

Projected Changes in New Zealand Drought Risk

An updated assessment using multiple drought indicators

*Prepared for Tonkin and Taylor,
as a contribution to the Deep South National Science Challenge project
“Drinking water, drought and climate change”*

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Figure 6-5: Same as Fig 6-3, but for Pukaki Dam, Canterbury. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black) in the left column in the historic period are compared with the ensemble mean for the four RCPs at 2040s (middle) and 2090s (right). This location experiences a similar but more intense signal of change than at the central Canterbury site (Fig. 6-3), with earlier, longer and more intense drought. 64

Executive summary

It is internationally accepted that human greenhouse gas emissions are the dominant cause of recent global climate change, and that further changes will result from already present and increasing amounts of greenhouse gases in the atmosphere. One of the expected changes for New Zealand is an increase in frequency and severity of droughts, with consequent detrimental impacts on water quality and availability, crop production, wild fire risk and the health of natural systems.

A report on “Drinking water, drought and climate change” was commissioned by the Deep South National Science Challenge, and is being led by the environmental and engineering consultancy Tonkin and Taylor. The material in the present document has been prepared by NIWA under a subcontract to Tonkin and Taylor to address the likelihood of how future New Zealand droughts will change in location and intensity, and provide improved insight into what impacts these changes may have on drinking water supplies.

Previous work has shown that the intensity, duration and frequency of future droughts for New Zealand will largely depend on the future greenhouse gas concentrations increase, with drought characteristics becoming more severe for the higher emission scenarios in most regions.

This report applies a series of indices used to monitor drought in New Zealand to develop an improved method of analysing future drought risk under scenarios of climate change, and thereby supports improved understanding of risks to potable water supplies resulting from climate change.

Some key findings of this report are:

- New Zealand drought is characterised by the “New Zealand Drought Index” (NZDI) and four constituent indices. The leading cause of increase in drought risk is the temperature-driven increase in atmospheric water demand which leads to drier soil conditions, water stress for vegetation and low hydrological flows. Lower emission scenarios will result in lower drought risk increase since temperature increase is considerably lower nationwide.
- Precipitation deficit due to changing precipitation patterns is also a major driver of drought in some regions, but increased drying due to increased temperature alone may be sufficient to trigger droughts even when there is no change in or even an increase in precipitation.
- Whilst in some regions the frequency of “back-to-back” droughts may appear to decrease due to higher winter and spring precipitation due to climate change, the national trend is that they will increase. Even in some regions, such as around Nelson and Tasman, with lower “back-to-back” drought risk conditions, higher risk of deeper drought in the main growing season is likely to have a strong impact.
- The lower drought risk conditions that are mostly prevalent in the winter and early spring season are in contrast to the higher risk of drought later in the main growing season.
- Stream and river flow and drinking water reservoir levels are likely be adversely affected especially in the late spring and summer seasons at all sites used in this study impacted by “very dry” to “drought” conditions.
- Drought risk in most regions, and for almost all sites used in this study, is mostly impacted by increases in summer temperature drying the soils, as evident in significant increase in Soil Moisture Deficit (SMD) and the climate drought index, Clim-NZDI. In the winter season,

some eastern and southern North Island and the two South Island sites are wetter than in the past (1990s) and can avoid “back-to-back” drought risk due to improved winter recharge. The Northland and Gisborne sites, on the other hand, are at higher risk of “back-to-back” drought due to drier winters.

- This report represents a major advance in the diagnosis of future New Zealand droughts. For the first time, the annual cycle of the drought indices is represented at a daily time-step, and the four constituent indices making up the Clim-NZDI allow us to assign causes to the drought changes, in particular whether they are driven by temperature or rainfall changes.

The drought calculations used in this study are derived from simulations by six global climate models, driven by four IPCC Fifth Assessment emission scenarios known as RCPs 2.6, 4.5, 6.0 and 8.5. The global models are dynamically downscaled using a 27-km regional climate model, and subsequently bias-corrected and further downscaled to a 5-km grid covering the whole country.

The drought index used is known as the New Zealand Drought Index (NZDI), which is similar to NIWA’s operational calculations from observed data but applied to the climate model output. However, some technical differences in the calculation that we use here require us to distinguish this new climate drought index which we refer to as “Clim-NZDI”. Clim-NZDI is comprised of four component indices, representing the Standardised Precipitation Index (SPI), the Soil Moisture Deficit (SMD), the Soil Moisture Deficit Anomaly (SMDA), and the Potential Evapotranspiration Deficit (PED).

1 Introduction

Future droughts are likely to be exacerbated through a warming climate and changing rainfall patterns with resulting increased risk of detrimental impacts on water quality and availability, crop production, wild fire risk and the health of natural systems. One of the potential risks is that drinking water supplies may decrease below critical levels for some communities in drought prone regions (Fig. 1-1). This study investigates regional differences to changes in drought vulnerability and characteristics across New Zealand in the latest future climate change projections of the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive of the Intergovernmental Panel on Climate Change (IPCC) - 5th Assessment (AR5) [IPCC, 2013; Stocker et al., 2013].

The higher resolution regional climate model (RCM) simulations for both historic (past) and future period for New Zealand [Ackerley et al., 2010; Sood, 2015], are performed forced by “best performing” lower resolution CMIP5 global climate models (NZ-CMIP5) [Mullan et al., 2013a, 2013b]. The bias corrected and high-resolution NZ-CMIP5 simulations enable determination of finer scale regional climate impact for the New Zealand region, from which we can explicitly compute drought indices. We examine the frequency, intensity, duration and geographic extent of the past and future meteorological droughts in New Zealand’s regional climate model simulations.

For the region as a whole, the future NZ-CMIP5 projections suggest that the area affected by both mild and severe meteorological drought will increase in the existing vulnerable regions in the second half of the 21st century. Extremes of wetness are also projected to increase from around mid-century (2040s) in western and southern South Island, with a *decrease* in drought occurrence and intensity in winter and spring seasons in those locations. Our analyses suggest that continued high emissions of greenhouse gases will increase the likelihood of the dry (and wet) extremes in most parts of the country due to large modifications in the hydrological cycle. These new estimates bring into sharp focus the need to assess the vulnerability and sustainable management of New Zealand’s drinking

water resources. These efforts to improve understanding of drought within this broader framework are required to support planning.



Figure 1-1: The water reservoir at Kiwitahi (left) that supplies water to Morrinsville, Waikato drying up during 2013 drought (NZ Herald, Christine Cornege) and Mangatangi Dam in the Hūnua Ranges that supplies water to Auckland was particularly low in late June 2019 (WATERCARE).

2 Brief review of historic drought analysis and assessments

The earliest study of projected increases in New Zealand drought risk under climate change was carried out by Mullan et al. (2005), based on two global climate models from the IPCC 2001 Third Assessment. The analysis calculated future changes in return period of the current one-in-twenty-year drought defined in terms of Potential Evapotranspiration Deficit (PED). Drought risk was projected to increase during the century in all areas currently already drought-prone, becoming at least twice as frequent by the 2080s under a 'low-medium' scenario, and more than four times as often under a more extreme 'medium-high' scenario. The regions most affected were parts of Northland, Bay of Plenty, Hawkes Bay, Wairarapa, Marlborough, eastern Canterbury and inland Otago.

A subsequent study by Clark et al. (2011) was based on the IPCC Fourth Assessment projections using the three major greenhouse gas emission scenarios B1, A1B and A2, and improved statistical downscaling methods to provide localised climate scenarios for New Zealand. The key finding was that New Zealand should plan for around 10% additional time spent in drought by the middle of the century for key eastern agricultural regions. The findings from earlier studies [Clark et al., 2011; Renwick et al., 2012; Mullan et al., 2018] that the drought risk is expected to increase during the 21st century in the current drought prone regions under 'medium' to 'high' emissions scenarios and not much change is evident in the 'low' emissions case are also generally corroborated in this study using latest "State-of-the-Art" climate data.

