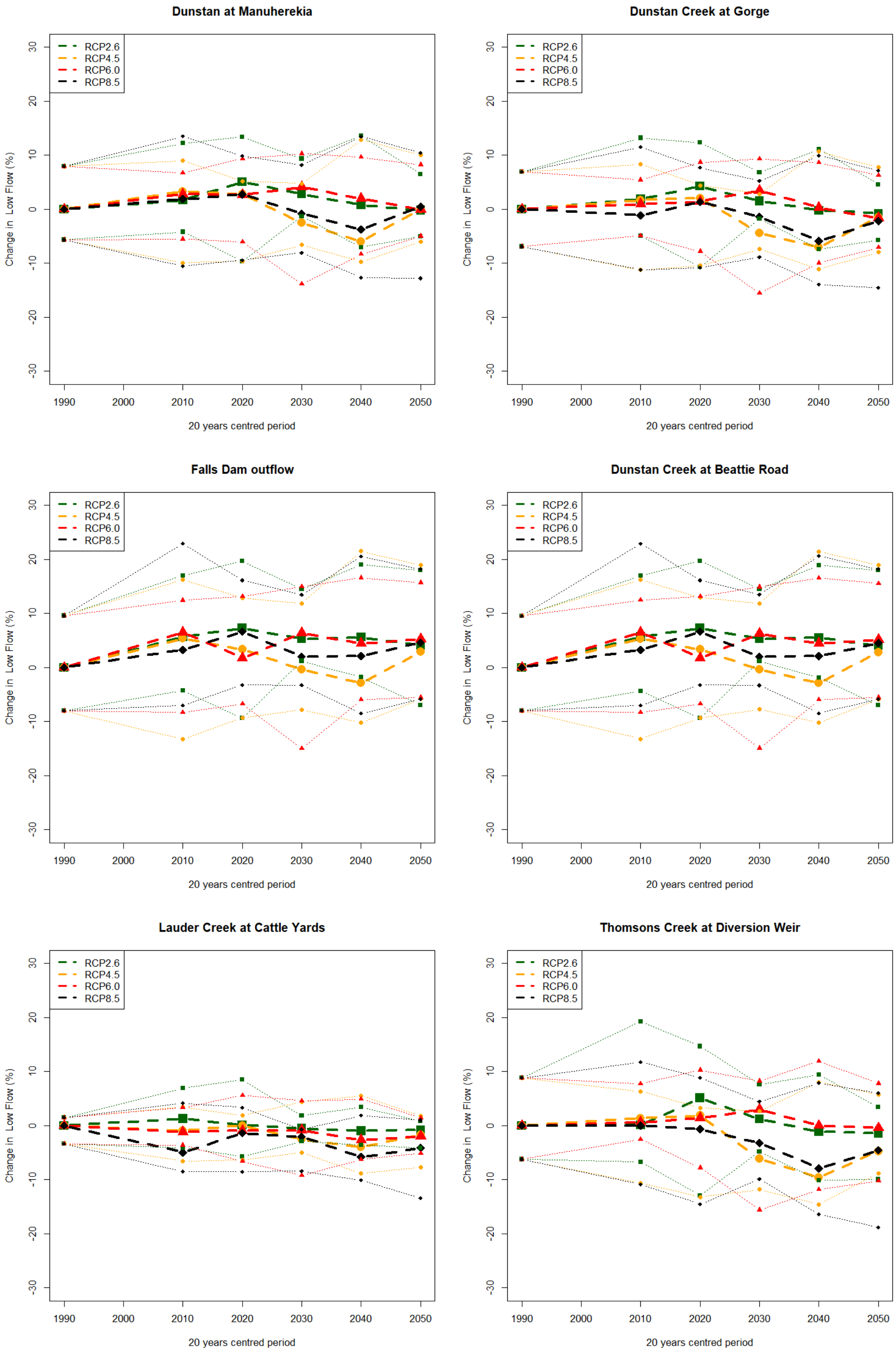

Figure D-1: 20-years centred change in low flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

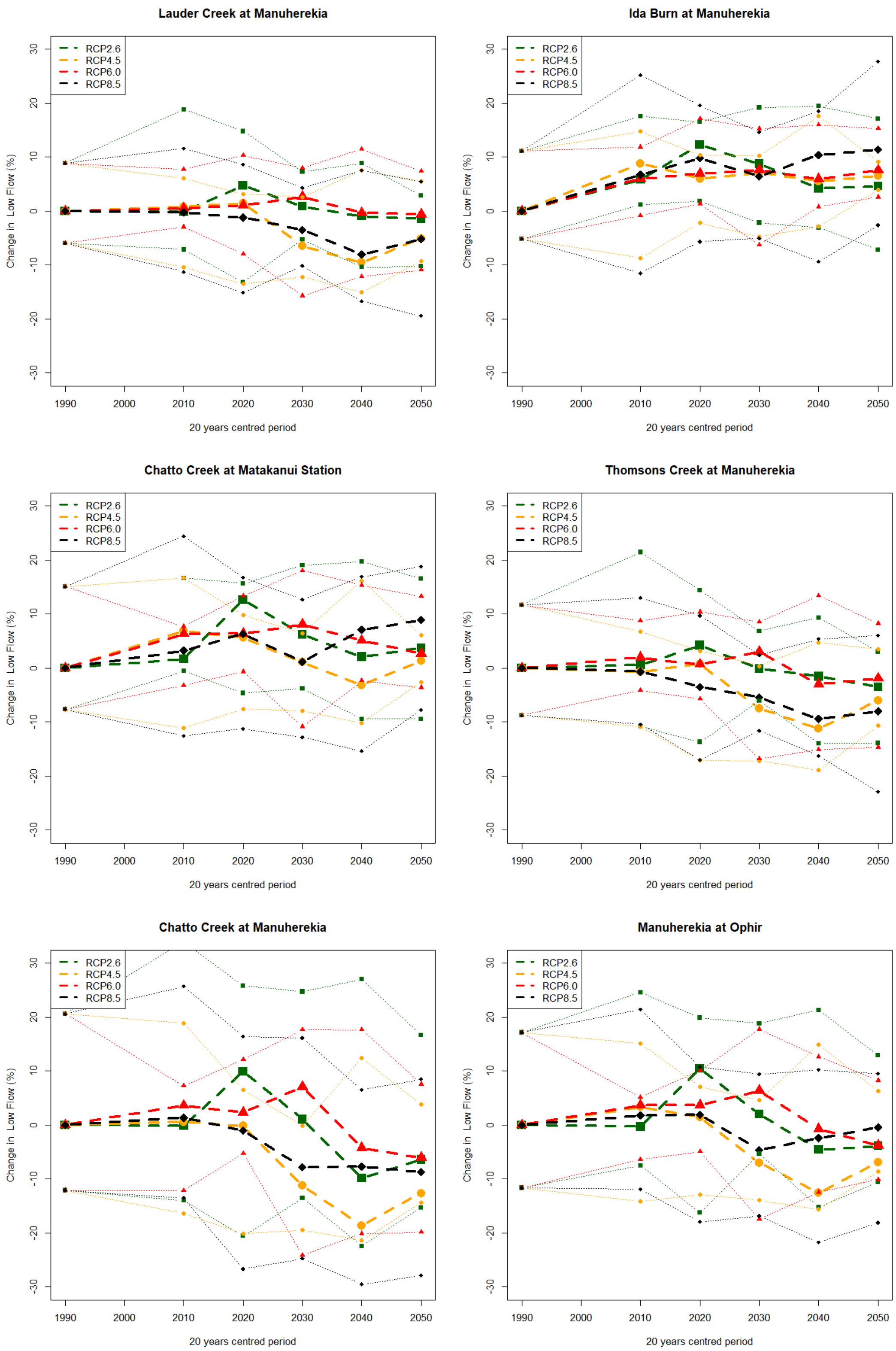

Figure D-2: 20-years centred change in low flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

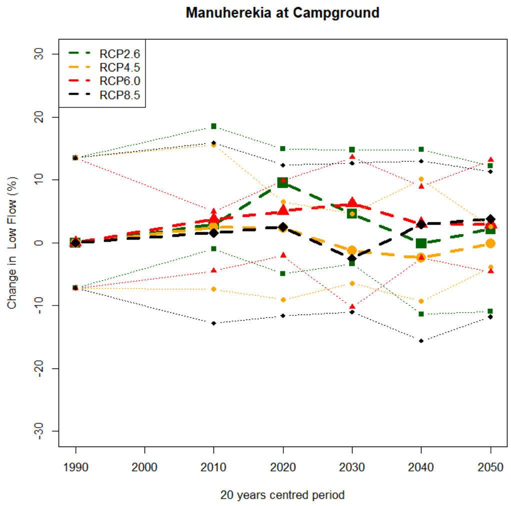

Figure D-3: 20-years centred change in low flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Appendix E Changes in 7-day MALF

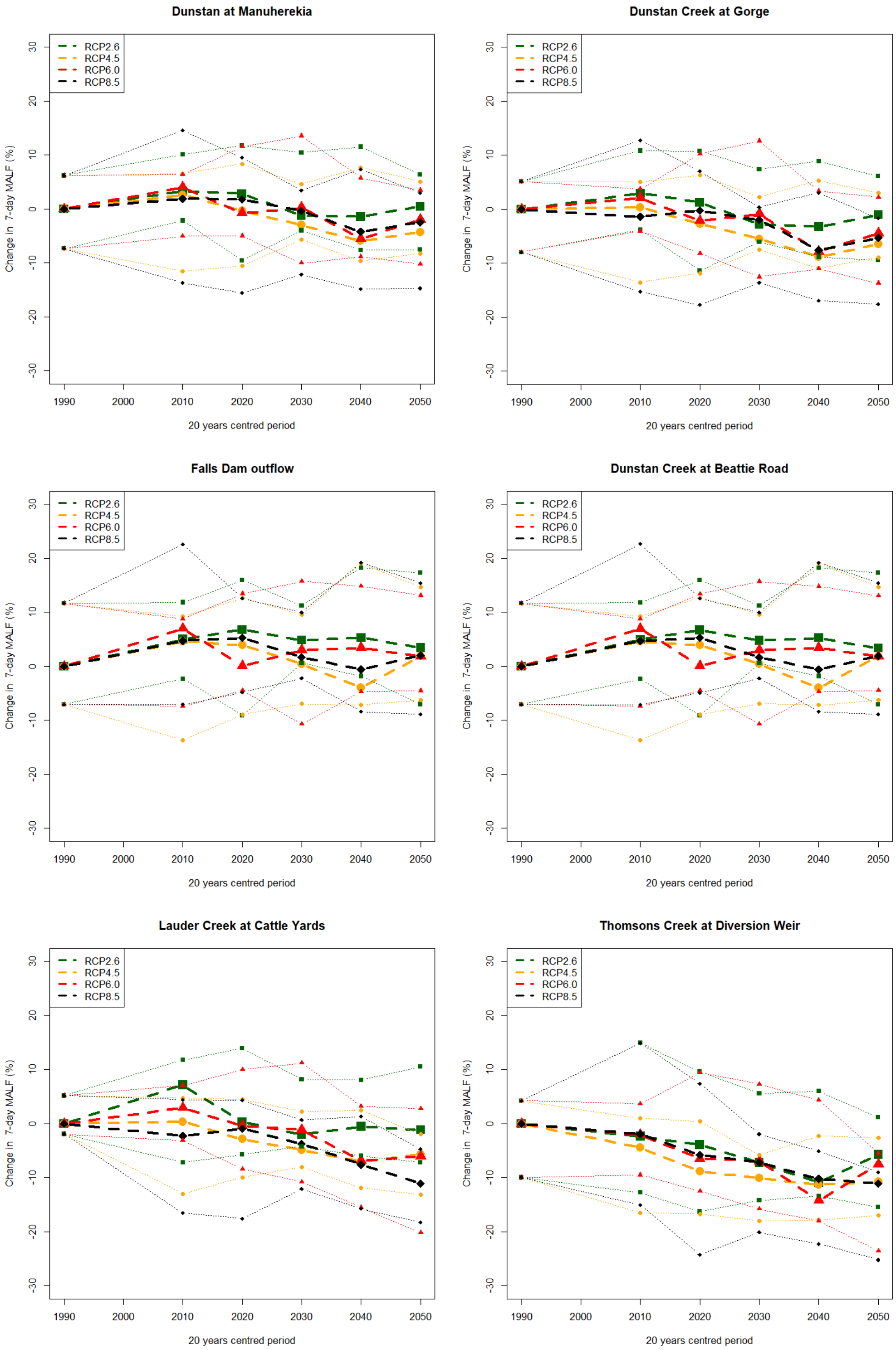

Figure E-1: 20-years centred change in 7-day MALF characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

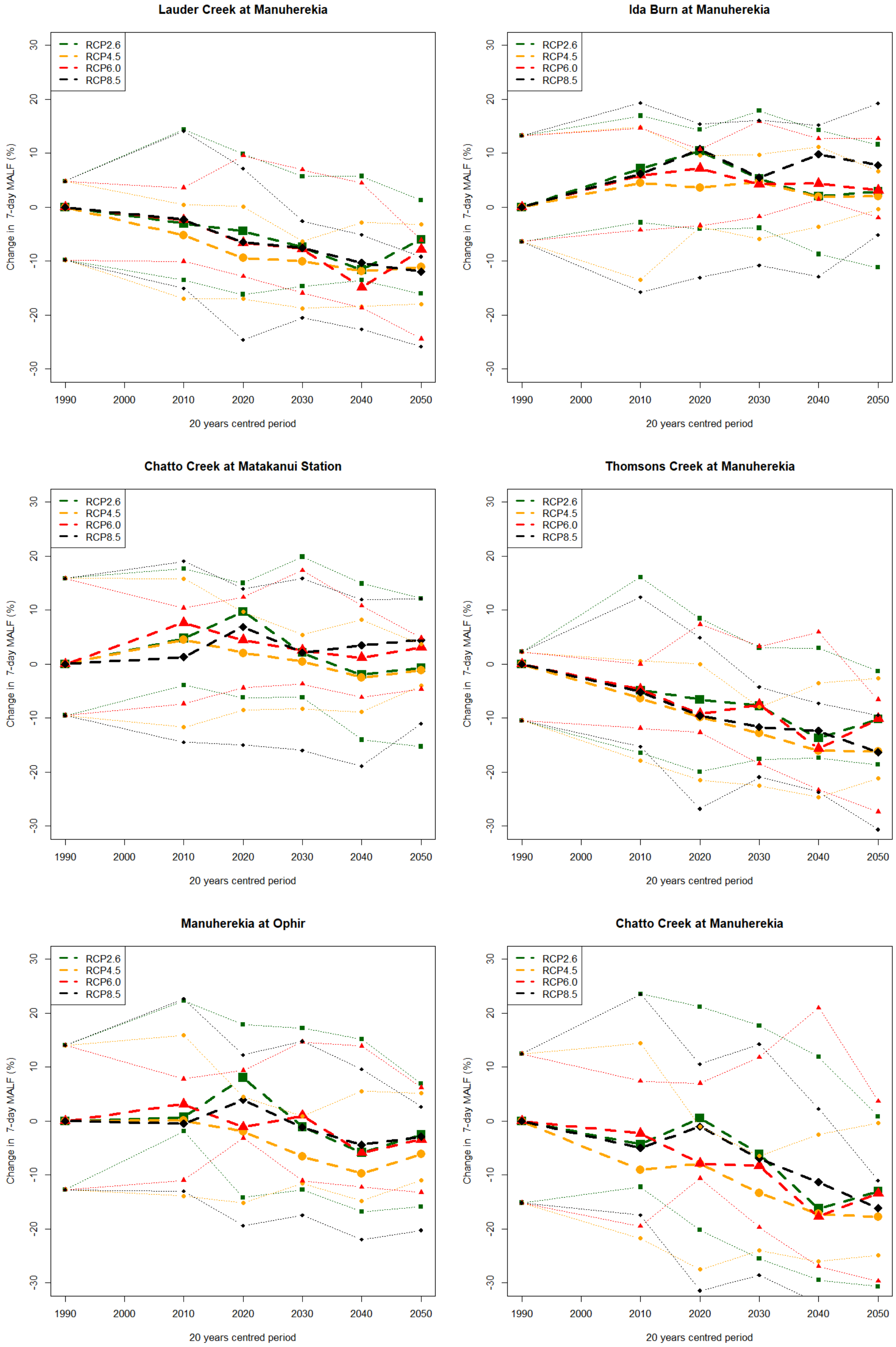

Figure E-2: 20-years centred change in 7-day MALF characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

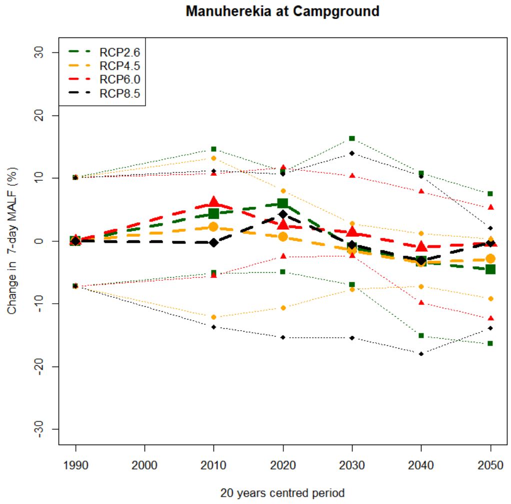

Figure E-3: 20-years centred change in 7-day MALF characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Appendix F Changes in Seasonal mean flow

Autumn

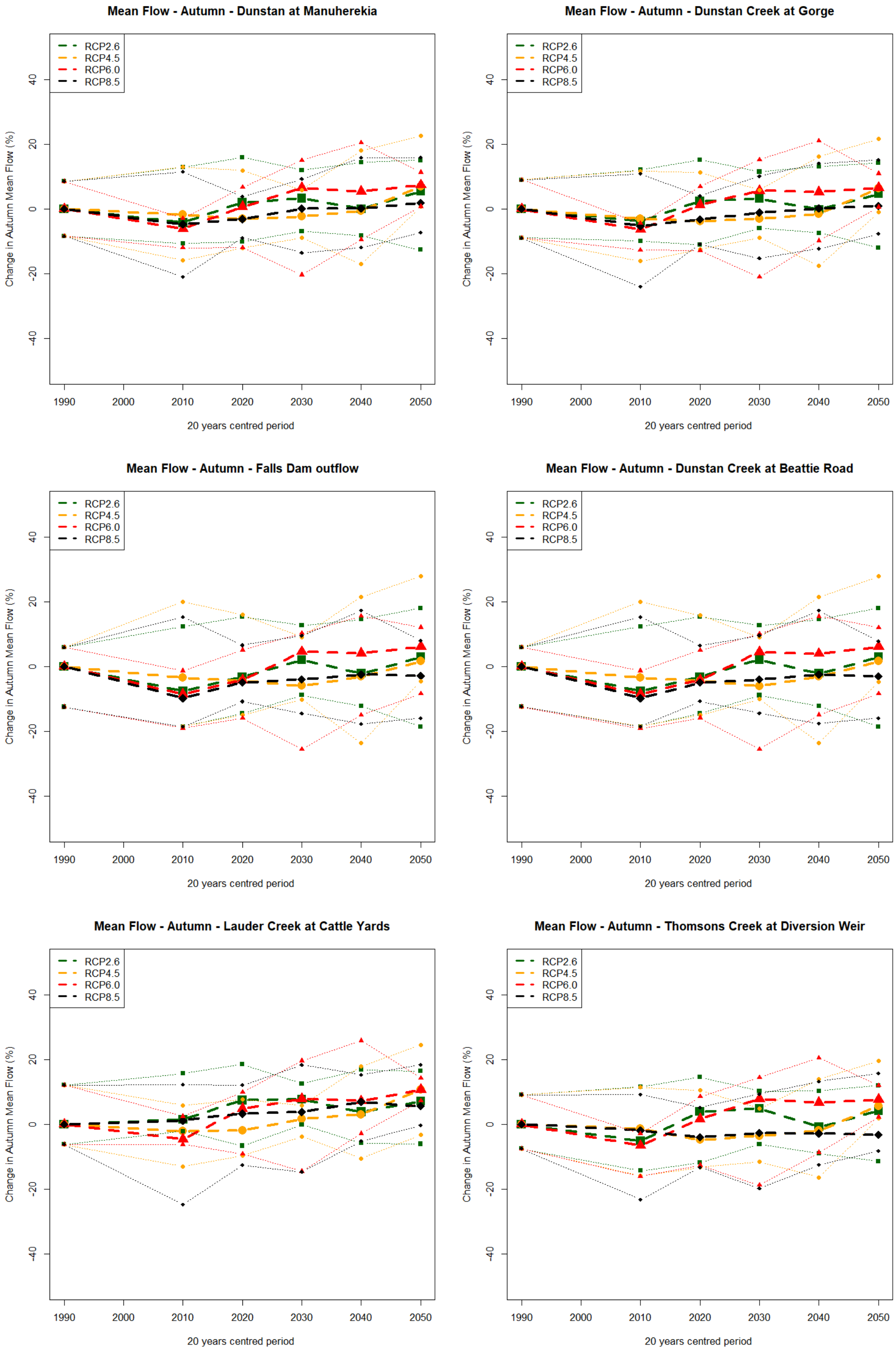

Figure F-1: 20-years centred change in Autumn mean flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

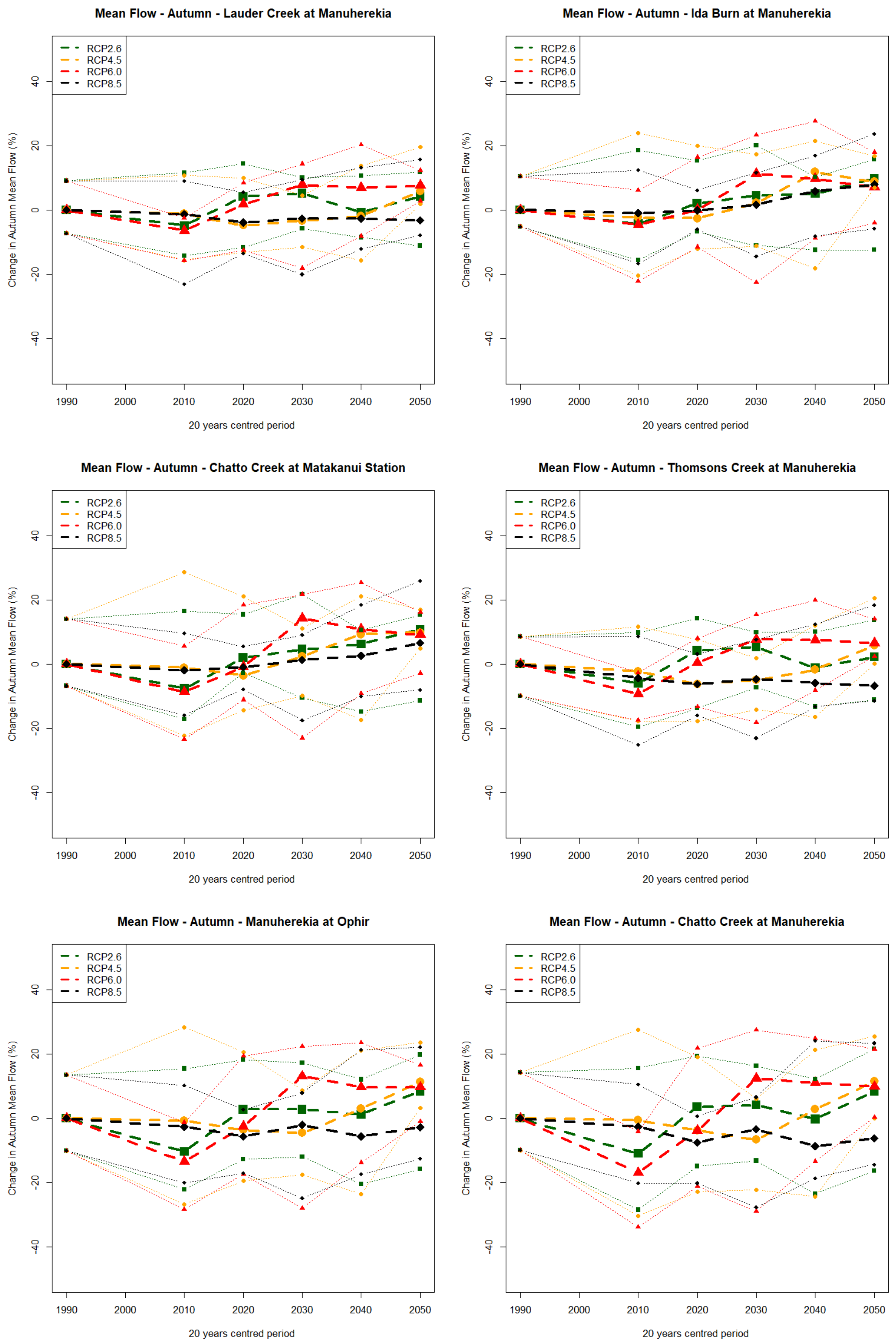

Figure F-2: 20-years centred change in Autumn mean flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

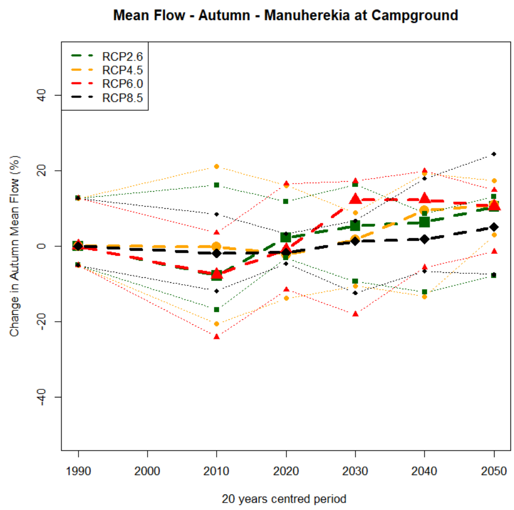

Figure F-3: 20-years centred change in Autumn mean flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Spring

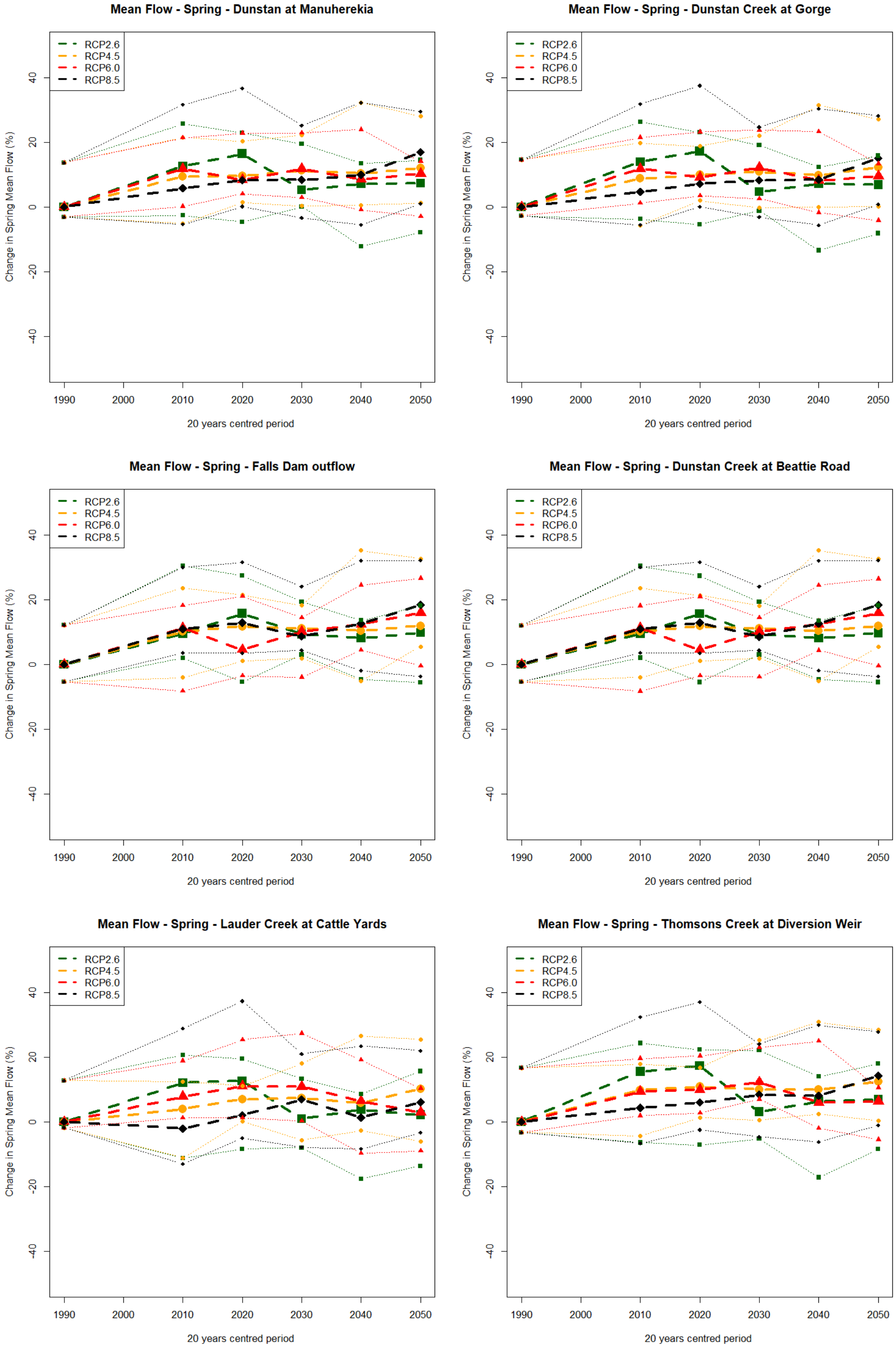

Figure F-4: 20-years centred change in Spring mean flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

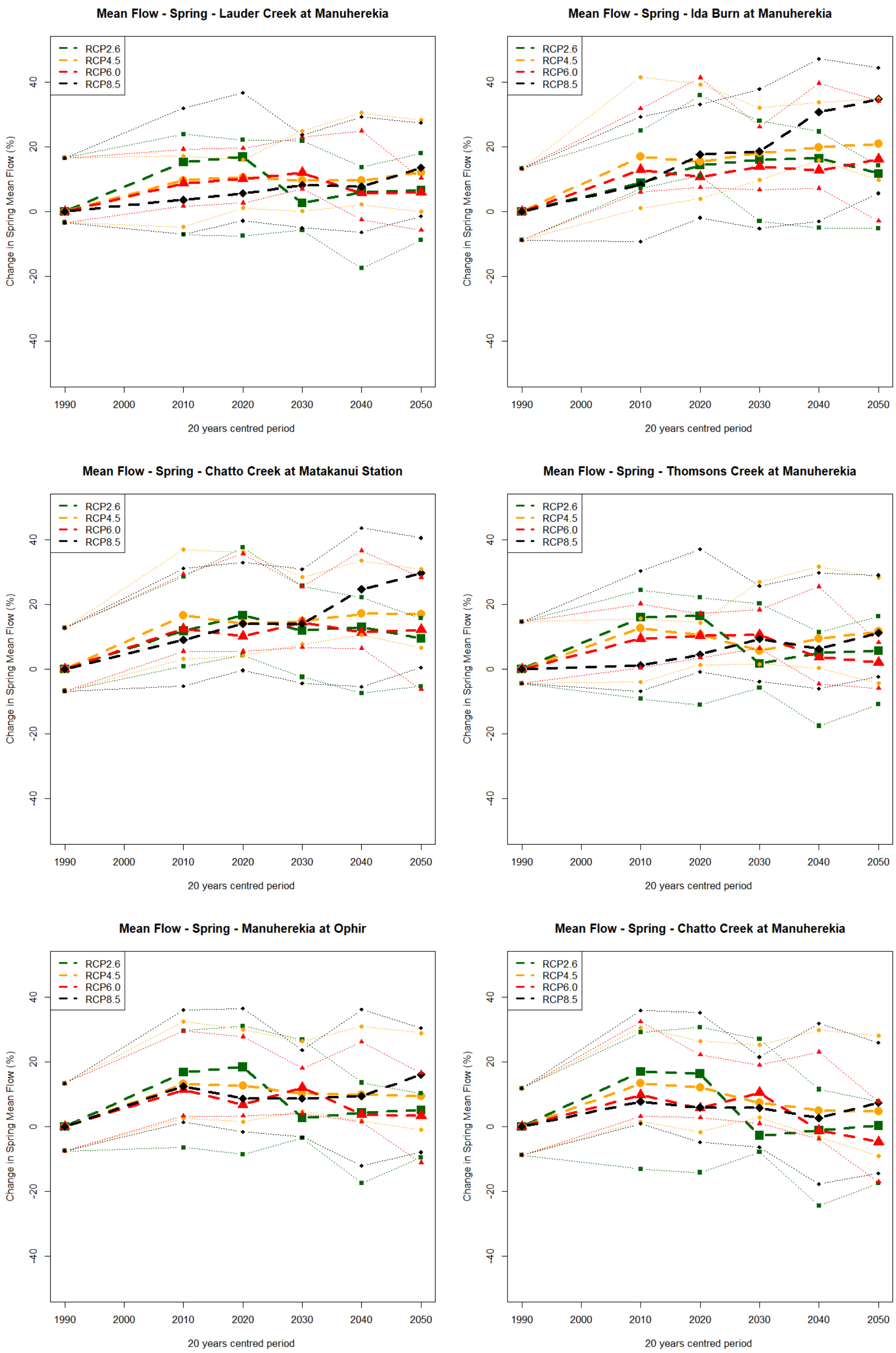

Figure F-5: 20-years centred change in Spring mean flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

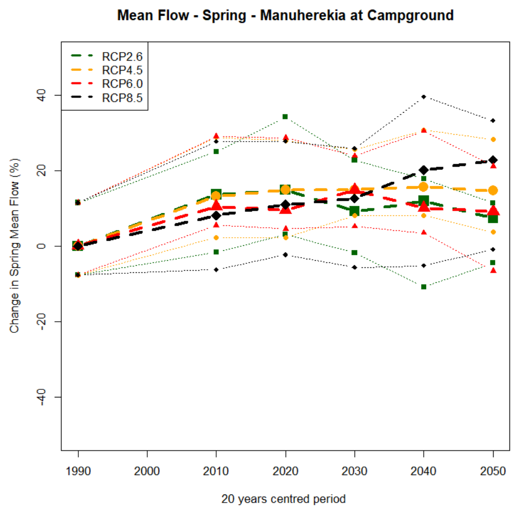

Figure F-6: 20-years centred change in Spring mean flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Summer

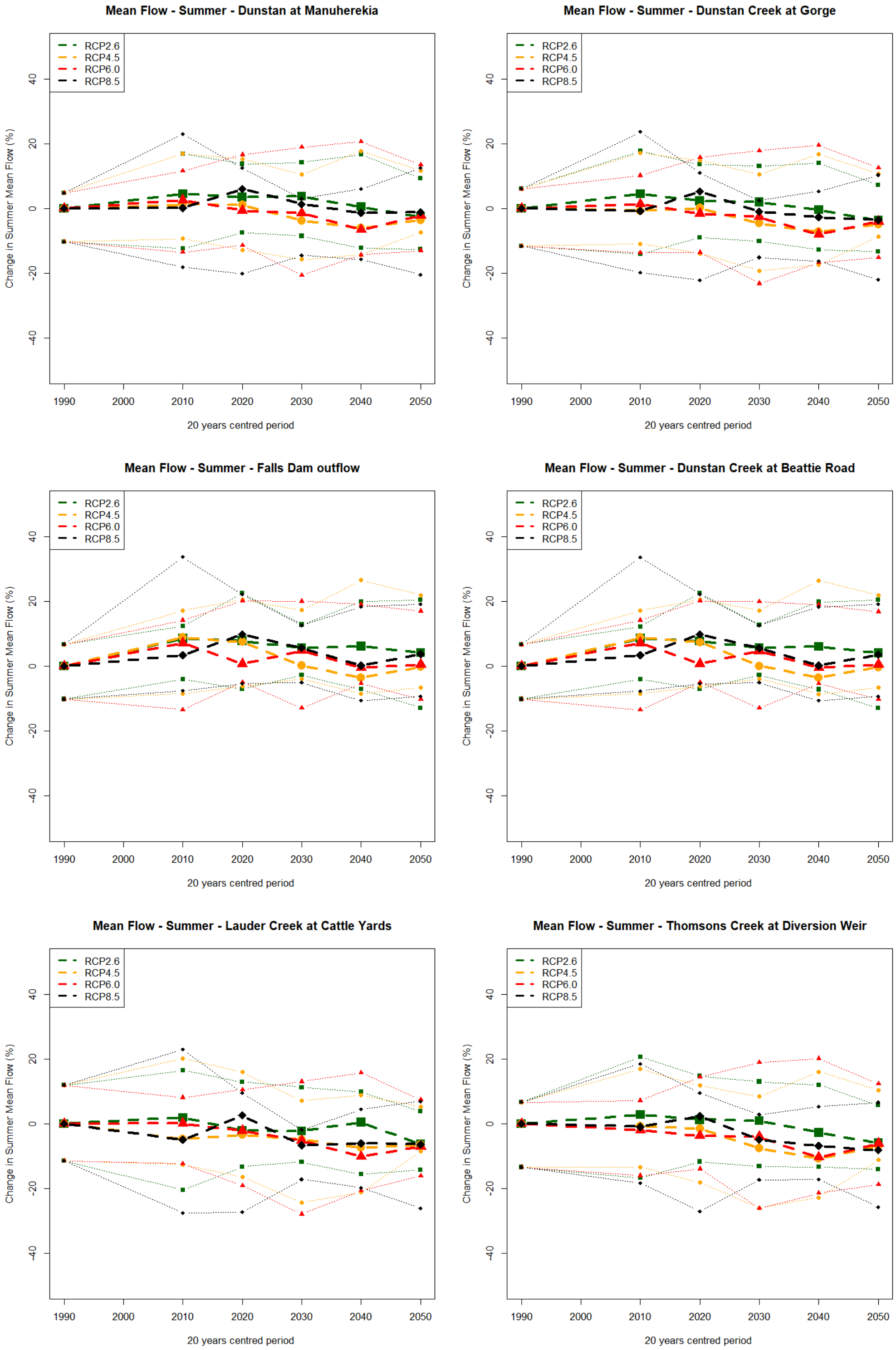

Figure F-7: 20-years centred change in Summer mean flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