The most plausible and consistent outcome based on these Fourth Assessment Report (AR4) climate models and different downscaling methods was a marked increase in drought on the east and north coast of the North and South Island. An equally strong signal was found for no significant change or even decrease in drought exposure on the West Coast of the South Island. Although the projections were not as consistent across the different climate models, strong evidence for increases in time spent in drought were also found around Hawkes Bay-Gisborne and Northland extending to the

Waikato. This overall geographic pattern of change was largely insensitive to climate model but with small differences between the ‘low’ and ‘medium to high’ emissions scenarios. For the remainder of the North Island and Nelson-Marlborough northern east coast on the South Island, the prospect of increased exposure to drought ranged from minimal change through to over a doubling in time spent in drought in these regions depending upon the climate model and scenario considered.

Drought conditions were unusually widespread across New Zealand during the 2012-13 agricultural season, and particularly serious in the North Island. The Ministry for Primary Industries requested an assessment by NIWA of the 2012-13 drought and a comparison against previous droughts as far back as records allowed. PED calculations were applied to long-record station observations, extending as far back as the early 1940s (Figure 2-1), and also to NIWA’s 5-km gridded data known as the Virtual Climate Station Network (VCSN) which begins in 1972. Both analyses showed that the 2012-13 drought was one of the most extreme on record for New Zealand. The VCSN calculations indicated the PED accumulation to May 2013 was the highest in 41 years at 34% of the North Island VCSN grid-points, which was a much larger areal coverage than any other drought in the VCSN period.

The most recent climate change projections for New Zealand [Mullan et al., 2018] provide a comprehensive national overview of changes in many climatic variables through to the end of the century and beyond, based on downscaling the six global models mentioned in Section 3-2. Variables considered are: temperature (maximum, minimum and mean), precipitation, hot days (above 25°C), frost days, dry and wet days, pressure, wind, solar radiation and relative humidity. Drought incidence is addressed through calculations of Potential Evapotranspiration Deficit (PED), which are superseded in this current report.

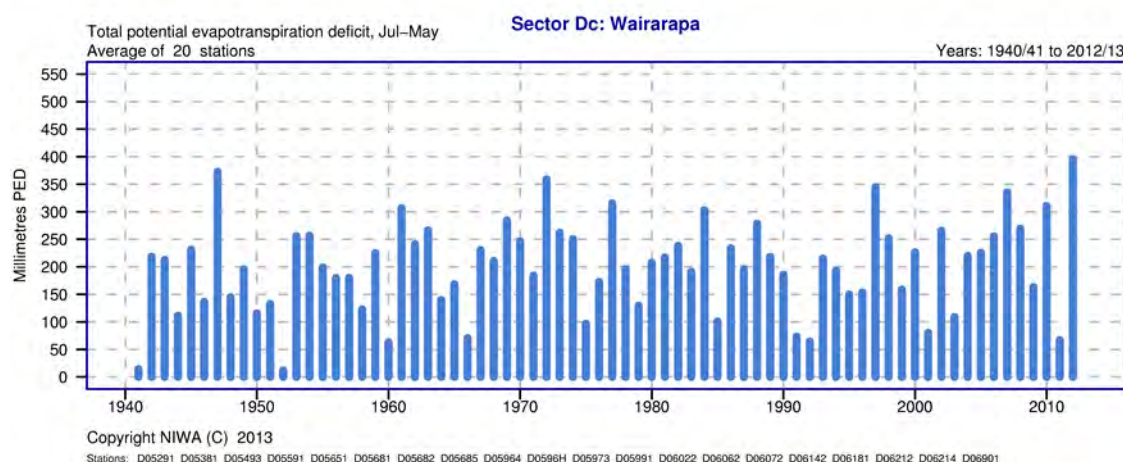


Figure 2-1: Total PED for July-May for years 1941/42 to 2012/13 for an average of 20 stations in the Wairarapa. (Reproduced from section 2.11 of Porteous and Mullan, 2013).

3 Climate Data and Drought Indices

Past and future climate is simulated by global climate models (GCMs), which include atmosphere, ocean, land and sea-ice components, and are driven by natural external climate forcings such as solar irradiance and historic volcanic emissions (no volcanic emissions in future projections), and by anthropogenic forcings which include greenhouse gases and aerosols. Additional information on land-use changes and biogeochemistry are incorporated in the latest version of GCMs, now termed earth system models (ESMs). The greenhouse gases emissions, that are consistent with socio-

economic developments over the 21st century, are used to determine greenhouse gases and aerosol pathways known as Representative Concentration Pathways (RCPs), [van Vuuren et al., 2011].

For the AR5 (IPCC, 2013), the four RCPs developed are described by their approximate total (accumulated) radiative forcing at 2100 relative to preindustrial year 1750: 2.6 W m⁻² for RCP2.6, 4.5 W m⁻² for RCP4.5, 6.0 W m⁻² for RCP6.0, and 8.5 W m⁻² for RCP8.5 (Fig 3-1, left). These RCPs include one mitigation pathway (RCP2.6, which requires removal of some of the CO₂ presently in the atmosphere), two stabilization pathways (RCP4.5 and RCP6.0), and one pathway (essentially “business as usual”) with very high greenhouse gas concentrations by 2100 and beyond. The corresponding mean overall global surface temperature response of the climate system presented in Figure 3-1 (right) for the four RCPs ranges from 0.5 to 5 °C above that of the preindustrial period.

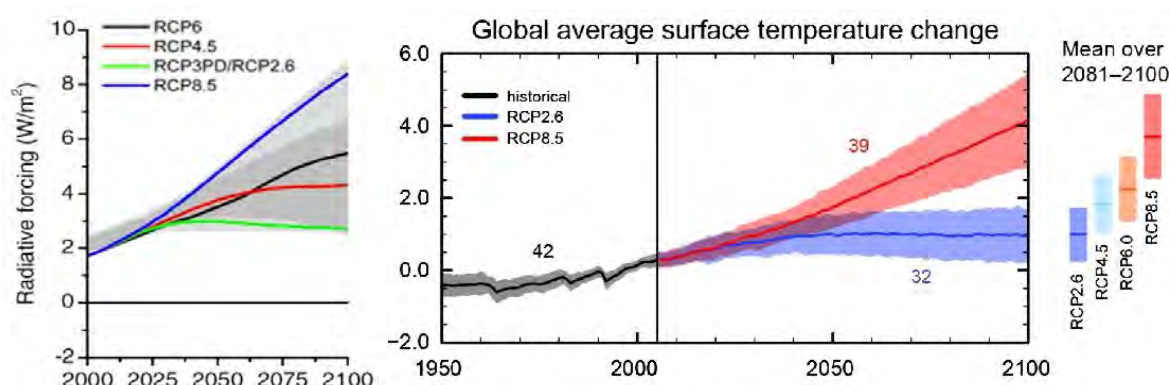


Figure 3-1: Radiative Forcing of the Representative Concentration Pathways (left panel, from IPCC-AR5). The light grey area captures 98% of the range in previous Integrated Assessment Modelling scenarios, and dark grey represents 90% of the range. Simulated time series from 1950 to 2100 for global annual mean surface temperature (right panel, from IPCC-AR5).

The number of global climate model (GCM) simulations available in the data archive for the AR5 varies with the selected RCP. The maximum numbers of GCMs with necessary archived data are: 41 (‘historical period’, 1800s up to 2005), 23 (RCP2.6), 37 (RCP4.5), 18 (RCP6.0), and 41 (RCP8.5). The future simulations begin in 2006 and extend beyond 2100 for some simulations. This current report only considers changes in drought through to 2100.