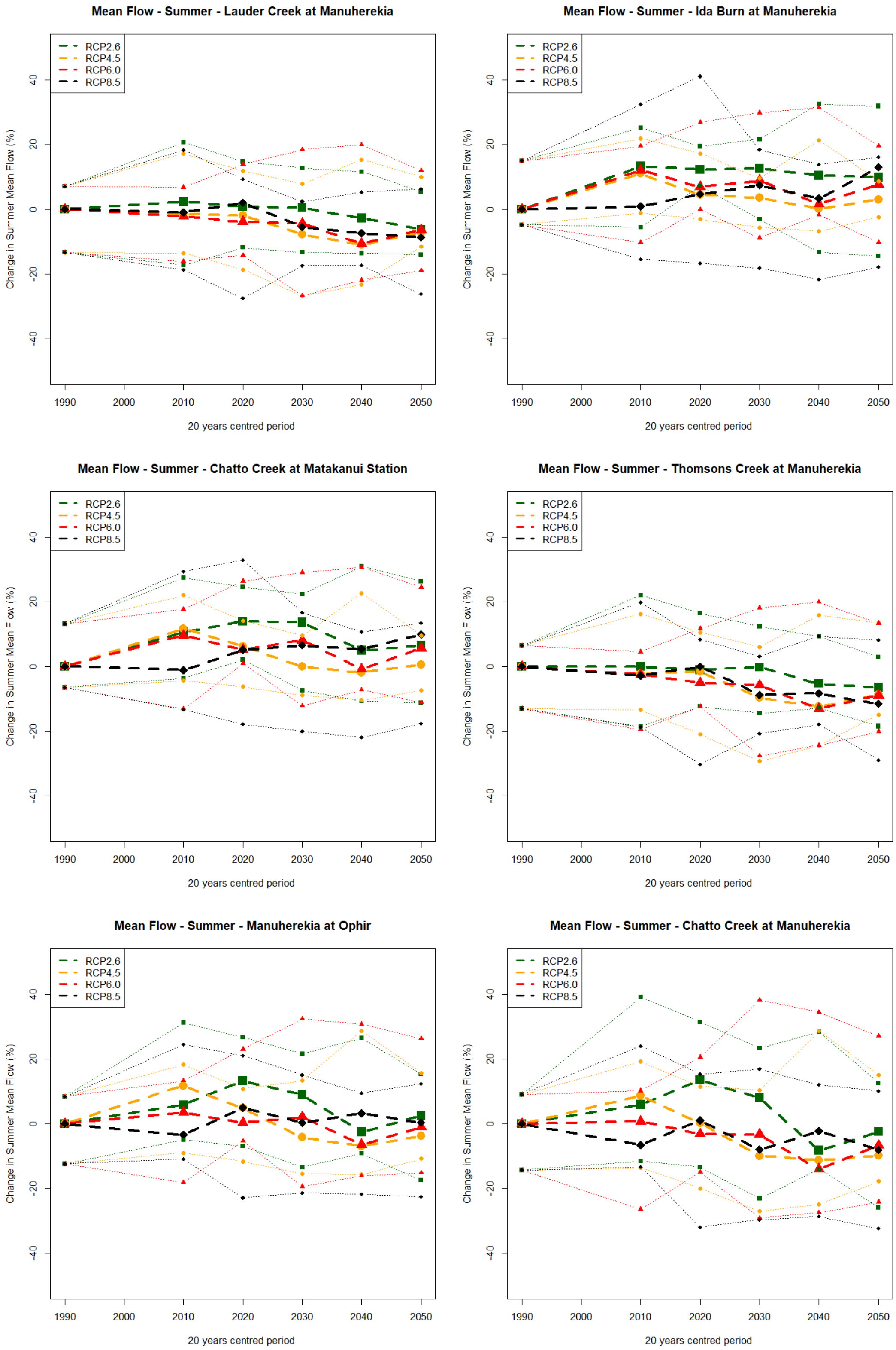

Figure F-8: 20-years centred change in Summer mean flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

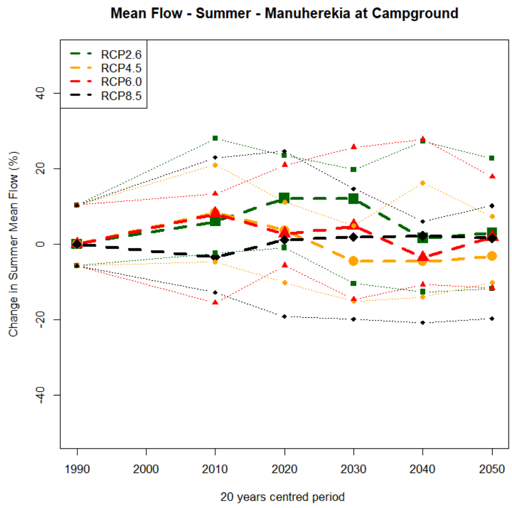

Figure F-9: 20-years centred change in Summer mean flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground. The green lines indicates results for RCP2.6, orange lines indicate results for RCP4.5, red lines indicate results for RCP6.0, black lines indicate results for RCP8.5, with the ensemble of change being bounded by maximum and minimum changes (thin dotted lines).

Winter

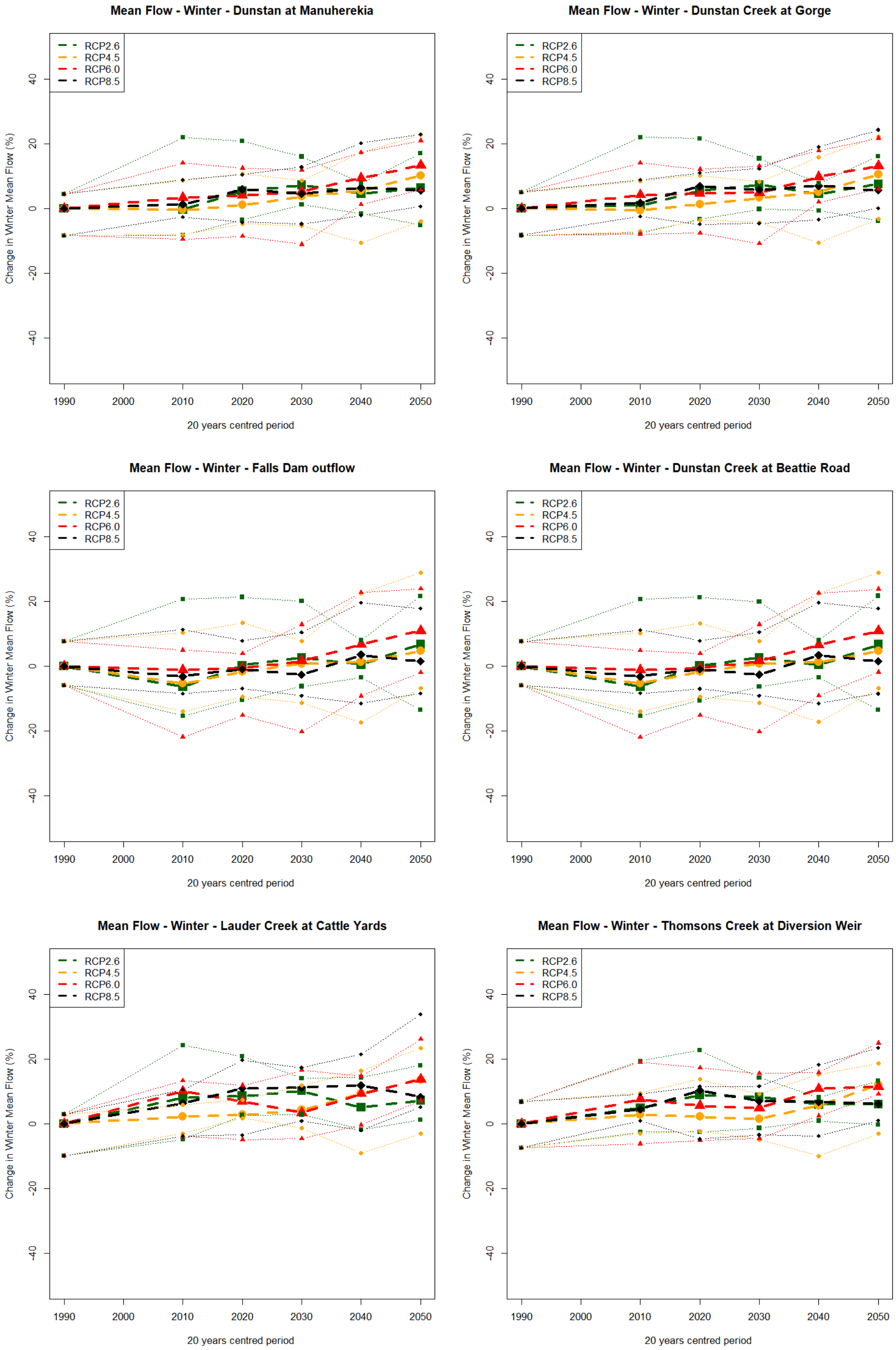

Figure F-10: 20-years centred change in Winter mean flow characteristic across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

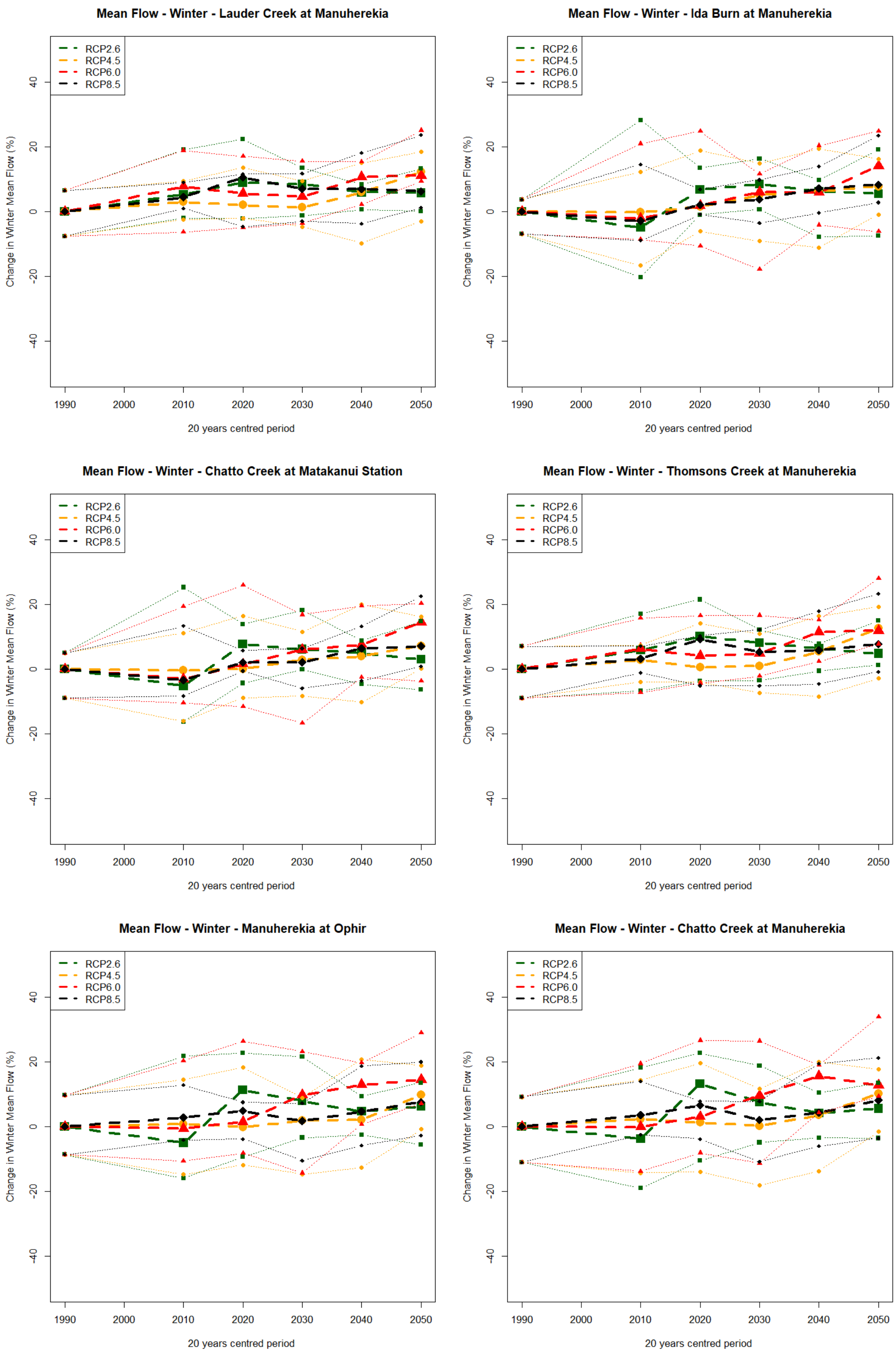

Figure F-11: 20-years centred change in Winter mean flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

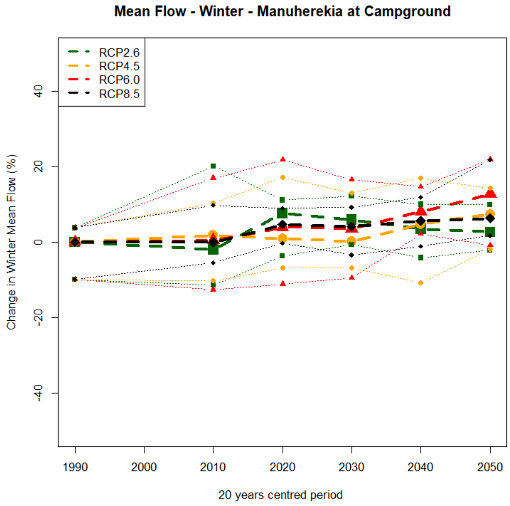

Figure F-12: 20-years centred change in Winter mean flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Appendix G Changes in Seasonal median flow

Autumn

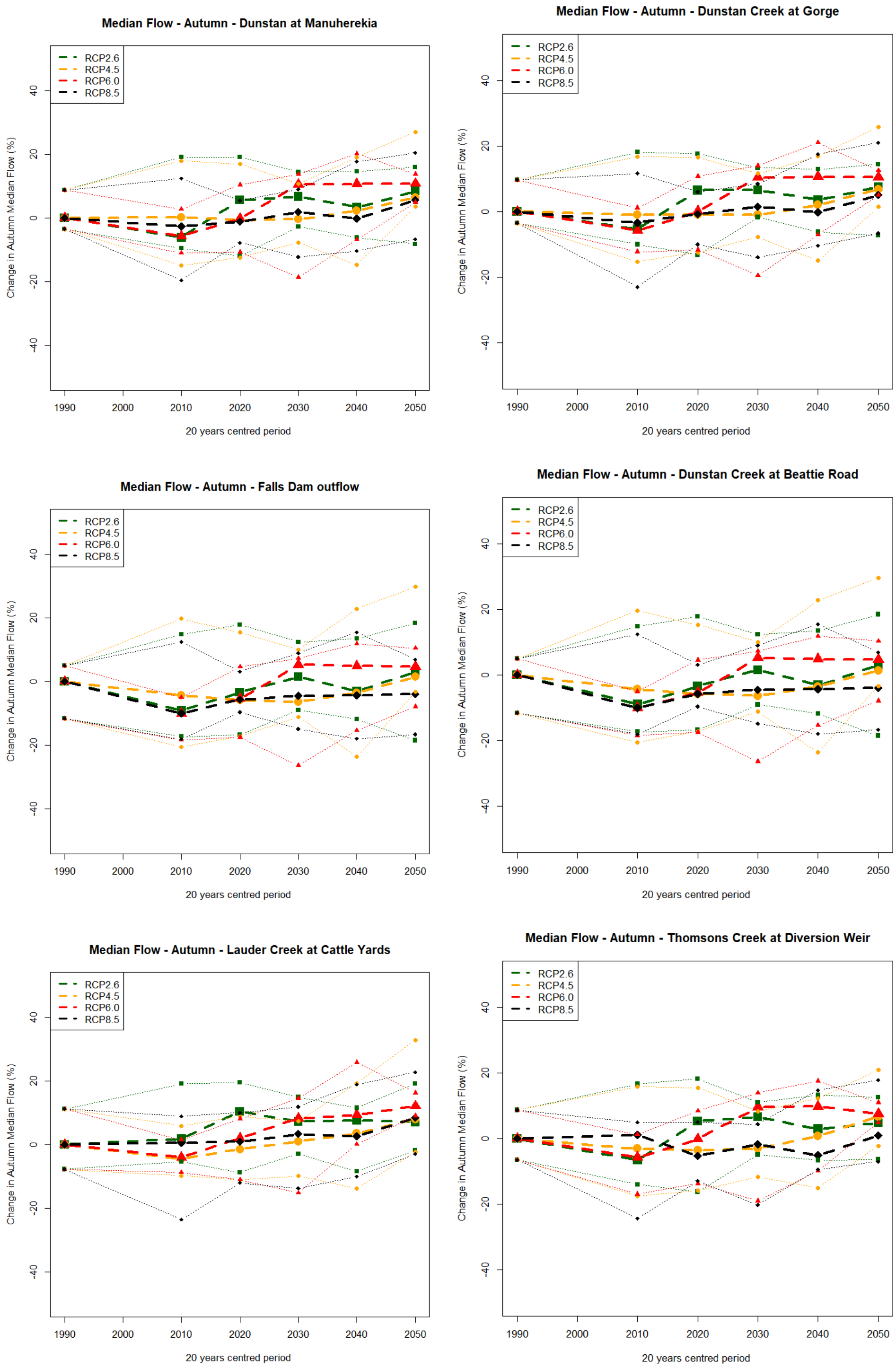

Figure G-1: 20-years centred change in Autumn median flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

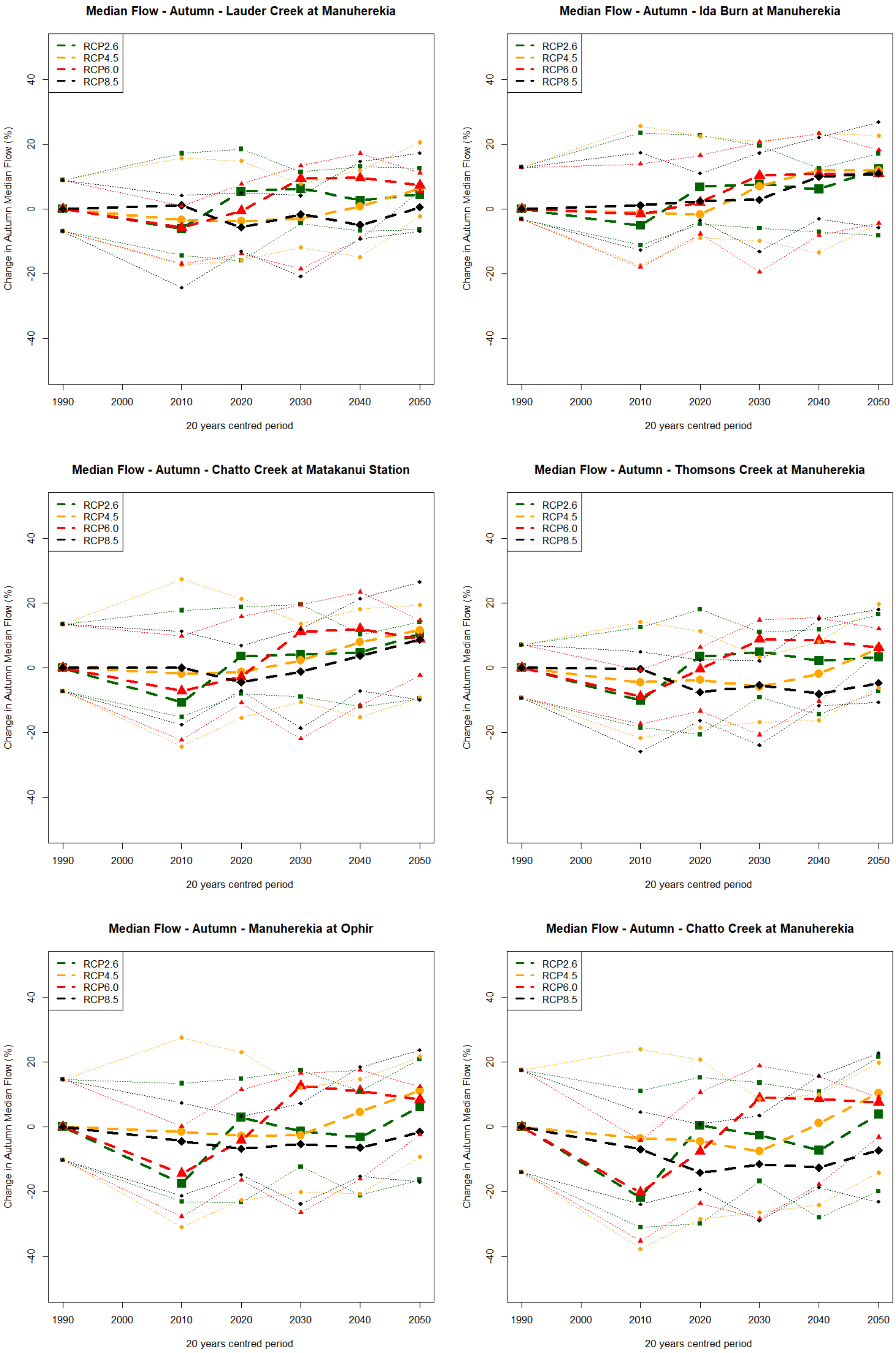

Figure G-2: 20-years centred change in Autumn median flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

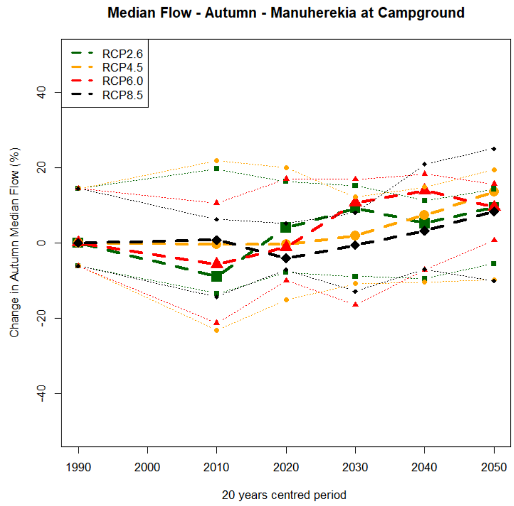

Figure G-3: 20-years centred change in Autumn median flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Spring

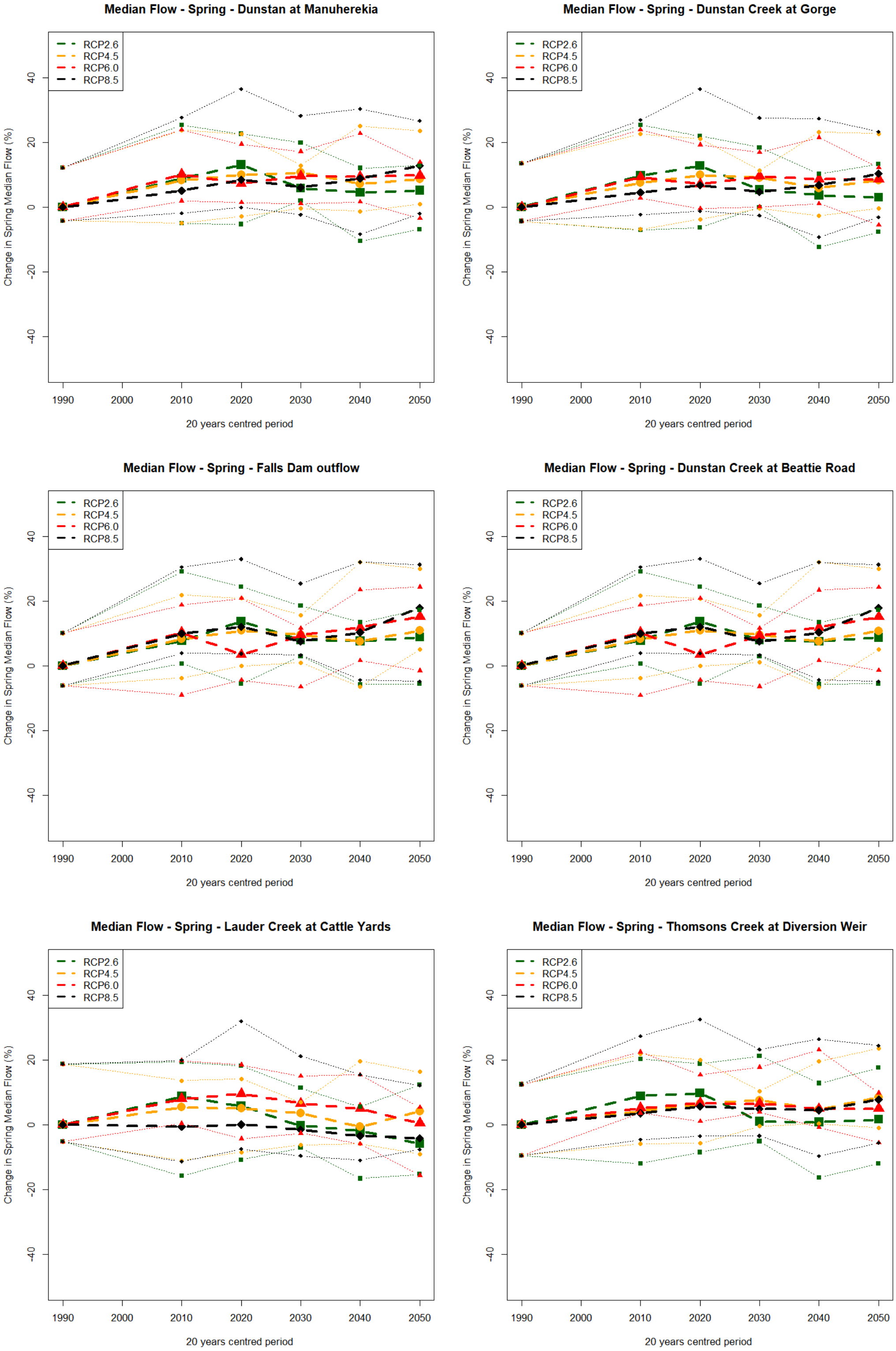

Figure G-4: 20-years centred change in Spring median flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

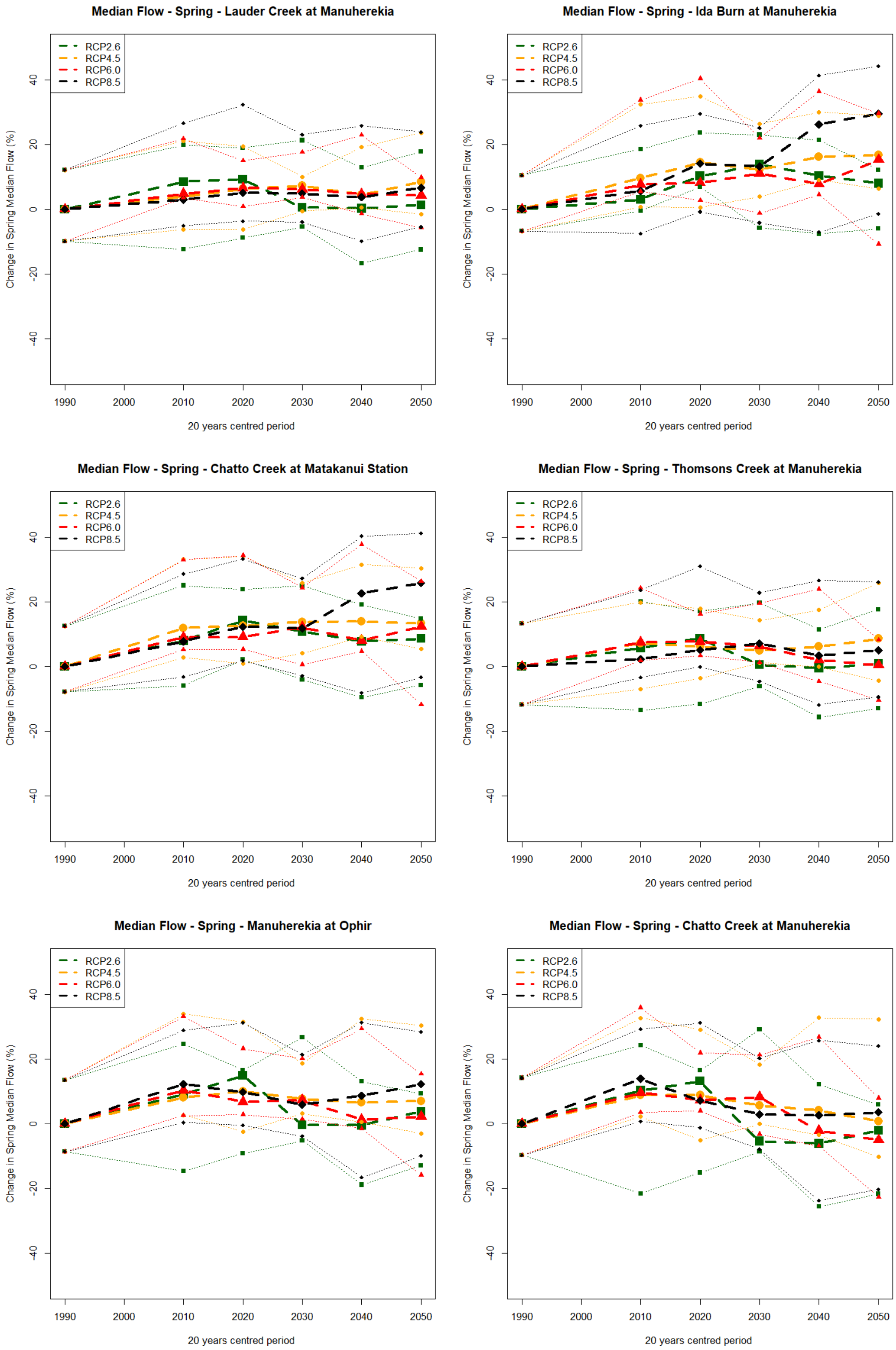

Figure G-5: 20-years centred change in Spring median flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

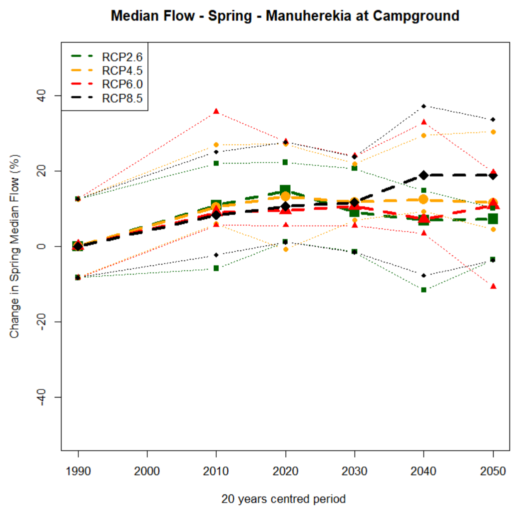

Figure G-6: 20-years centred change in Spring median flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Summer

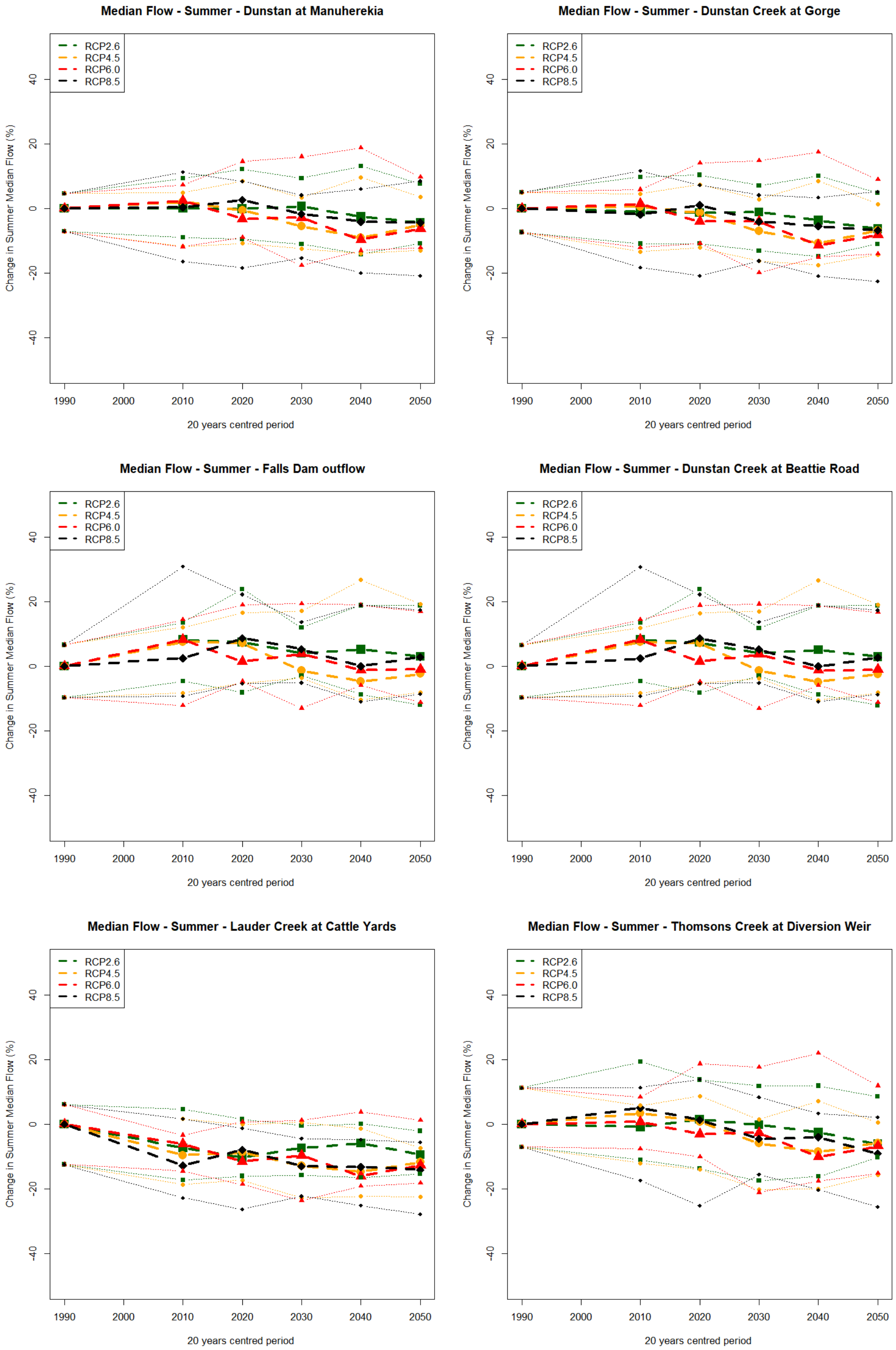

Figure G-7: 20-years centred change in Summer median flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