3.1 Regional Climate data

The global model performance is quantified in terms of a metric that aggregates many different circulation and climatic factors: the position and intensity of the westerly wind maximum and the subtropical high pressure belt; spatial patterns in the key climate variables (e.g., correlation of summer minus winter rainfall, temperature and pressure patterns, observed versus modelled), El Niño-Southern Oscillation teleconnections (correlations of the Southern Oscillation Index versus rainfall, temperature and pressure fields); and annual cycles in key circulation indices such as the Trenberth Z1 and M1 indices [Mullan et al., 2013a,b; Mullan et al., 2018]. There is a general improvement in the CMIP5 models in simulating mean climate and seasonal and interannual variability in the New Zealand-Pacific region relative to the earlier CMIP simulations.

Based on the above analysis and available simulations (all emission scenarios), six coupled global circulation models (GCMs) from different institutions with mostly independent model developments were selected for dynamical downscaling (Table 3-1). The selected models validated well on present climate and were as different as possible in the parent global model in order to span the likely range

of IPCC projections. The bias corrected sea surface temperatures (Figure 3-2) taken from the selected models force the atmospheric component of the GCM (AGCM) [Anagnospoulou et al., 2008] at low resolution (~150 km), which in turn drives a higher resolution (~27 km) regional climate model (RCM) over New Zealand [Ackerley et al., 2012]. The RCM output data are bias-corrected relative to a 1980-1999 climatology, and further downscaled to a 5 km grid [Sood, 2015]. The processed RCM output, NZ-CMIP5, is used to determine the drought indices nation-wide and run NIWA's TopNet hydrological model to simulate river flow for the catchments used in this study.

Table 3-1: Listing of the six CMIP-5 models dynamically downscaled via NIWA's regional climate model (RCM), and the scenarios and periods of the simulations.

CMIP5-Models	Historic	RCP2.6	RCP4.5	RCP6.0	RCP8.5
HadGEM2-ES MOHC (UK)	1971-2005	2006-2120	2006-2120	2006-2099	2006-2120
CESM1-CAM5 NSF-DOE-NCAR (USA)	1971-2005	2006-2120	2006-2120	2006-2120	2006-2100
NorESM1-M NCC (Norway)	1971-2005	2006-2100	2006-2100	2006-2100	2006-2100
GFDL-CM3 NOAA-GFDL (USA)	1971-2005	2006-2100	2006-2120	2006-2100	2006-2100
GISS-E2-R NASA-GISS (USA)	1971-2005	2006-2120	2006-2120	2006-2100	2006-2120
BCC-CSM1.1 BCC (China)	1971-2005	2006-2120	2006-2120	2006-2099	2006-2120

Figure 3-2 shows the bias-adjusted sea surface temperatures used to force the NIWA's AGCM and RCM, presented here only for the mean value over the RCM domain. For the mitigation pathway (RCP2.6), sea temperatures increase to a maximum around mid-century, and thereafter decline slightly. In the other pathways, SSTs continue to increase throughout the period, with a much larger rate of change in the high greenhouse gas pathway (RCP8.5).

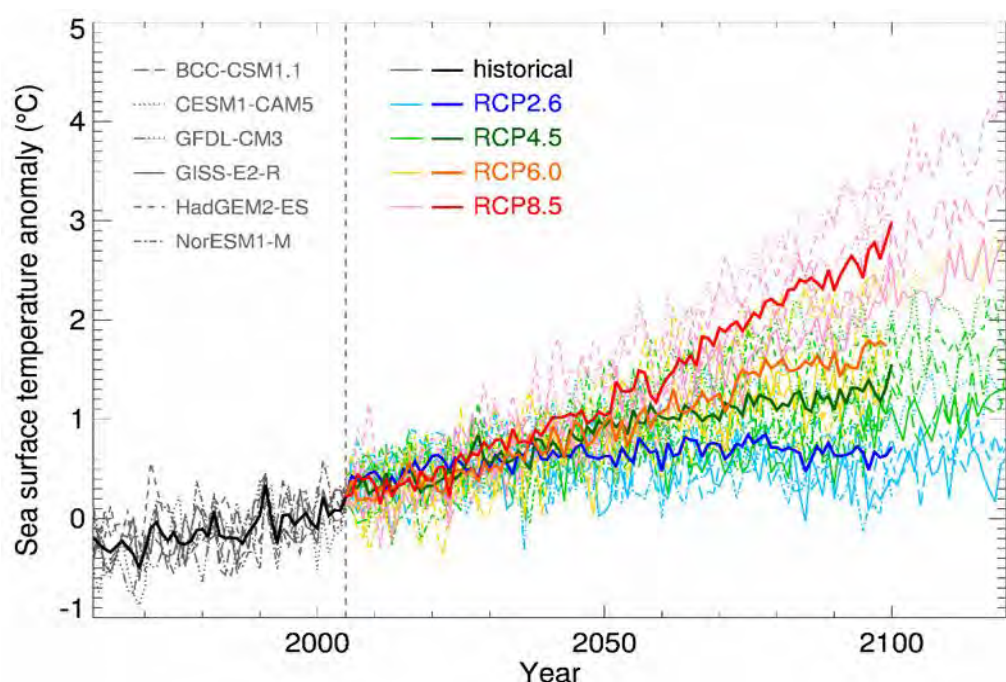


Figure 3-2: Bias-adjusted sea surface temperatures, averaged over the RCM domain, for 6 CMIP5 global climate models, and for the historical simulations (here 1960-2005) and four future simulations (RCPs 2.6, 4.5, 6.0 and 8.5), relative to 1986-2005. Individual models are shown by thin dotted or dashed or solid lines (as described in the inset legend), and the 6-model ensemble-average by thicker solid lines, all of which are coloured according to the RCP pathway.

The “added value” in dynamical downscaling lies in the realistic simulations of a physically consistent set of temporally and spatially highly resolved fields. The interactions of the large-scale circulation with higher resolution orography and other surface features (e.g., land-sea interface, vegetation cover, large lakes etc.) are well captured in Regional Climate Model (RCM) simulations resolving a diverse range of climatic features. Nevertheless, errors inherent in representing local surface conditions, atmospheric processes and external forcing in RCMs lead to considerable systematic biases in simulating regional variables. By removing systematic errors and thus reducing biases, RCM data are more realistic over the historic period [Sood, 2015]. Subsequently, the corrected data are input in downstream environmental models for realistic outputs which are comparable to observations and are necessary to improve the confidence in regional climate impact studies. The iterative dynamical downscaling procedure developed at NIWA is designed to reduce systematic biases over a wide range of spatiotemporal scales.

Since the ‘free-running’ global climate simulations are not constrained by observations for the past period, the model climatological characteristics are compared to observations over a common reference period. Thus, year-to-year variability in a model and observation do not match pointwise. This is why only the climatologies of the observed and simulated data rather than the time series are compared.

In this project, projections for all four RCPs, and for two future time periods which are abbreviated as “2040” and “2090” were used. The two time periods represent changes for the 20-year periods 2031-2050 and 2081-2100, respectively, relative to the baseline 1986-2005. This is the same baseline as used in the IPCC AR5 Report (IPCC, 2013), and NIWA’s recent projections [Mullan et al., 2018], and the last 20 years of what CMIP5 refer to as the “historical” or the “past” period.

3.2 Calculation of daily New Zealand Drought Index (NZDI)

The New Zealand Drought Index (NZDI) is a combination of four constituent drought indices (DIs), which are defined in Section 3.2.1 such that positive values indicate dry conditions. Since the individual indices can have different ranges and units and are not directly comparable, they are normalized and transformed using a logarithmic function to synchronise characteristics for coinciding values before merging.

The NZDI is used for current national drought monitoring applications [Mol et al., 2017]. The operational New Zealand Drought Monitor produces updated maps daily and time series products are available online at NIWA web site (<https://niwa.co.nz/climate/information-and-resources/drought-monitor>). The NZDI products were previously reviewed by stakeholders from the meteorological, agricultural and government sectors to provide a decision support service that can be applied to many uses, as needed and determined by the users.

The operational NZDI and the constituent drought indicators (DIs) calculate: (Standardised Precipitation Index (SPI), Soil Moisture Deficit (SMD) and its anomaly (SMDA), and Potential Evapotranspiration Deficit (PED)), which we have further developed and modified for climate application and refer to as Clim-NZDI. The Clim-NZDI and adjusted DI's are determined using bias corrected regional climate model (NZ-CMIP5) projections downscaled on 5-km horizontal grid [Sood, 2015] based on 6 selected CMIP5 (Table 3-1) models [Mullan et al., 2013a].

3.2.1 Drought Indicators Definitions

Drought is a period of very dry weather conditions with significantly reduced surface water causing severe hydrologic imbalances. The primary cause of drought occurrence is inadequate precipitation to sustain environmental water demands. The first DI we use is the unitless localized **Standardized Precipitation Index (SPI)** based only on precipitation, which is a widely used drought indicator [McKee et al., 1993]. It is a normalized index defined locally as the total precipitation over a suitable accumulation period relative to its long-term (20-year) average for the same period. This enables direct comparison between precipitation variation between locations with different precipitation regimes. The SPI is especially relevant for spatially diverse New Zealand precipitation with large orographic imprint. The selection of a 60-day accumulation period is based on the observation that a period of around two months with well-below normal rainfall is usually sufficient to trigger drought-like conditions in New Zealand [Mol et al., 2017]. A gamma distribution is fitted to the historical precipitation data and transformed into a normal distribution. The SPI value is then defined as the z-score on that distribution. Positive (negative) SPI values represent less (greater) than median precipitation, and application-specific SPI thresholds can be defined to characterise the onset and end of drought conditions [Guttman, 1998]. The more positive the SPI, the drier the conditions.

A precipitation-based index is inadequate to completely characterize droughts since they are complex phenomena exacerbated by the reduction of soil moisture due to the lack of rainfall or increased evapotranspiration or both combined. Surface evapotranspiration is the process where water from the surface transfers to the atmosphere through soil surface evaporation and evapotranspiration from plants (includes water transported by plants from deeper soil layers). The next two DIs characterise soil moisture deficit (SMD) and SMD anomaly (SMDA).

As the temperature increases (for an annual cycle which starts in July and ends in June) and the austral seasons advance from winter to spring and summer, the amount of water removed from soil through evapotranspiration begins to exceed recharge through rainfall, leading to a decrease in soil

moisture content (SM). The soil moisture content is determined by the soil water budget shown in equation (1). It is the incremented daily with the difference between rainfall and actual evapotranspiration (AET) below the soil water carrying capacity threshold termed available water capacity (AWC). The soil type and characteristics determine AWC, where an AWC of 150mm is typical for New Zealand's silt-loam soils [Porteous et al., 1994] and used to define a simple single layer soil model. The excess of surface water budget above the AWC threshold is inferred as the surface runoff.

$$SM(day) = SM(day - 1) + Precipitation(day) - AET(day), \text{ if } SM(day) \leq AWC \quad (1)$$

$$\begin{aligned} Runoff(day) &= SM(day) - AWC, \\ &\text{and} \quad \text{if } SM(day) > AWC \\ SM(day) &= AWC \end{aligned} \quad (2)$$

The **Soil Moisture Deficit** (SMD) is the amount of water in the soil (SM) short of field capacity (AWC).

$$SMD(day) = AWC - SM(day) \quad (3)$$

The **SMD anomaly** (SMDA) is calculated locally at each land grid point with respect to a 20-year (1986-2005) SMD reference period. As an example, if the SMD is higher than 110 mm, and the anomaly is more than 20 mm drier than normal, then soils are often referred to as 'severely drier than normal' and drought conditions (if not present already) may be imminent.

As soil moisture decreases, the plant production becomes moisture-constrained and actual evapotranspiration (AET) can no longer meet atmospheric demand. This demand, termed potential evapotranspiration (PET), is the amount of water that will evaporate and transpire given unconstrained water availability [Lu et al., 2005]. PET is calculated using the FAO-56 Penman-Monteith method [Allen et al., 1998, Prudhomme et al., 2012] for an idealized grass reference crop of 0.12 m height and an albedo of 0.23 [Allen et al., 1998]. Based on the single layer water balance model of Porteous et al. (1994), if half or more of the total soil moisture capacity (HAWC=AWC/2) is available, PET and AET are set equal. If less than half of the total soil moisture capacity is available, AET reduces linearly proportional to PET.

$$\begin{aligned} AET &= PET \left(1 - \frac{SMD - HAWC}{HAWC} \right), \text{ if } HAWC < SMD < 150 \quad \text{and} \\ AET &= PET, \text{ if } SMD \leq HAWC \end{aligned} \quad (4)$$

The difference between the potential (PET) and the actual evapotranspiration (AET) is defined as the '**Potential Evapotranspiration Deficit**' (PED) (e.g., Mullan et al. 2005), the fourth and last DI. Since AET is always equal to or less than PET, PED remains positive or zero. Days with positive PED when the water demand is not met, and pasture growth is reduced, are referred to as days of potential evapotranspiration deficit. PED is designed to provide a measure of drought intensity and duration taking environmental demand into account. In practice, PED represents the total amount of water required by irrigation, or that needs to be replenished by precipitation, to maintain plants growing at optimum levels. Thus, higher PED totals indicate drier soils. An increase in PED of 30 mm or more corresponds to about an extra week of reduced grass growth.

3.2.2 The Climate-NZDI

The present implementation of NZDI [Mol et al., 2017] used for operational monitoring applications requires appropriate modifications for climate applications. A fixed past time slice is used to define a reference period, unlike the daily shifting reference period used operationally. The arbitrary smoothing and weighting factors are avoided in computing the **Climate-NZDI** (Clim-NZDI) and averaging or reference periods among the constituent DIs are aligned. The Clim-NZDI is defined as the average of the positive part of four DIs with reference to the accumulation period “p”, where p is set to 60 days for daily SPI and PED indices in this study. Accumulation for SMD and SMDA indices is not required since they are defined incrementally which includes historic imprint.

The SPI (SPI60) is based on normalized and standardized (z-scores) precipitation which is rescaled using logarithmic transformation to a range from -3 to 3. The range of 0.75 – 1 indicate drier than normal, 1-1.25 very dry, 1.25-1.5 extremely dry, 1.5-1.75 drought and above 1.75 severe drought conditions. The other three indices are normalized and logarithmically transformed and rescaled to match the SPI range (equation 5).

$$\begin{aligned}
 indDI &= -\log_2 \left(1 - \frac{DI}{DI_{max}} \right) \\
 DI_{max} &= AWC \quad \text{if } DI = SMD \\
 DI_{max} &= \max_{day}(SMDA(day)) \quad \text{if } DI = SMDA \\
 DI_{max} &= \max_{day}(PED60(day)) \quad \text{if } DI = PED60
 \end{aligned}
 \tag{5}$$

where

In Fig 3-3, we see the dry part of the distribution of constituent DI's and the merged Clim-NZDI is based on all drought drivers: precipitation, temperature, soil and vegetation. The grey lines are the ensemble-average over six models (coloured lines) for the four DI's, and the black line indicates the corresponding ensemble-average of the Clim-NZDI.