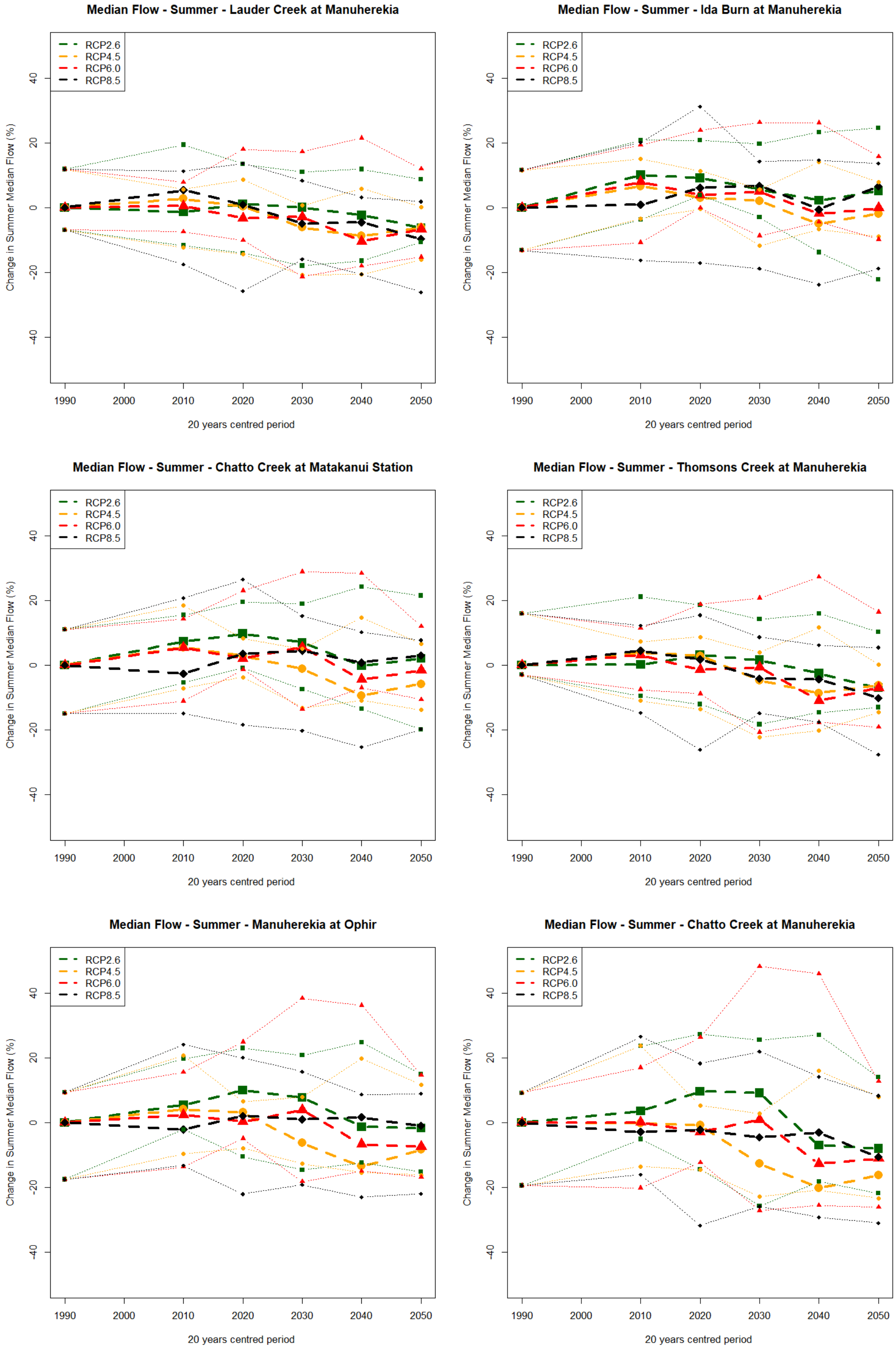

Figure G-8: 20-years centred change in Summer median flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

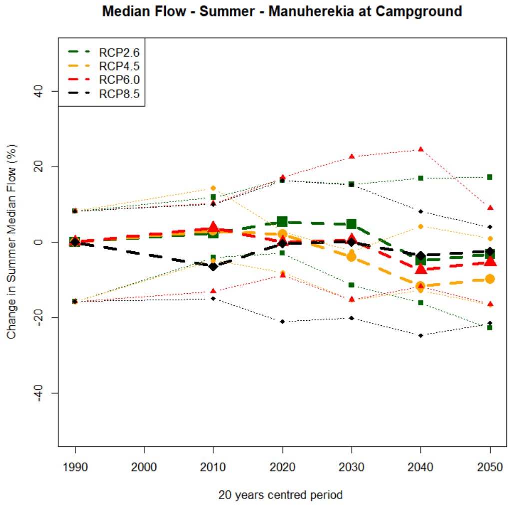

Figure G-9: 20-years centred change in Summer median flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Winter

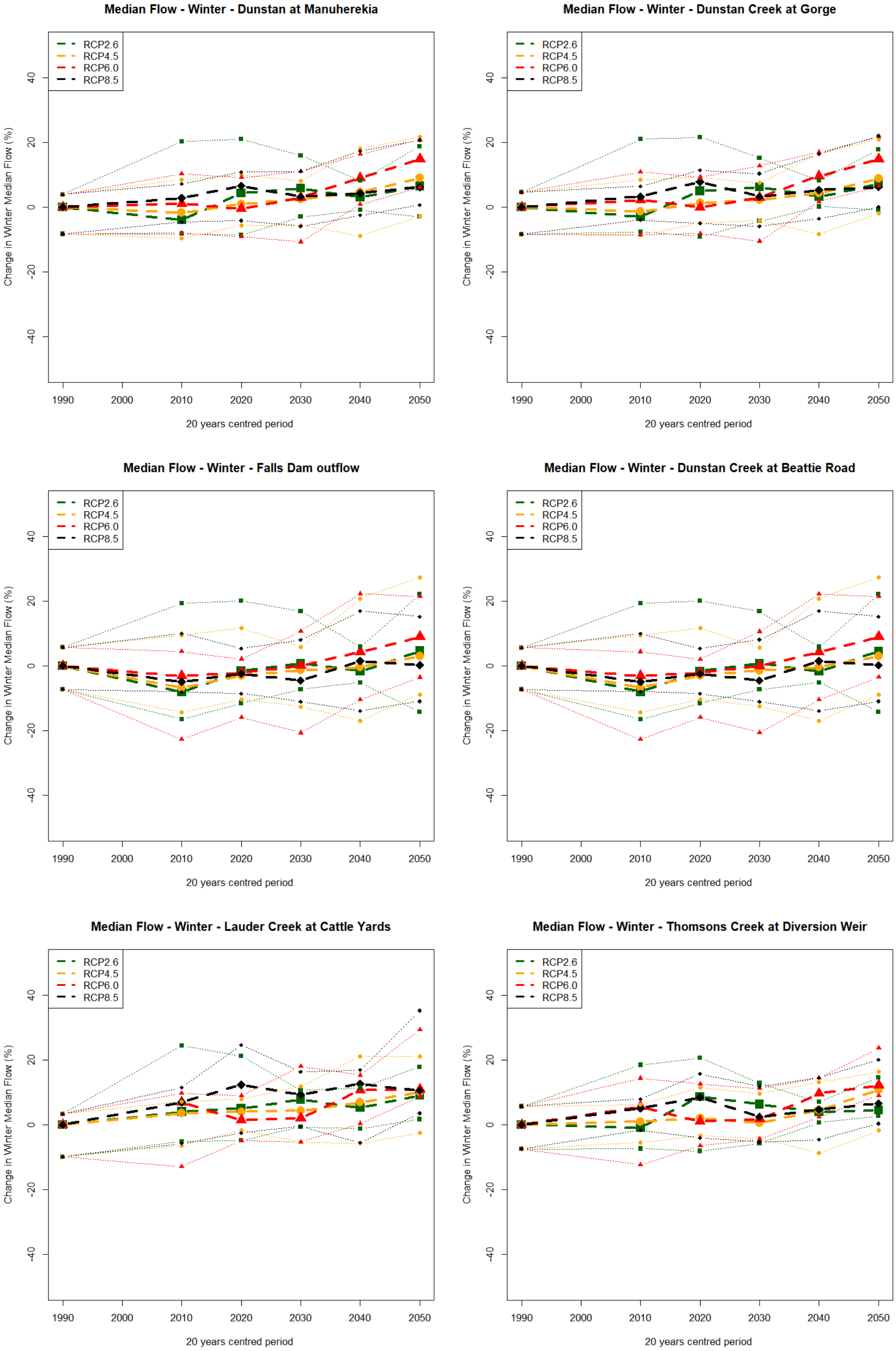

Figure G-10: 20-years centred change in Winter median flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

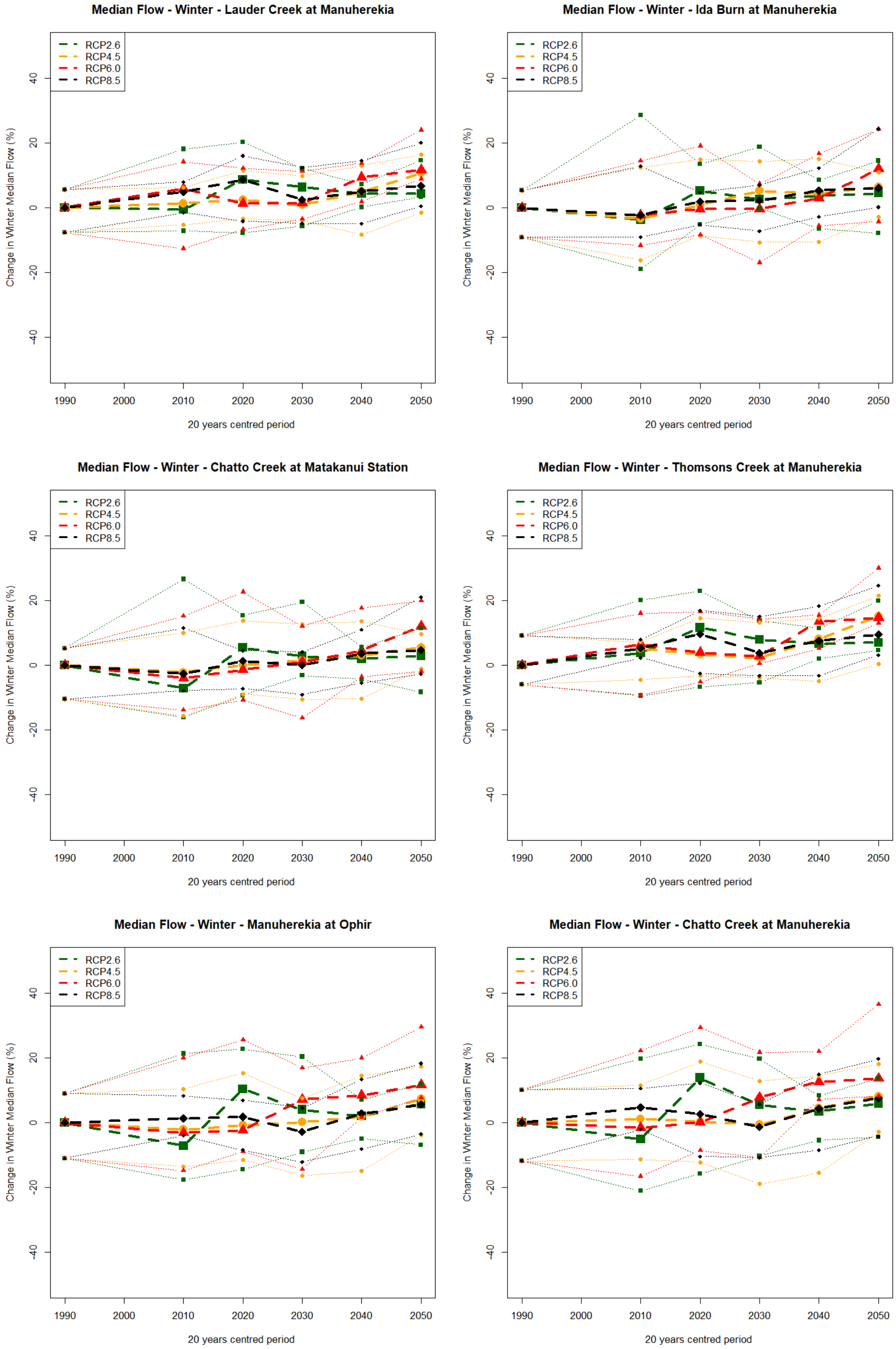

Figure G-11: 20-years centred change in Winter median flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

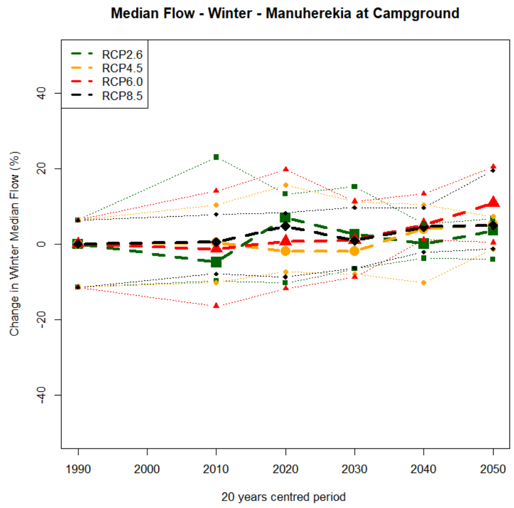

Figure G-12: 20-years centred change in Winter median flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Appendix H Changes in Seasonal low flow

Spring

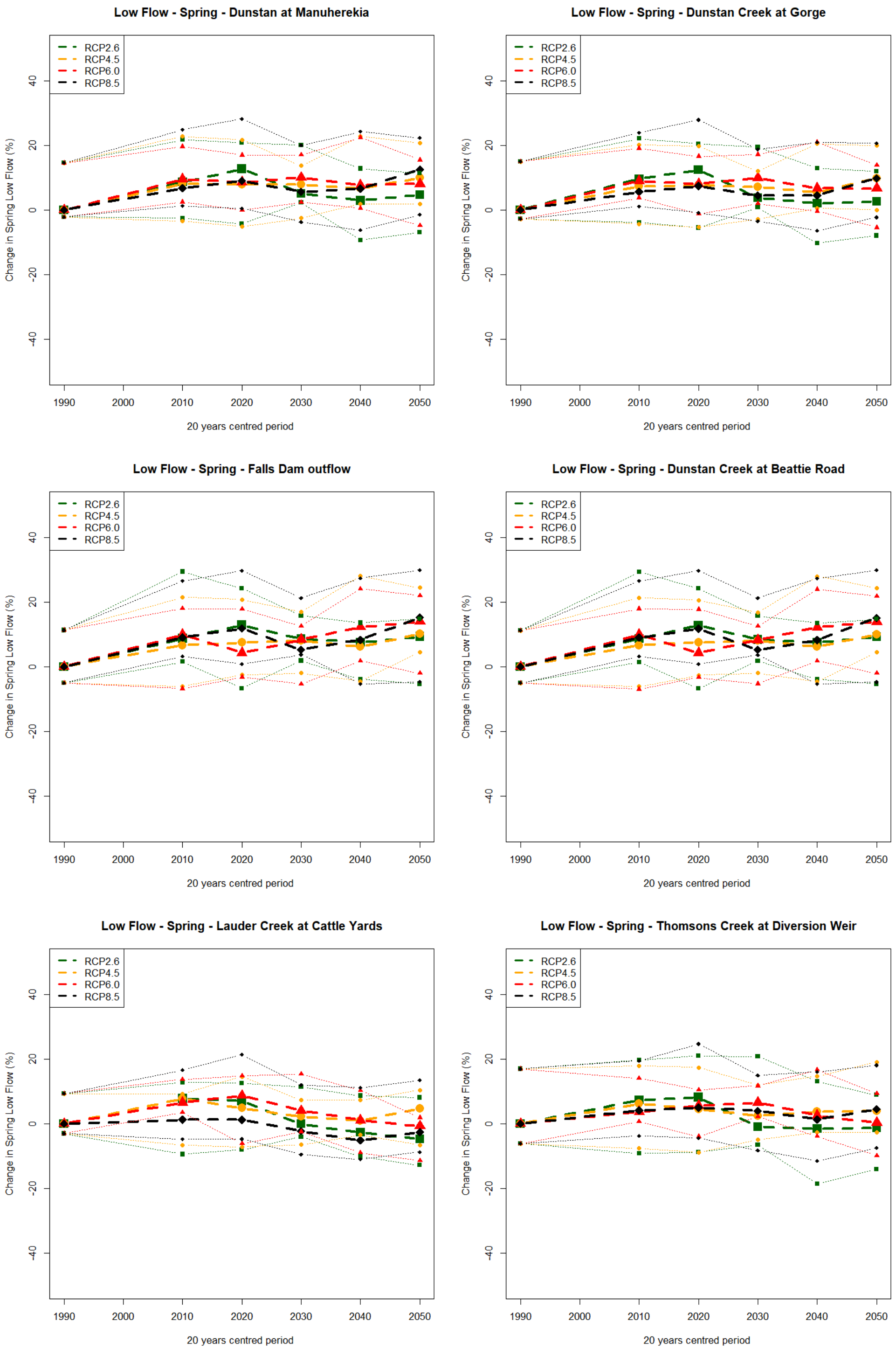

Figure H-1: 20-years centred change in Spring low flow characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

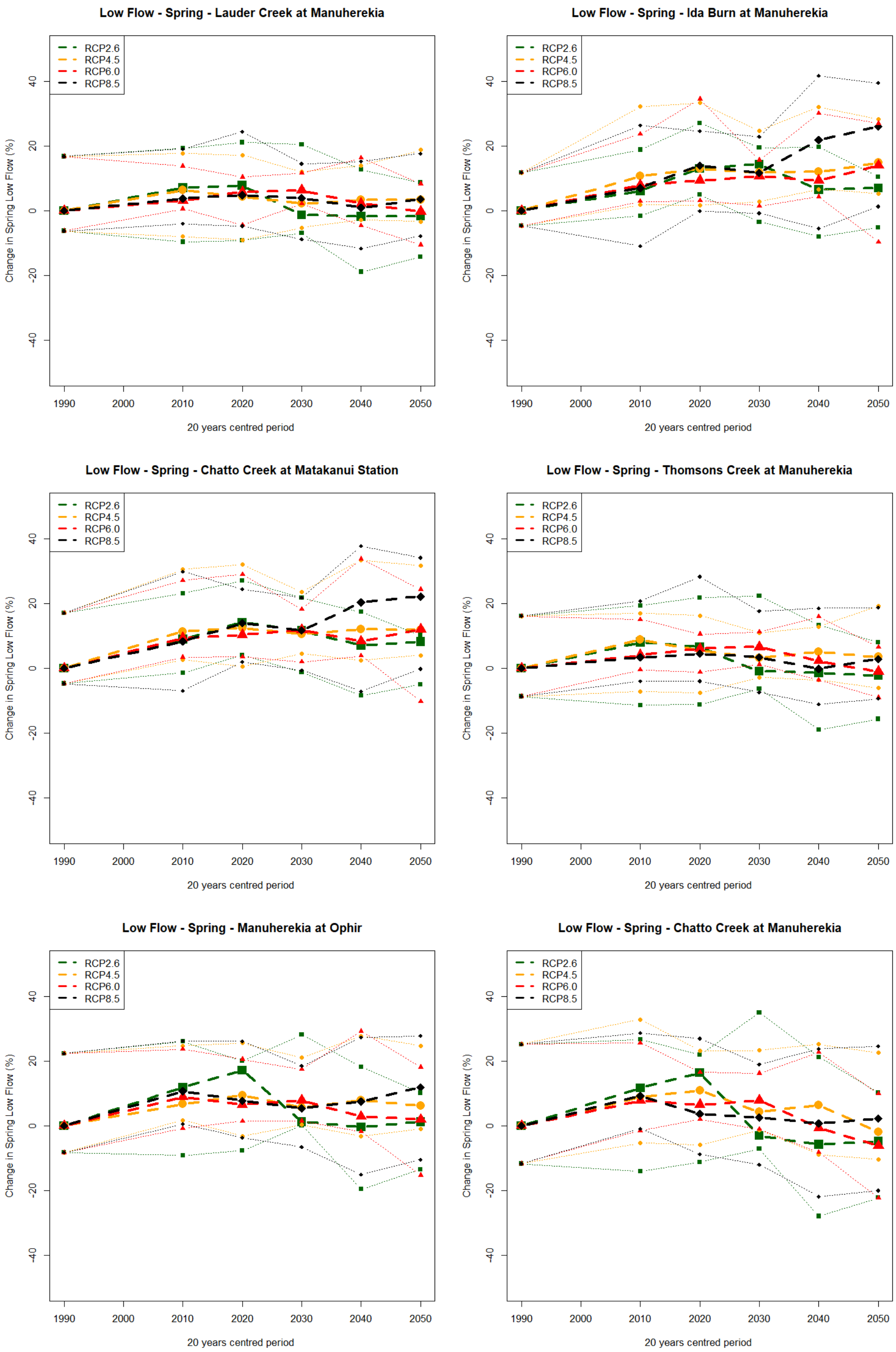

Figure H-2: 20-years centred change in Spring low characteristic across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