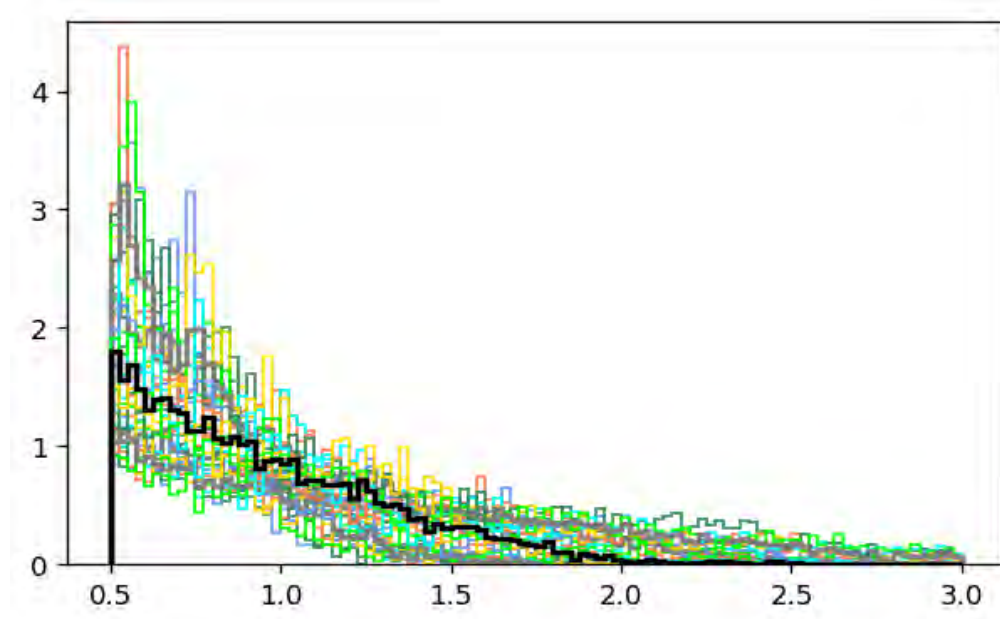


Figure 3-3: The tail of distribution of individual DIs for the 6 CMIP5 model projections (coloured), their ensemble mean (grey) and the merged index, NZDI (black) for the historic reference period at one site.

4 Regional Impact

Here we present the simulated drought conditions for the past reference and future periods with expected changes in frequency and intensity of droughts, especially in the drought prone regions. The spatial patterns provide a general picture of likely changes at the national level (Sections 4.1 and 5). The changes in disparate drought characteristics are illustrated in more detail for two selected sites at Wairoro Stream, Northland (Sections 4.1.1) and central Canterbury (Section 4.1.2) from the case studies. The relative influence of rainfall deficit (SPI60) versus soil moisture deficit (SMD) on droughts varies by their location. For the two example sites presented here, the SPI60 changes dominate for the Northland site, whereas the SMD changes dominate for Central Canterbury site.

The drought indices vary considerably regionally, but a general finding is for droughts to intensify progressively in the future, as indicated by higher Clim-NZDI. Under higher emission scenarios, droughts occur earlier in the July-June water year, which we refer to here as the annual cycle. In some regions, the drought conditions do not improve much during the typically wet winter season, which can lead to an increased likelihood of multi-region and multi-year ‘back-to-back’ droughts towards the end of the 21st century (Section 4.2).

4.1 Time Evolution and Spatial Variability of 21st Century Droughts

The spatial patterns of future droughts over New Zealand are generally similar to those in the historic period but they are likely to intensify over the 21st century in most regions. The changes increase with higher emissions with the largest changes observed in the RCP8.5 scenario. The changes in the underlying drivers of drought significantly alter the seasonal patterns. This is illustrated in Fig. 4-1 (left columns), showing intensification of mean summer drought conditions (top row) over all of New Zealand other than a few isolated coastal regions of the South Island as distinguished by the Clim-NZDI. An increase of 0.5 in the climate change signal in Fig. 4-1 corresponds to a change in drought classification by two levels, for example from “very dry (larger than 1)” to onset of “drought (larger than 1.5)”, depending on the baseline dryness. The changes in the drought patterns is already evident in the mid-century (top, first column), which further intensifies towards the end of the century (2090s; top second column). The preceding spring season (bottom, first column), on the other hand, shows a decrease in drought conditions over parts of Waikato and Manawatu region of the North Island and most of the South Island other than the Nelson-Marlborough region and inland central South Island in the mid-century. This spatial pattern again further intensifies at the 2090s period with enhanced drying mostly in the north and east of the North Island but is weaker than in the summer season.

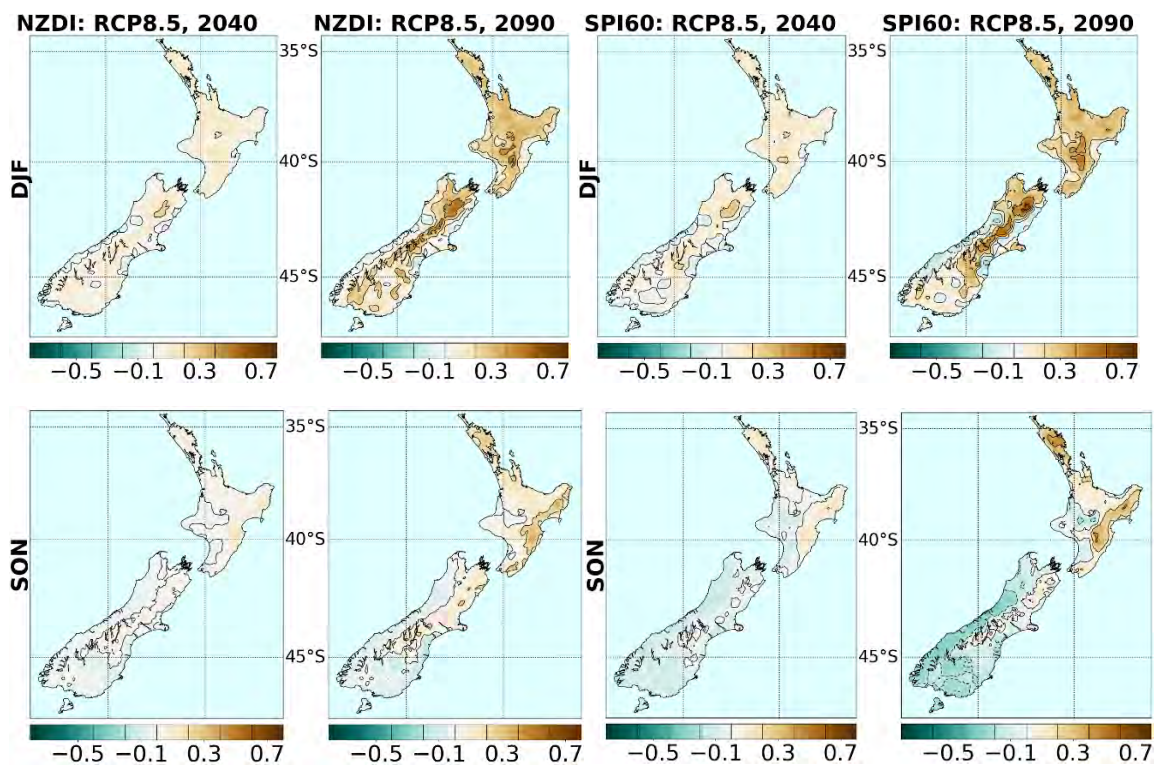


Figure 4-1: The climate change signal for Clim-NZDI (first and second columns) and the SPI60 (third and fourth columns) of the model ensemble mean for RCP8.5 emission scenario for the 2040s (first and third columns) and 2090s (second and fourth columns) time slices based on NZ-CMIP5 climate project data. The brown shades indicate increased drier conditions with respect to 1990s reference past period.

These changes in Clim-NZDI are directly driven by the changes in the precipitation patterns as indicated by SPI60 (right columns). Other than some isolated pockets in the north-east and central South Island, all regions in New Zealand experience drying in the summer season, due to decrease in rainfall which becomes more evident in the 2090's. Thus, the SPI60 is the main indicator of summer droughts. The increase in PET further intensifies the drought contributing to increasing Clim-NZDI. Even in the spring season, the increase in precipitation is partially unable to counteract the increase in water demand (PET) due to increasing temperature. As a result, the spring drought risk does not decrease, but may even increase in wetter regions (bottom panels).

The above example is to elucidate the changes in the drought patterns and their relationship with the underlying drivers. Refer to Section 5 for a complete description of all drought indices and emission scenarios.

The explicit changes in drought intensity (Clim-NZDI) and their underlying drivers (DIs) at two study locations, Wairoro Stream near Kaikohe in the Far North (Northland) and in central Canterbury (South Island), are presented below in more detail.

4.1.1 Wairoro Stream, Northland

The Wairoro Stream site (35.458 S, 173.827 E) lies in the midst of a drought prone region of the Far North District. The reference past-, mid- and late-21st century time slices of Clim-NZDI derived using all models are presented for the high-end RCP8.5 emission scenario. In Fig. 4-2 the droughts become progressively more intense over the 21st century, with nearly all models (coloured lines) exceeding the threshold for dry conditions (0.75) every year in the 2090s period, and the drought threshold

(1.50) is crossed more frequently and by more models than in the past or the 2040s period (top and middle panels). This implies that the droughts are more likely and more frequent with all ensemble members showing a generally increasing drought likelihood as the century progresses.

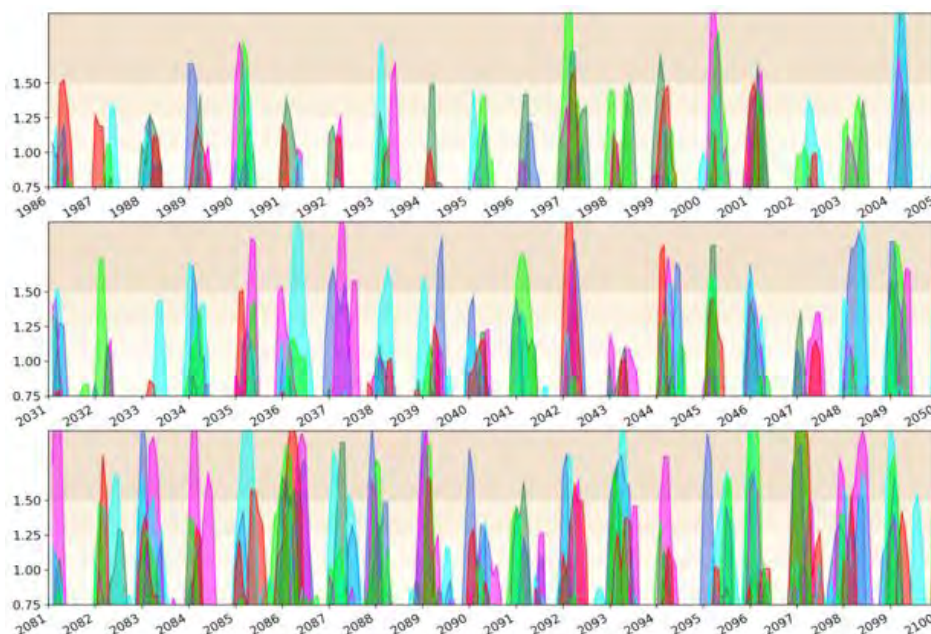


Figure 4-2: The 1990s (past, top) and the two future (2040s, middle; 2090s, bottom) time series of Clim-NZDI for all NZ-CMIP5 ensemble members for the RCP8.5 emission scenario. The 1.50 threshold represents drought conditions. Different colours refer to the six global models.

Fig. 4-3 separates out the SPI60 from the Clim-NZDI to emphasise the impact from precipitation changes alone. The larger values of SPI60 in the 2040s and 2090s are indicative of much drier conditions resulting from a decrease in precipitation due to changing seasonal precipitation patterns later in the century. The conditions become progressively drier over the century with nearly all models (coloured lines), indicating anomalously dry conditions in the 2090s with brief respites mainly in the winter season. Thus, drought risk is high in future periods even without an increase in PET and related SMD.

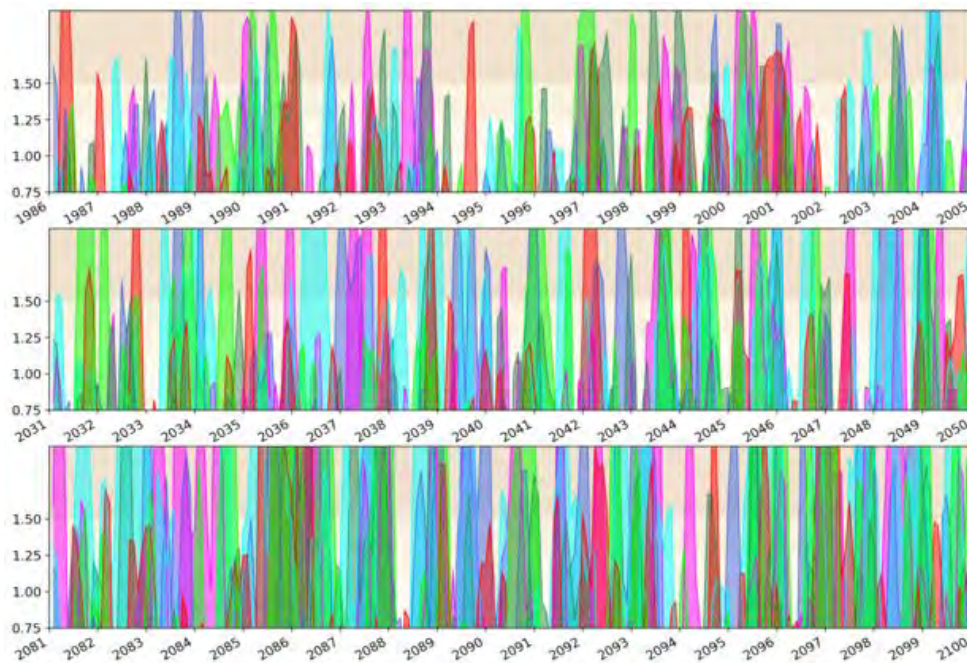


Figure 4-3: The 1990s (past, top) and the two future (2040s, middle; 2090s, bottom) time series of SPI60 for all NZ-CMIP5 ensemble members for the RCP8.5 emission scenario.

The drier soil conditions seen in Fig. 4-4 (SMD) and Fig. 4-5 (SMDA) result from a combined effect of lack of precipitation and increased PET. The conditions become progressively drier over the century with nearly all models (coloured lines) indicating anomalously dry conditions (above 0.75) every year in the 2090s period, and the drought threshold (1.50) is crossed more frequently. Even though dry soil conditions are more or less an annual feature in the past 1990s period (top panel), in the future periods the soil conditions are even drier with larger recharge required to break the drought.