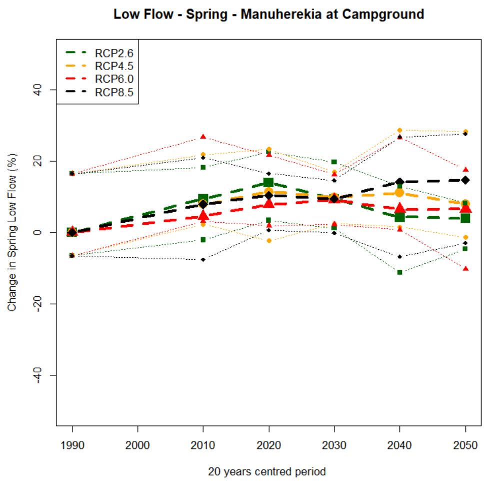

Figure H-3: 20-years centred change in Spring low flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Summer

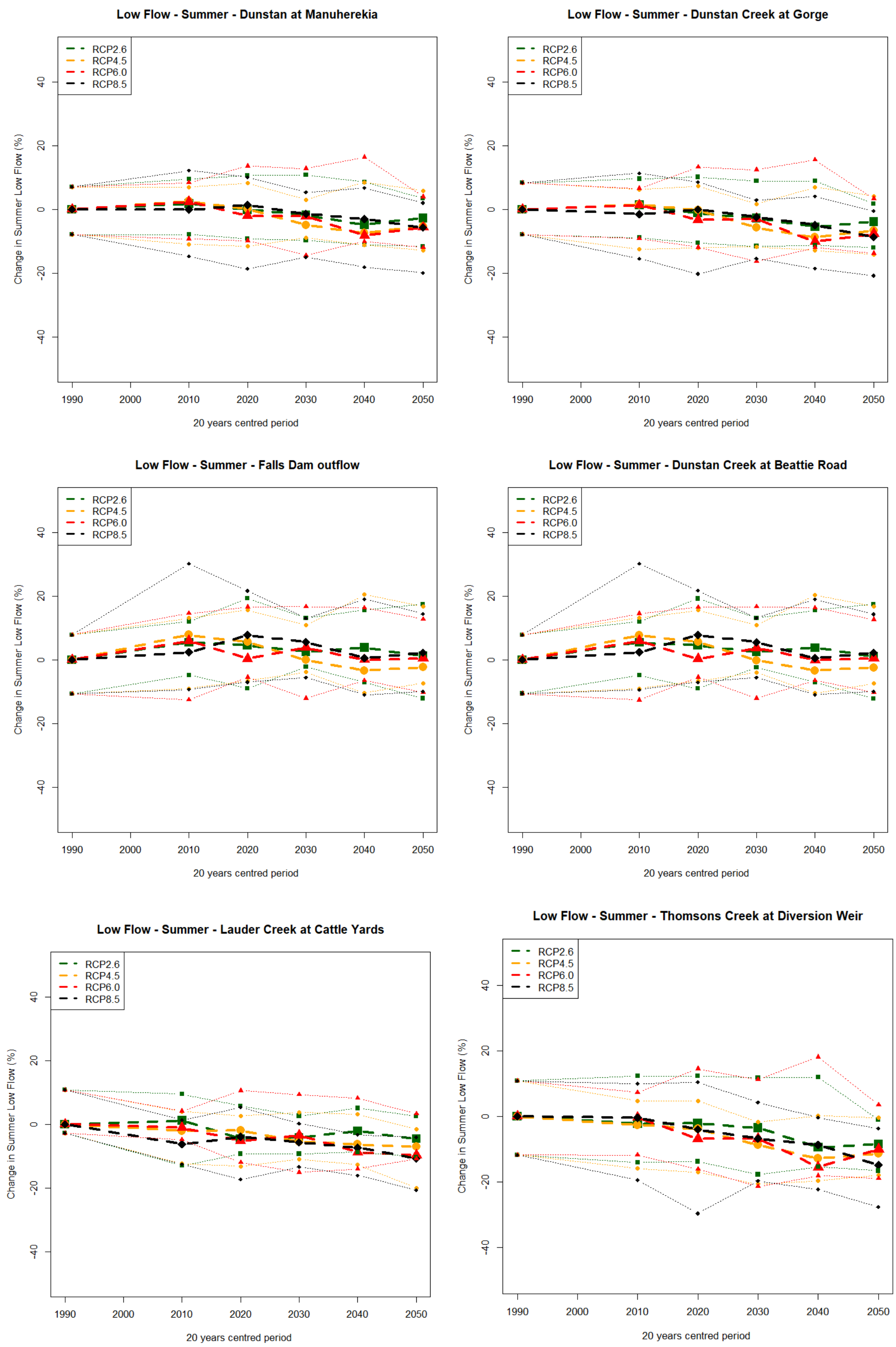

Figure H-4: 20-years centred change in Summer low flow characteristic across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

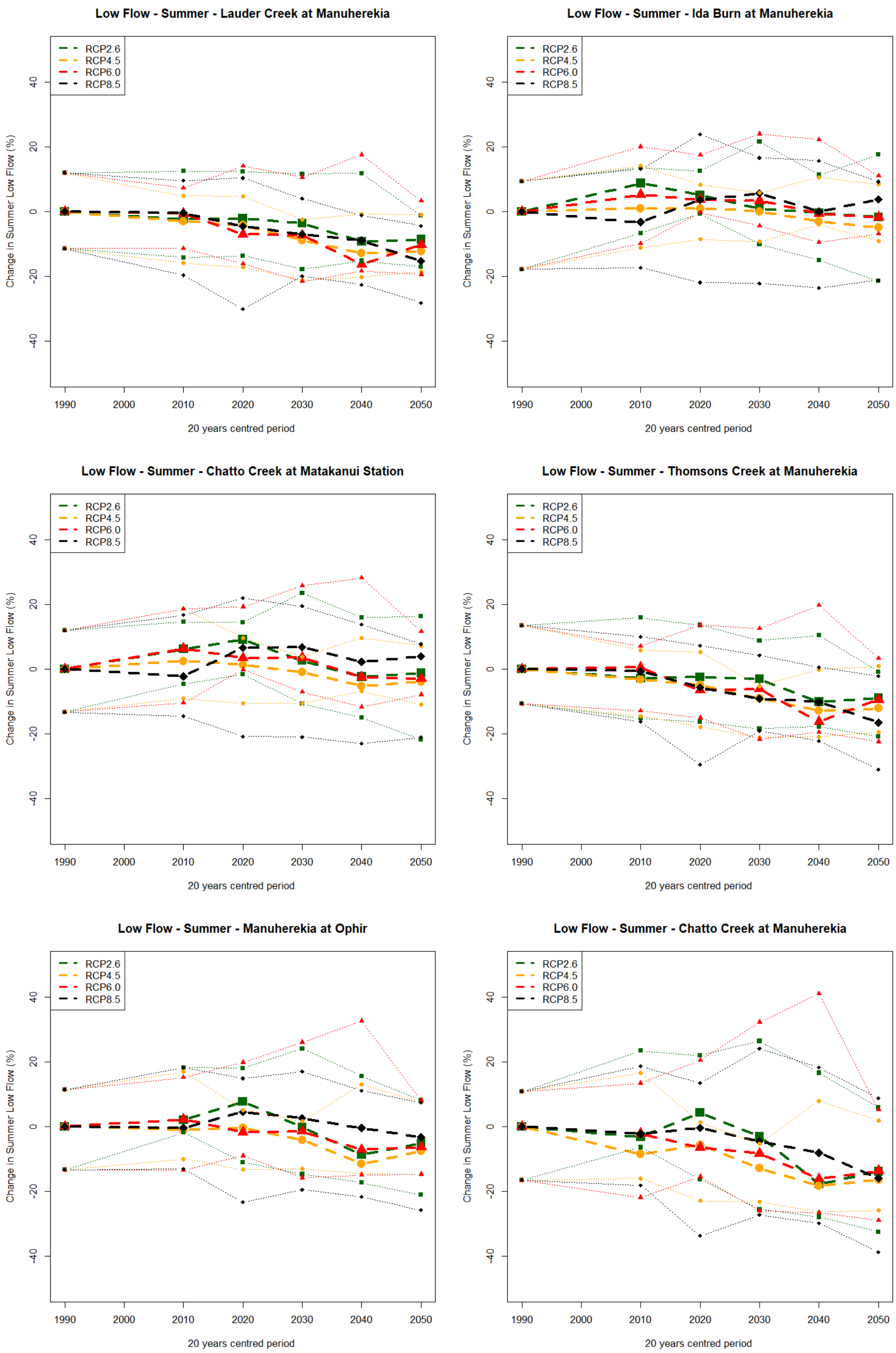

Figure H-5: 20-years centred change in Summer low flow characteristic across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

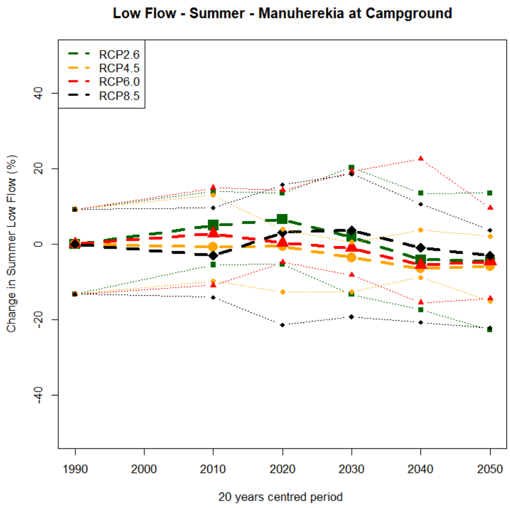

Figure H-6: 20-years centred change in Summer low flow characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.

Appendix I Changes in maximum and median number of consecutive events below historical 7-day MALF

Maximum

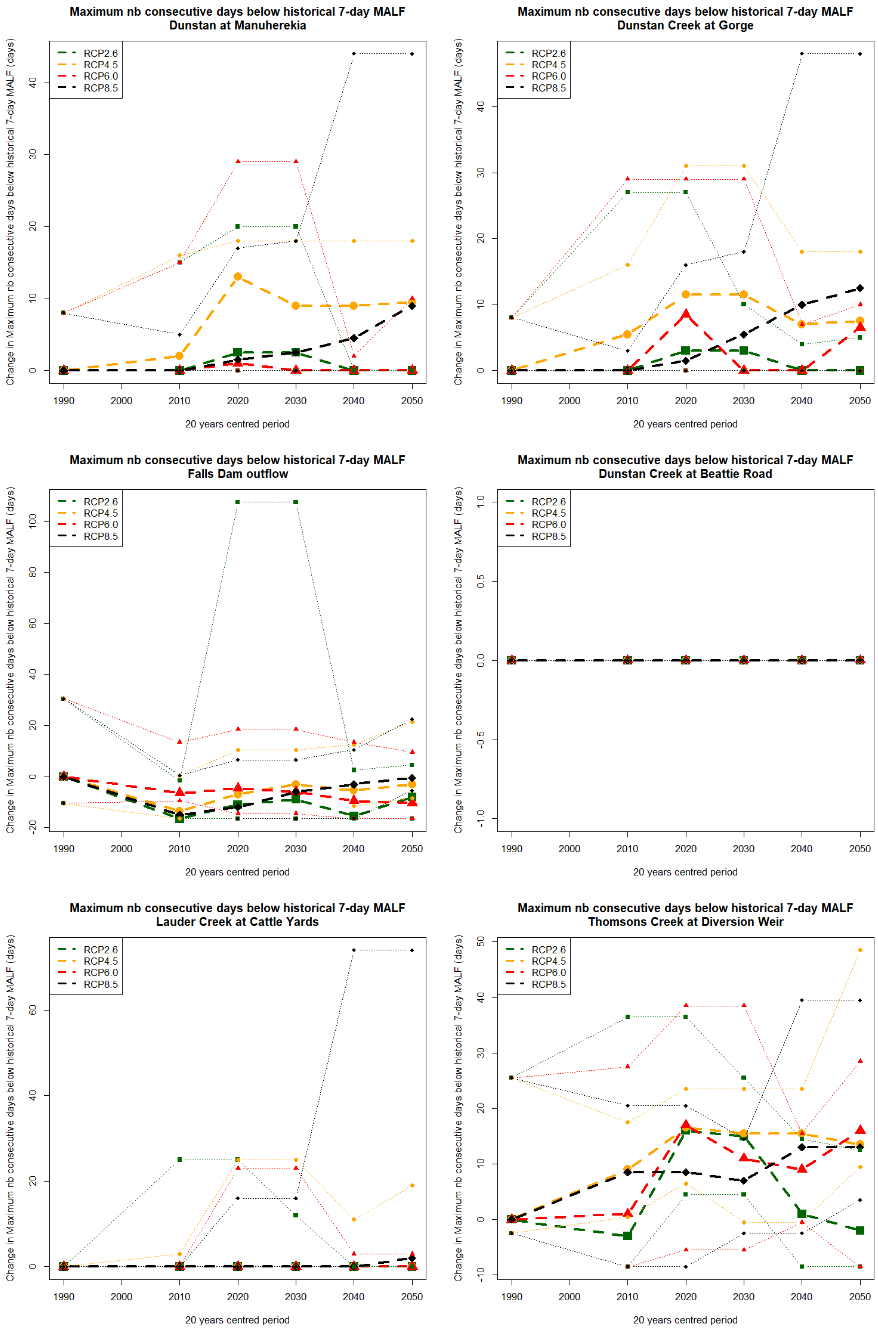

Figure I-1: 20-years centred change in maximum number of consecutive events below historical 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

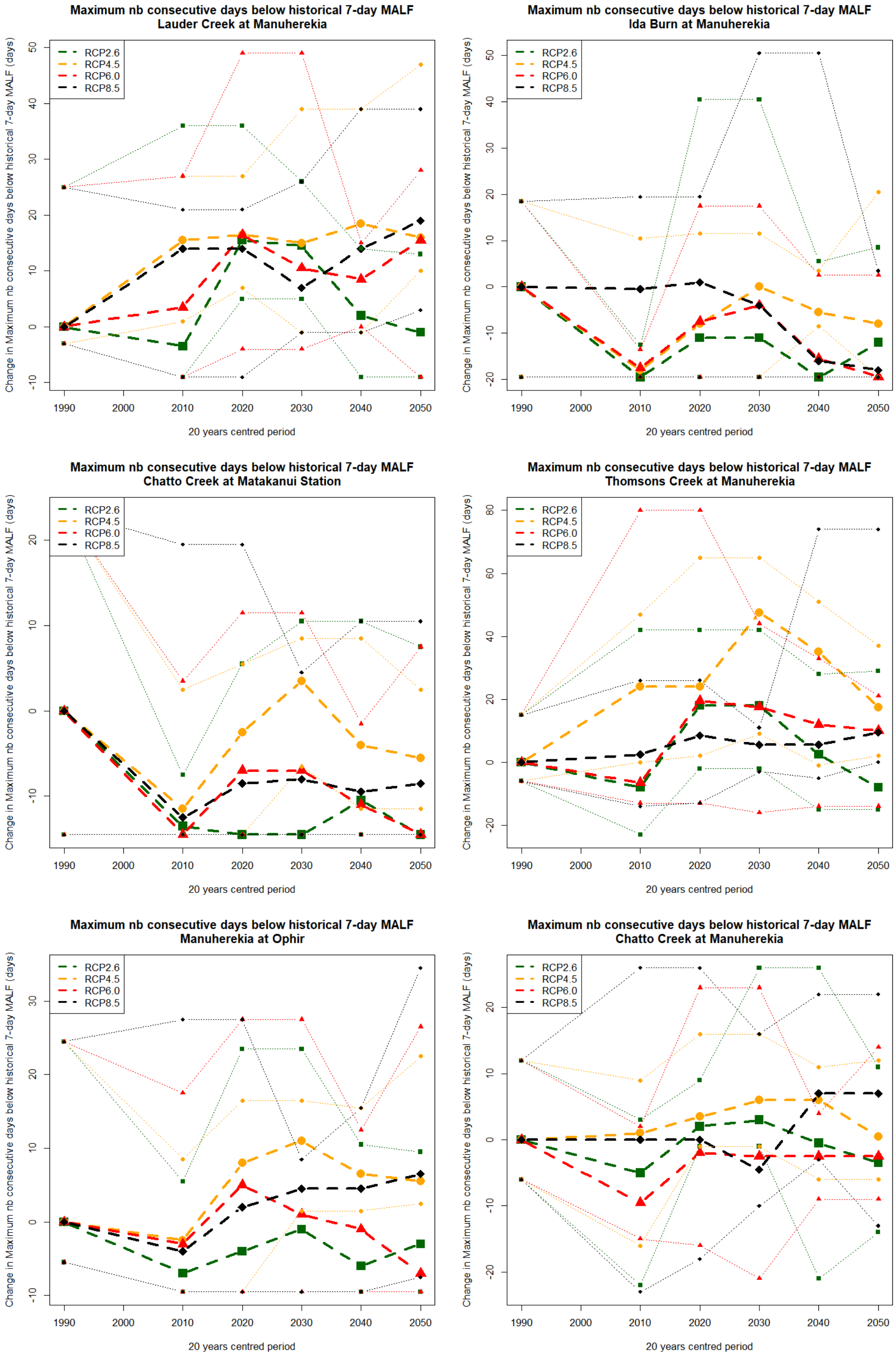

Figure I-2: 20-years centred change in maximum number of consecutive events below historical 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

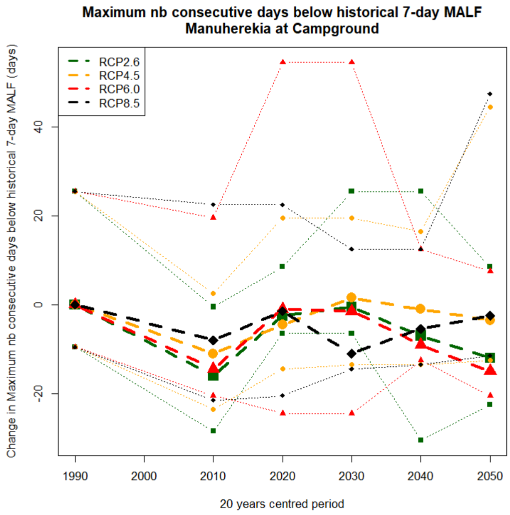

Figure I-3: 20-years centred change in maximum number of consecutive events below historical 7-day MALF across RCPs over the period 2006-2060 at Manuherekia at Campground.