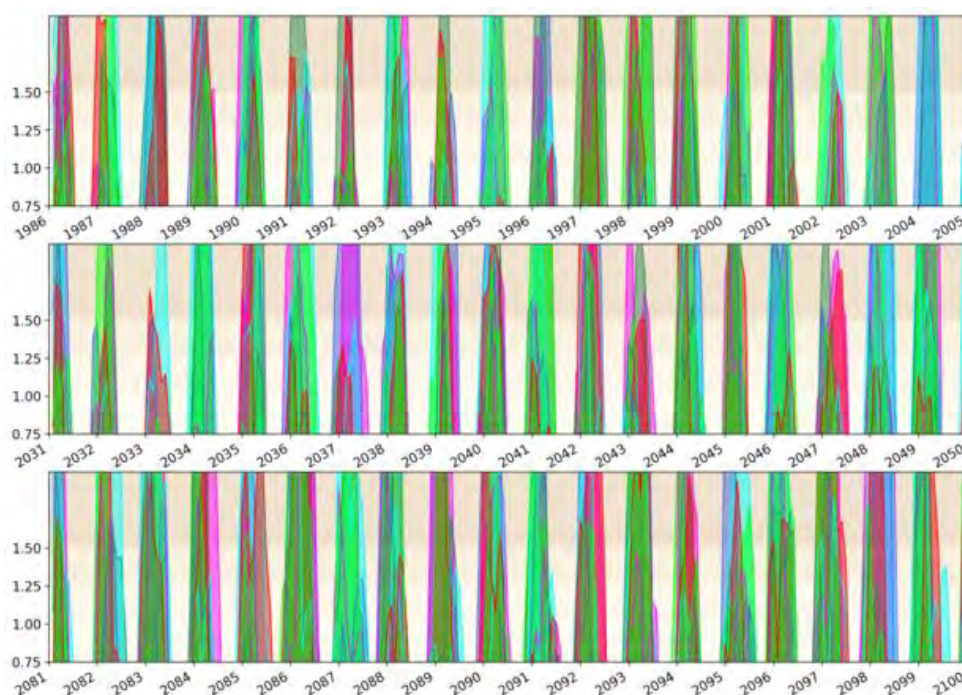


Figure 4-4: The 1990s (past, top) and the two future (2040s, middle; 2090s, bottom) time series of SMD for all NZ-CMIP5 ensemble members for the RCP8.5 emission scenario.

The large SMDA values in the future period (Fig. 4-5, middle and lower panel) indicate that the drier soil conditions were much less likely at this location in the 1990s and point to regional change with considerable impact for the stakeholders in the primary sector. Again, these changes are much smaller for low emission scenario (RCP2.6) than in higher emission projections.

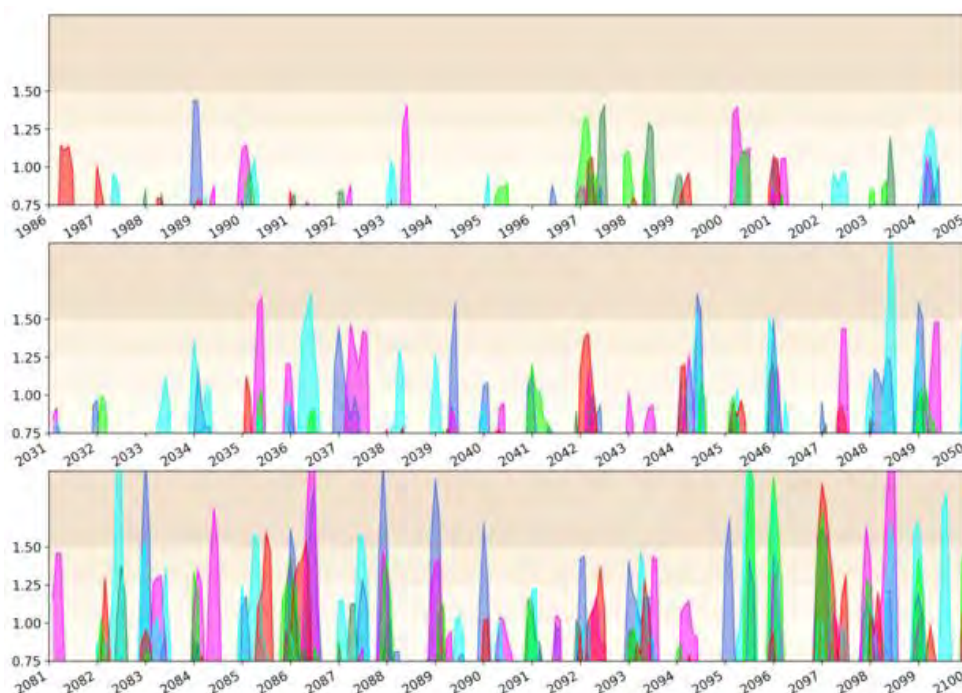


Figure 4-5: The 1990s (past, top) and the two future (2040s, middle; 2090s, bottom) time series of SMDA for all NZ-CMIP5 ensemble members for the RCP8.5 emission scenario

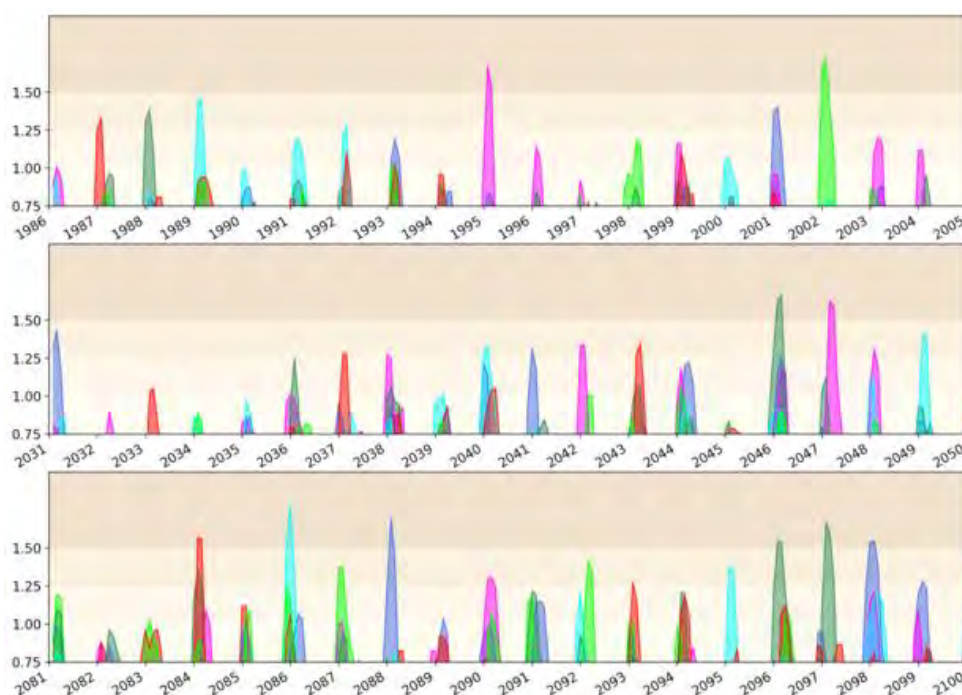


Figure 4-6: The 1990s (past, top) and the two future (2040s, middle; 2090s, bottom) time series of PED60 for all NZ-CMIP5 ensemble members for the RCP8.5 emission scenario.

The larger values PED60 in the future period (Fig. 4-6) are indicative much drier soil conditions not meeting “crop” water demand resulting from a combined effect of lack of precipitation and increased PET. The conditions become progressively drier over the century with most models (coloured lines) crossing dry and drought conditions threshold. Since SPI60, PED60 and SMDA are defined with respect to local conditions, they describe changes in local drought conditions. Note that the changes in drought conditions in already dry drought-prone regions can be small in some seasons since they cannot dry much further when soil moisture levels are already severely depleted.