Median

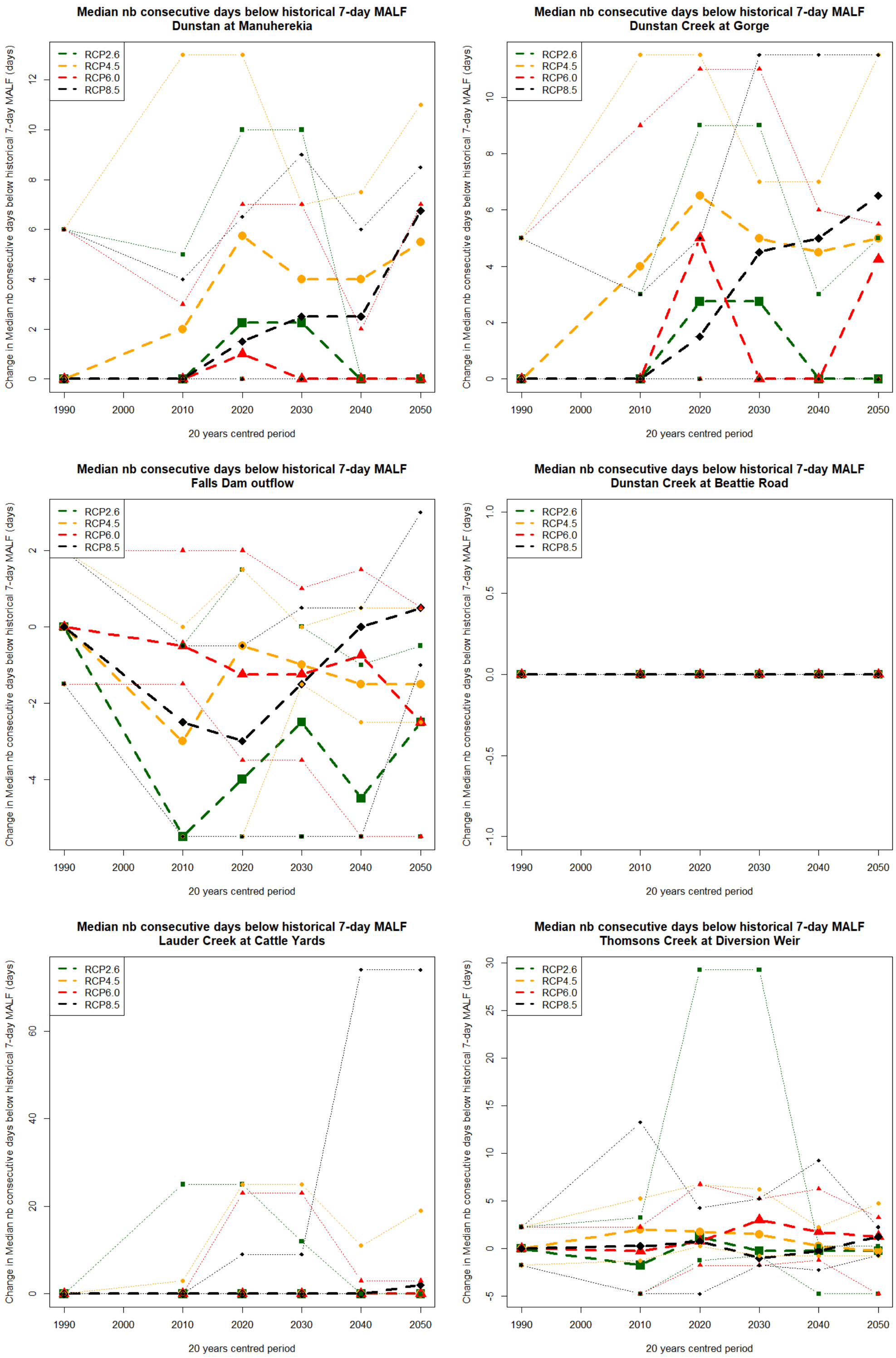

Figure I-4: 20-years centred change in median number of consecutive events below historical 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

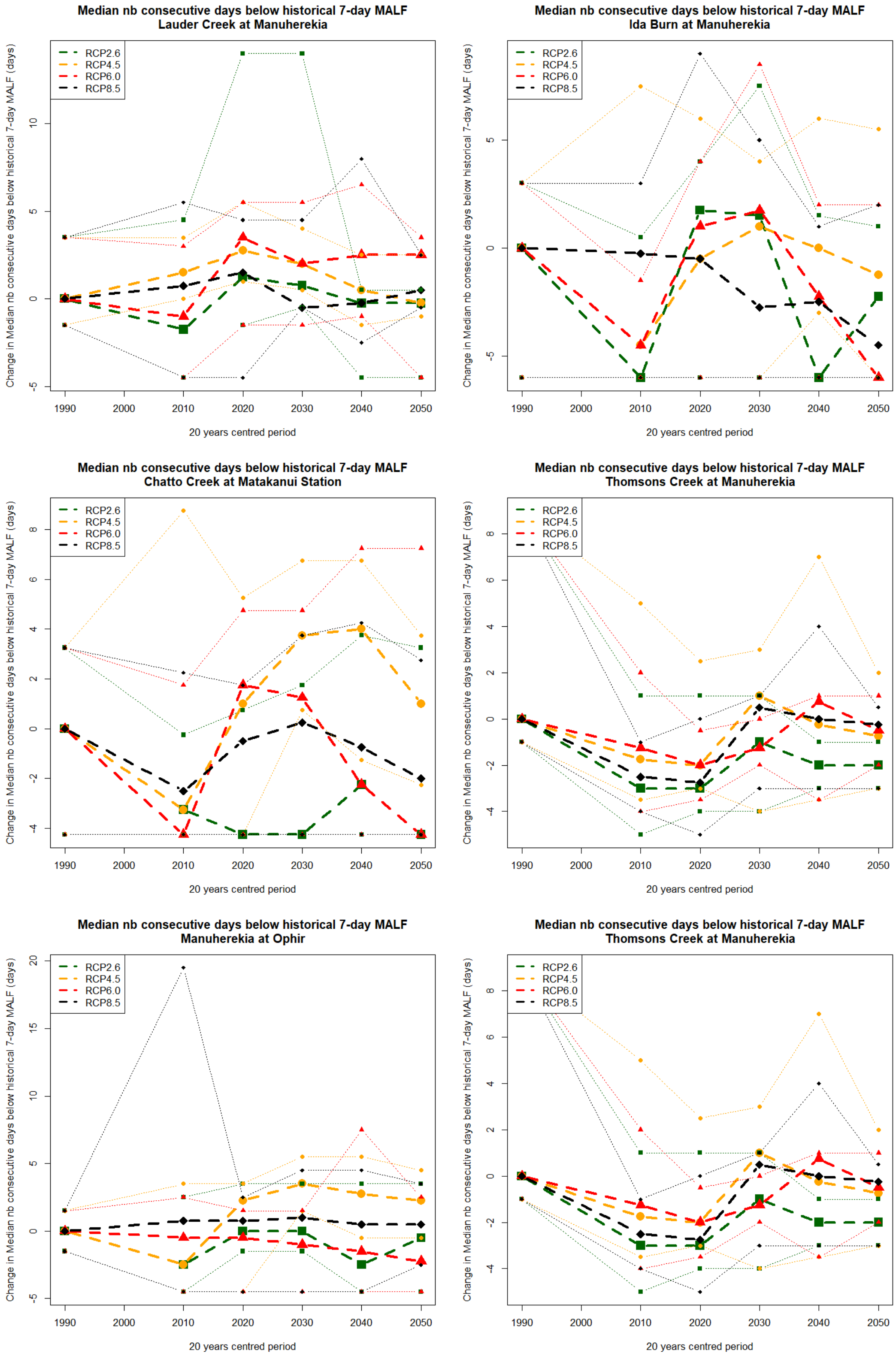

Figure I-5: 20-years centred change in median number of consecutive events below historical 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

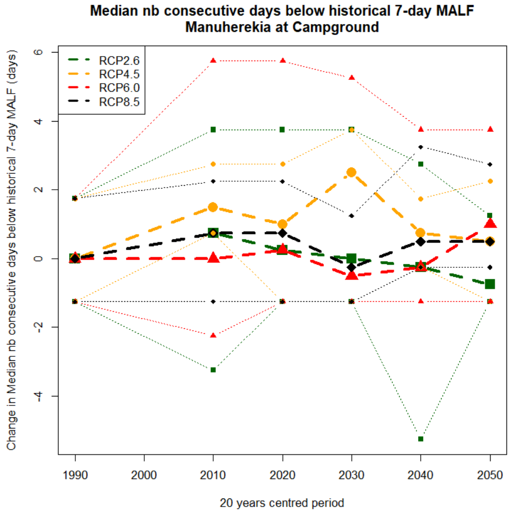

Figure I-6: 20-years centred change in median number of consecutive events below historical 7-day MALF across RCPs over the period 2006-2060 at Manuherekia at Campground.

Appendix J Changes in median and maximum number of consecutive five-day events below historical 7-day MALF

Maximum

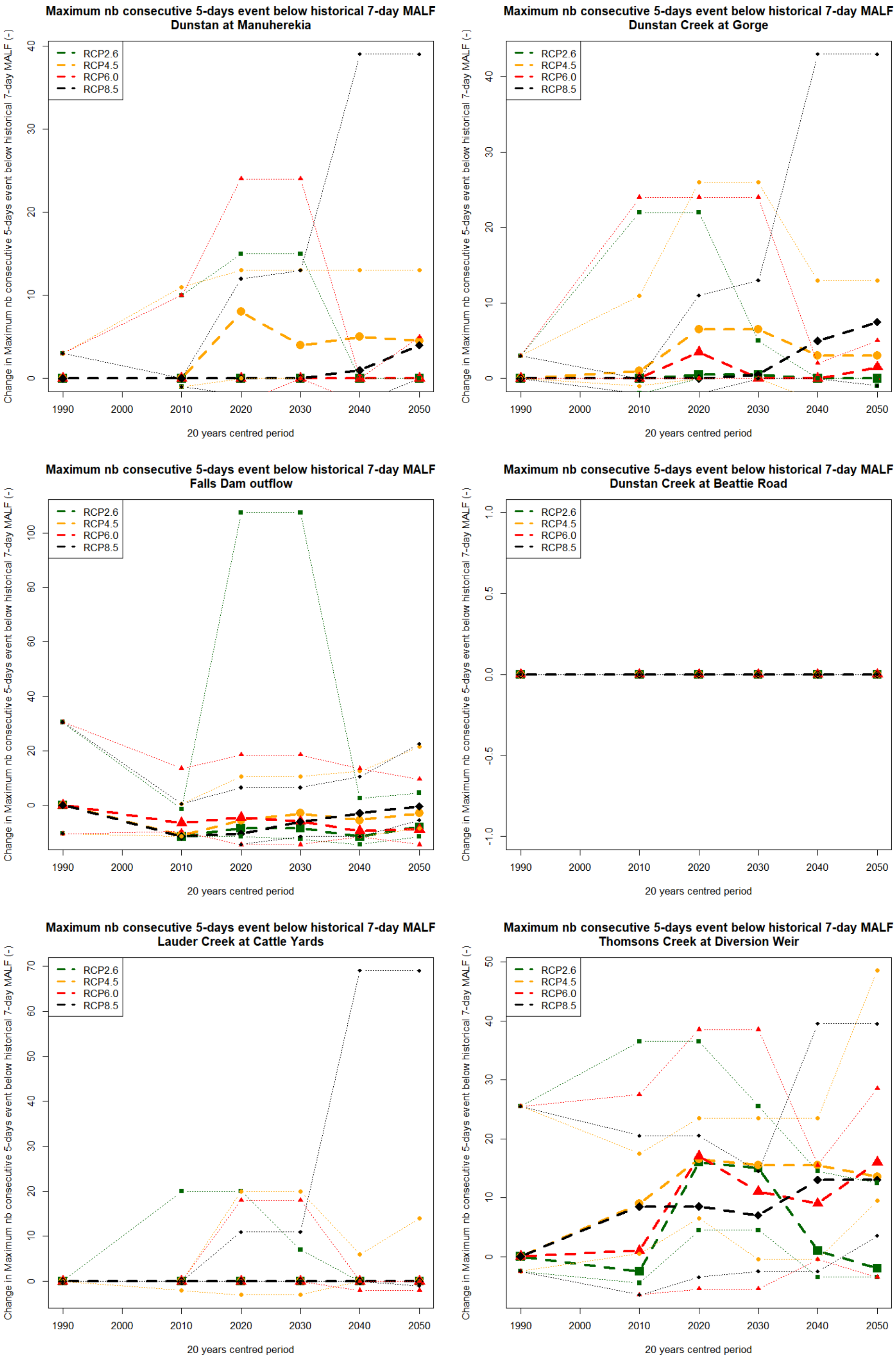

Figure J-1: 20-years centred change in maximum number of consecutive five-day events below historical 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

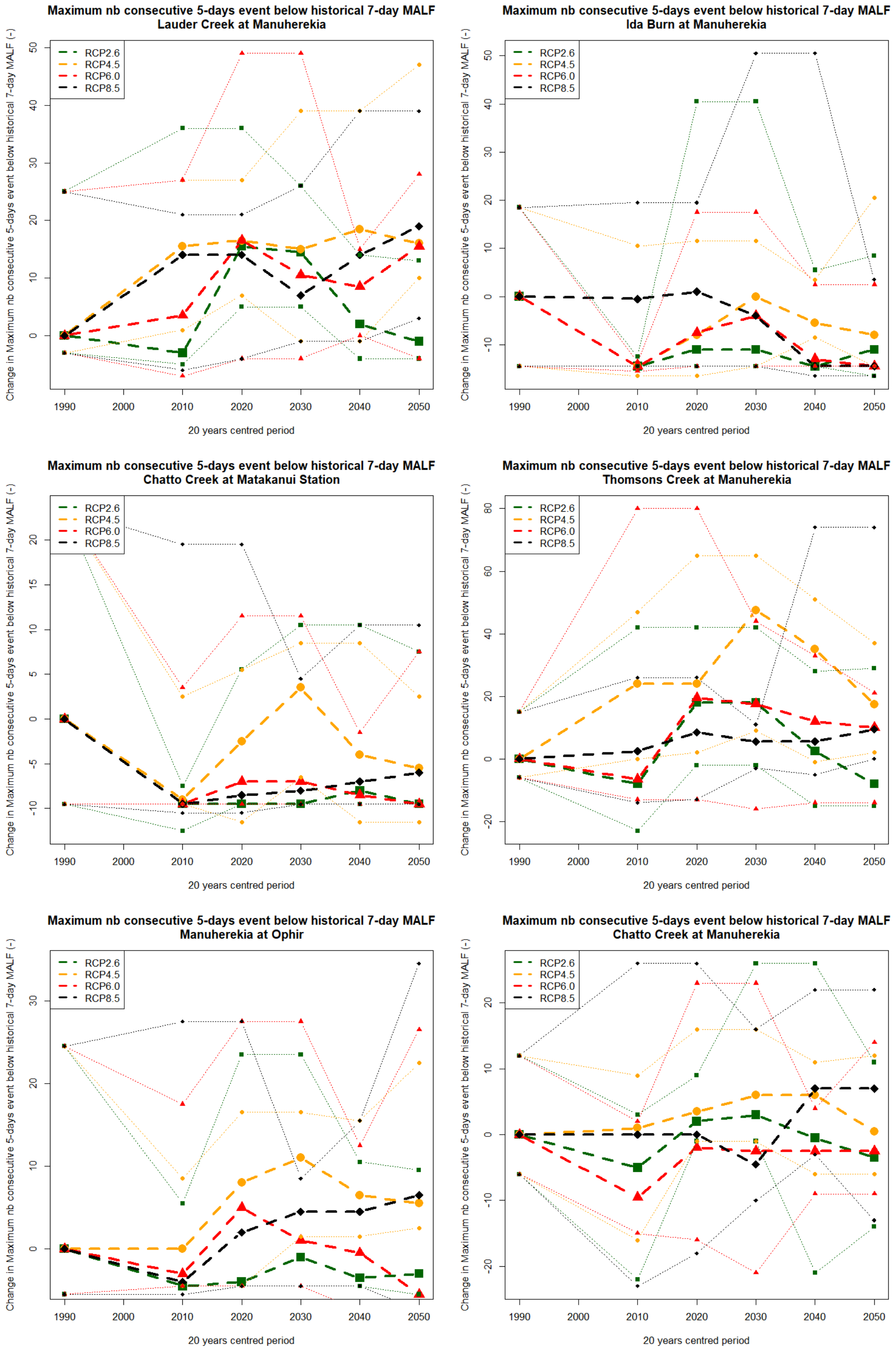

Figure J-2: 20-years centred change in maximum number of consecutive five day events below historical 7-day MALF across RCPs over the period 2006-2060 at four locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

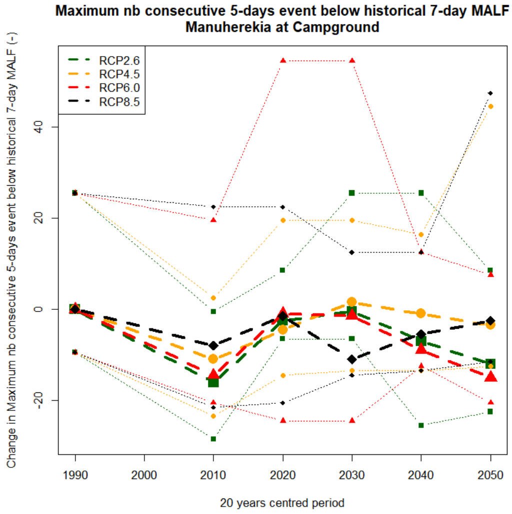

Figure J-3: 20-years centred change in maximum number of consecutive five day events below historical 7-day MALF across RCPs over the period 2006-2060 at Manuherekia at Campground.

Median

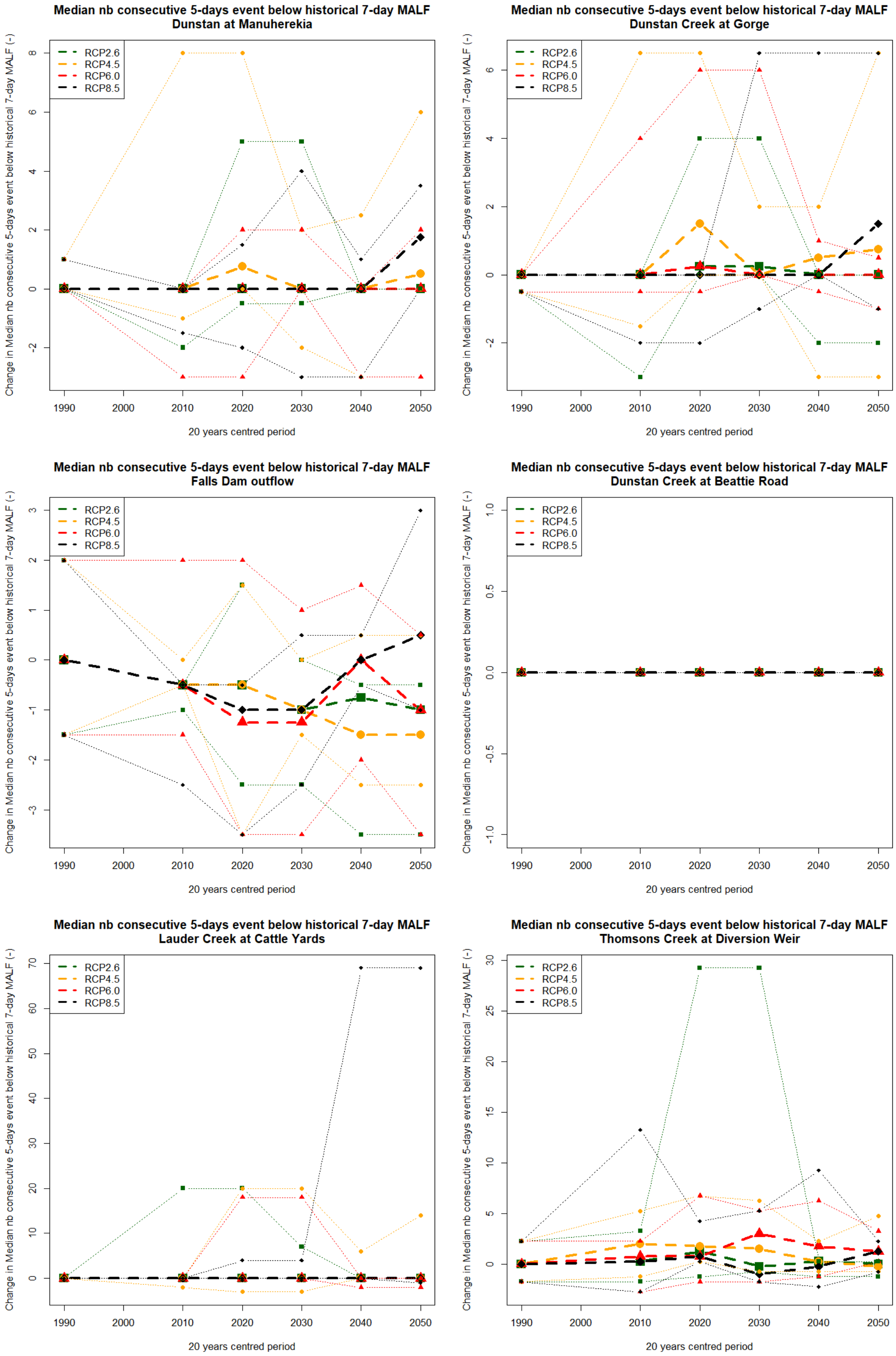

Figure J-4: 20-years centred change in median number of consecutive five day events below historical 7-day MALF across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

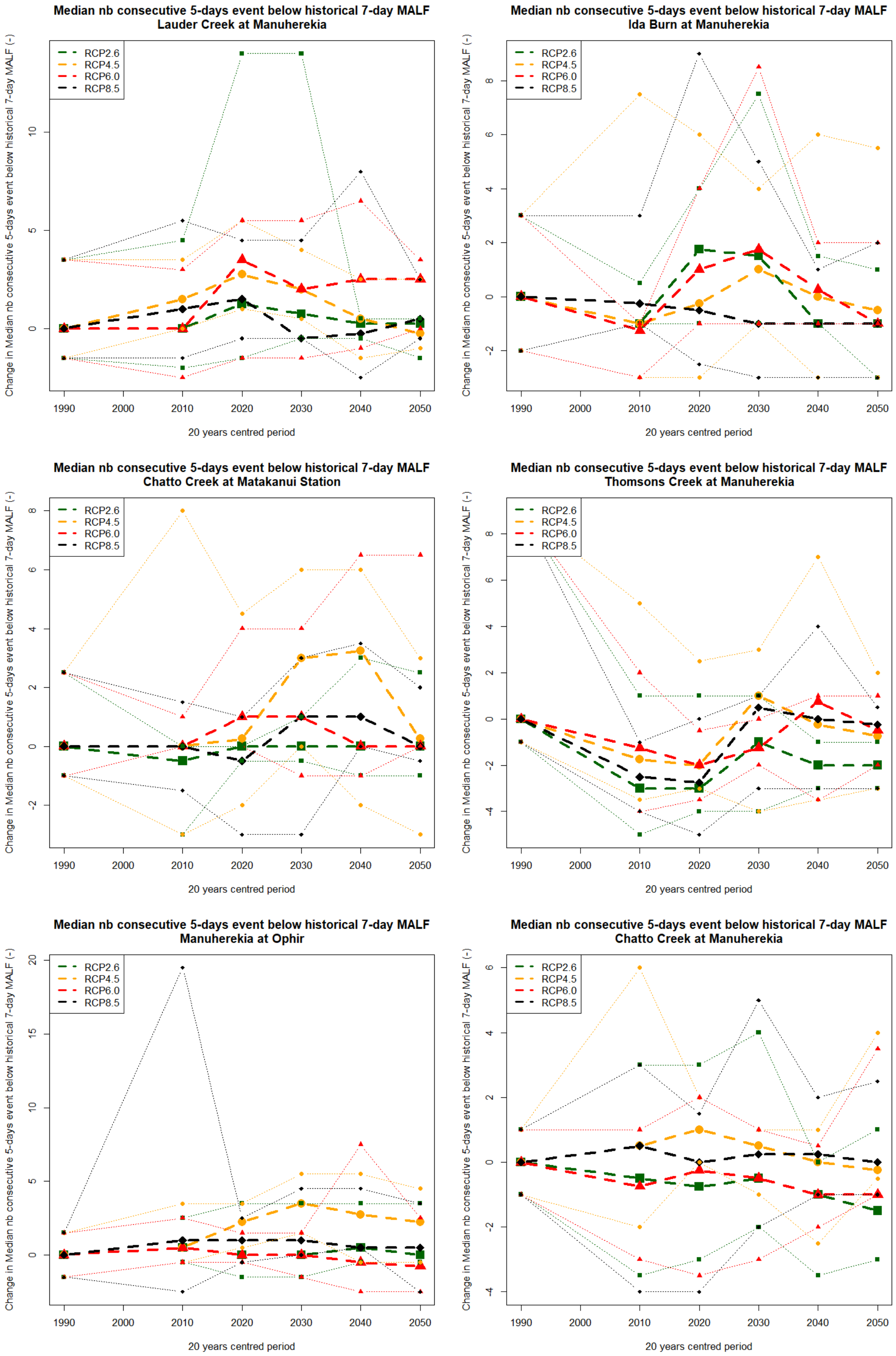

Figure J-5: 20-years centred change in median number of consecutive five day events below historical 7-day MALF across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

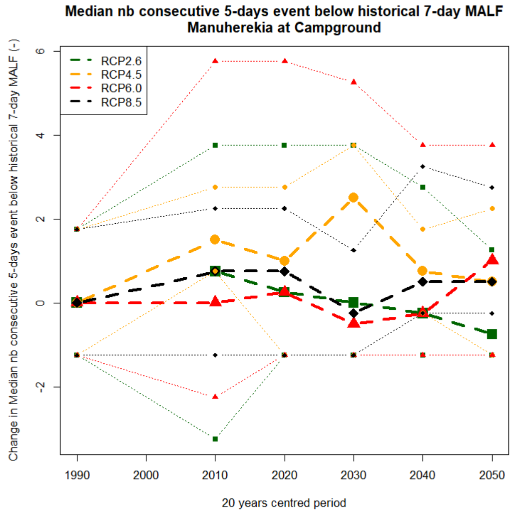

Figure J-6: 20-years centred change median number of consecutive five day events below historical 7-day MALF across RCPs over the period 2006-2060 at Manuherekia at Campground.

Appendix K Changes in frequency of 7-day MALF

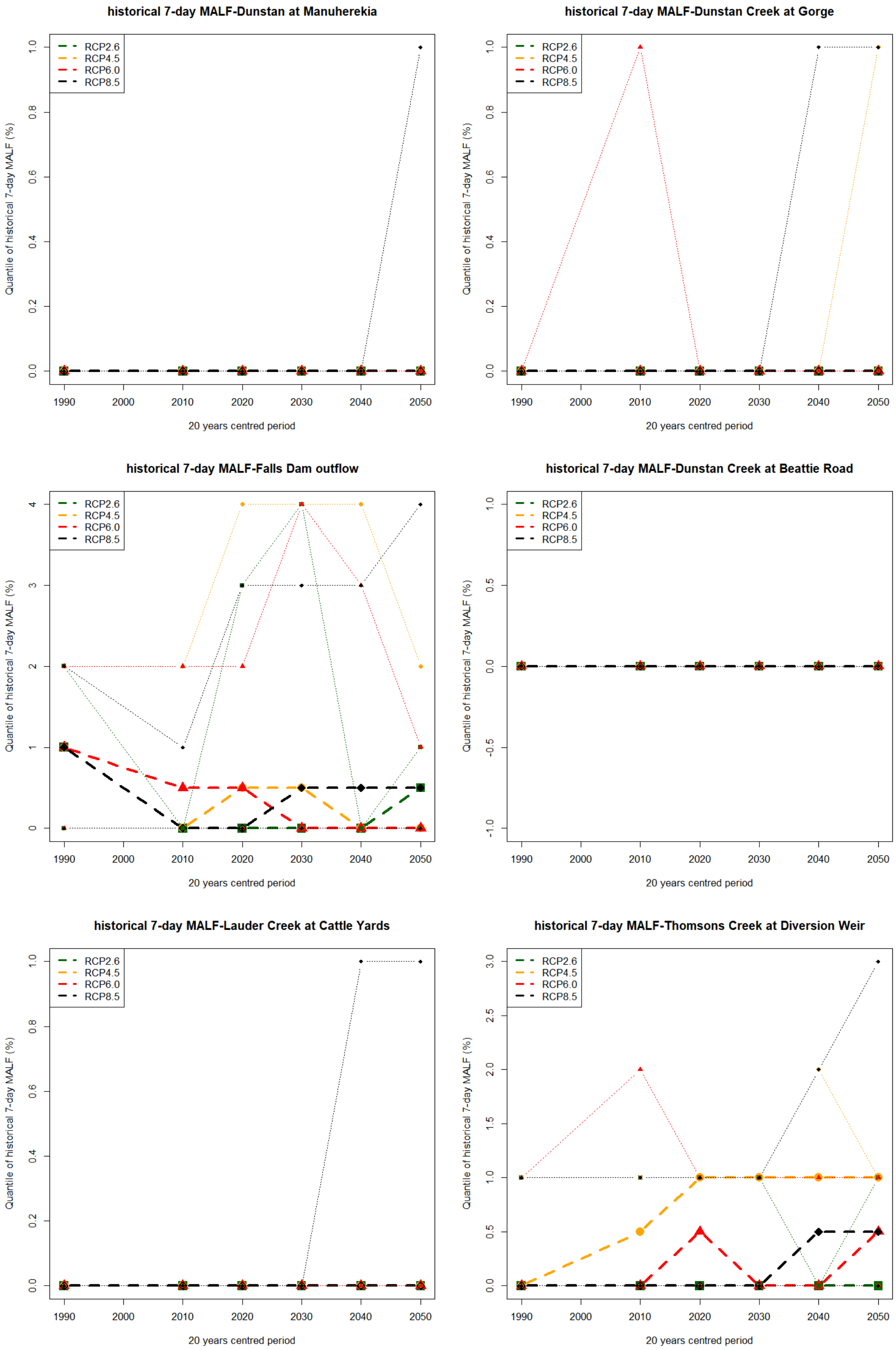

Figure K-1: 20-years centred change in in frequency of historical 7-day MALF across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Dunstan at Manuherekia, the top right plot shows the changes for Dunstan Creek at Gorge, the middle left plot shows the changes for Falls Dam outflow, middle right plot shows the changes for Dunstan Creek at Beattie Road, bottom left plot shows the change for Lauder Creek at Cattle Yards and bottom right shows the changes for Thomsons Creek at Diversion Weir.

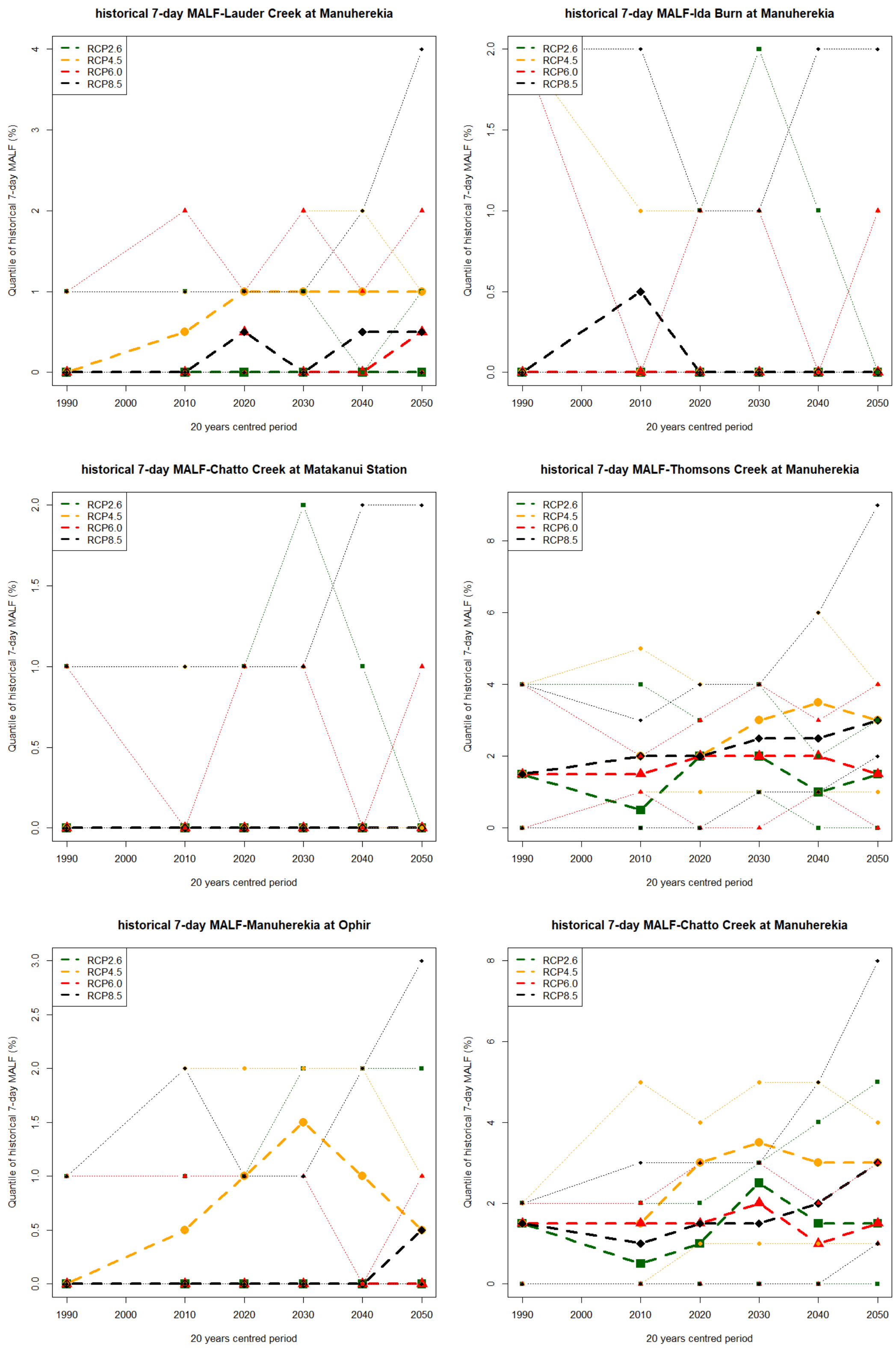

Figure K-2: 20-years centred change in in frequency of historical 7-day MALF across RCPs over the period 2006-2060 at six locations in the Manuherekia catchment. Top left plot shows the changes for Lauder Creek at Manuherekia, the top right plot shows the changes for Ida Burn at Manuherekia, the middle left plot shows the changes for Chatto Creek at Matakanui Station, middle right plot shows the changes for Thomsons Creek at Manuherekia, bottom left plot shows the change for Manuherekia at Ophir and bottom right shows the changes Chatto Creek at Manuherekia.

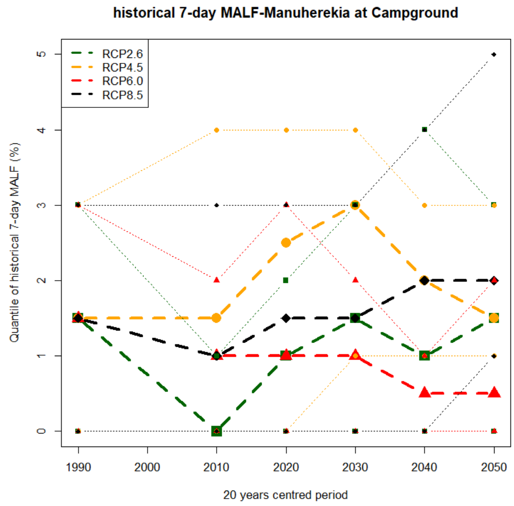

Figure K-3: 20-years centred change in frequency of historical 7-day MALF characteristic across RCPs over the period 2006-2060 at Manuherekia at Campground.