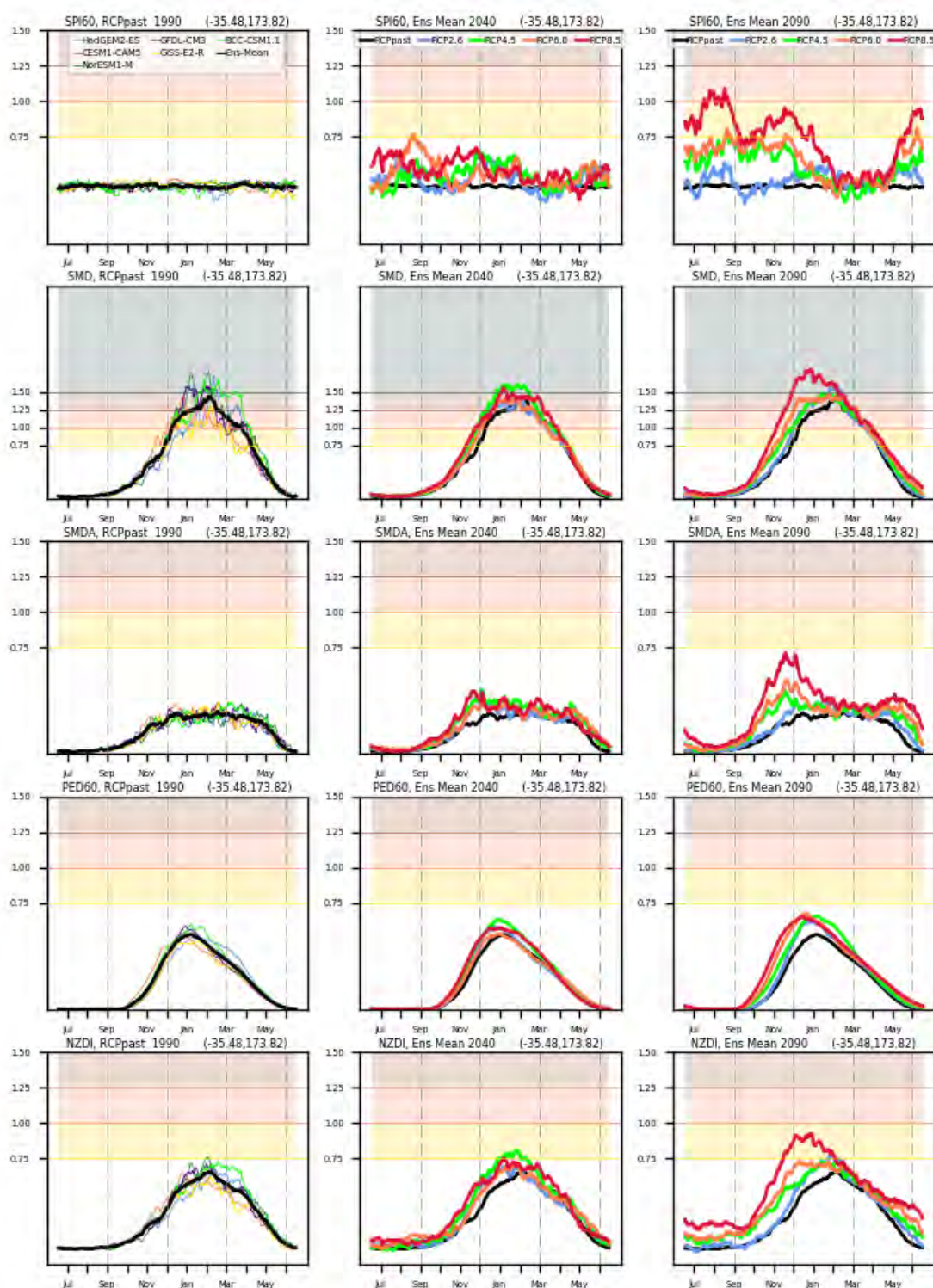


Figure 4-7: The mean annual cycle (July-June) with the drought classification (background colours) is presented above for Far North Northland location. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black, thick) in the left column in the historic period are compared with the ensemble mean for the four RCP's at 2040s (middle column) and 2090s (right column). The drought behaviour at the three sites (Punakitere River, Wairoro stream and Lake Omapere) is very similar since they lie in close proximity to each other.

Fig. 4-7 highlights the changes in the annual cycle of the Clim-NZDI and its constituent indices. The large increase earlier in the season in the 2090s relative to the historic period (Fig 4-7, left column, black) indicates higher risk of earlier drought and the larger values at the beginning and end of the annual cycle indicate higher risk of "back-to-back" droughts. The strongest signal is mostly due to a large increase in surface temperature increasing evapotranspiration, for the high emission scenario (RCP8.5, red), whereas the optimistic low emission scenario (RCP2.6, blue) indicates small increases in drought likelihood (bottom left) in the summer season.

4.1.2 Central Canterbury

The central South Island site (43.875 S and 170.875.) lies east of a drought-prone region of the Canterbury plains in the eastern foothills with a cooler, wetter and windier climate. The reference past and mid- and late 21st century time slices of Clim-NZDI and all models are presented for the high-end RCP8.5 emission scenario similar to the above example for Wairoro Stream. In Fig. 4-8 we show that the droughts again become progressively more intense over the 21st century, with nearly all models (coloured lines) exceeding the threshold for dry conditions (0.75) every year in the 2090s period, and the drought threshold (1.50) is crossed more frequently and by more models than in the past or the 2040s period (top and middle panels). This implies that the droughts are more likely and more frequent with all ensemble members showing increasing drought likelihood. However, in the winter and spring seasons the values rarely exceed this threshold indicating low risk of "back-to-back" droughts at this site.

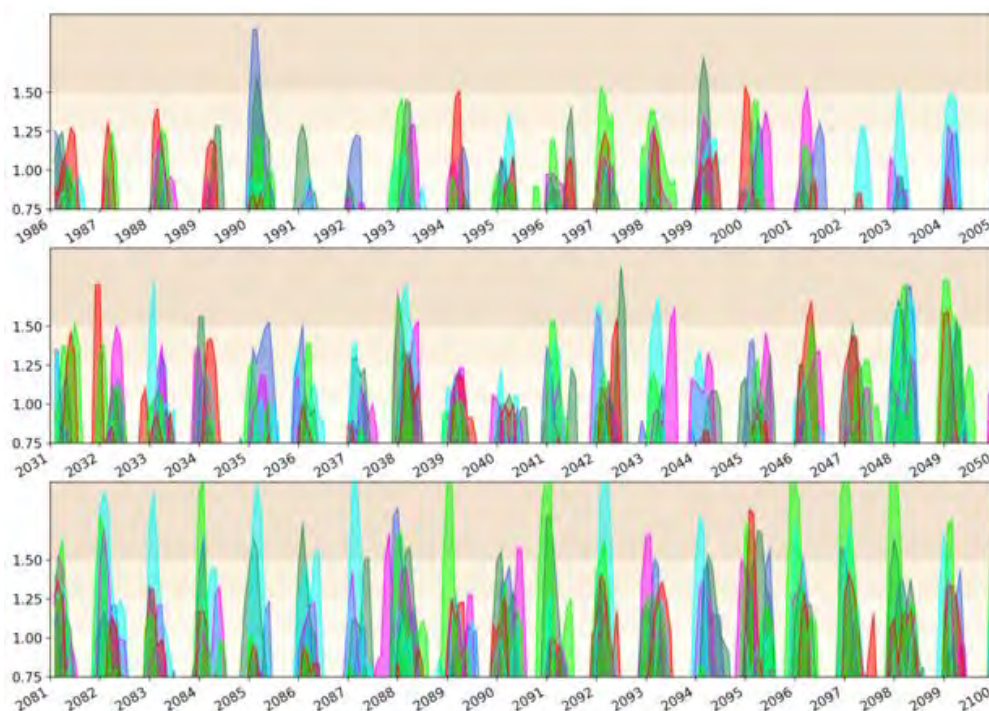


Figure 4-8: The 1990s (past, top) and the two future (2040s, middle; 2090s, bottom) time series of Clim-NZDI for all NZ-CMIP5 ensemble members for the RCP8.5 emission scenario. The 1.50 threshold represents drought conditions.

The SPI60 has lower values in some seasons (Fig 4-9, lower two panels), which are indicative of wetter conditions resulting from an increase in winter precipitation due to changing seasonal precipitation patterns. The winter conditions are progressively wetter over the century with most

models (coloured lines). This implies that the drought risk for “back-to-back” droughts is lower in future at this Canterbury site, decreasing towards the end of the 21st century (2090s).

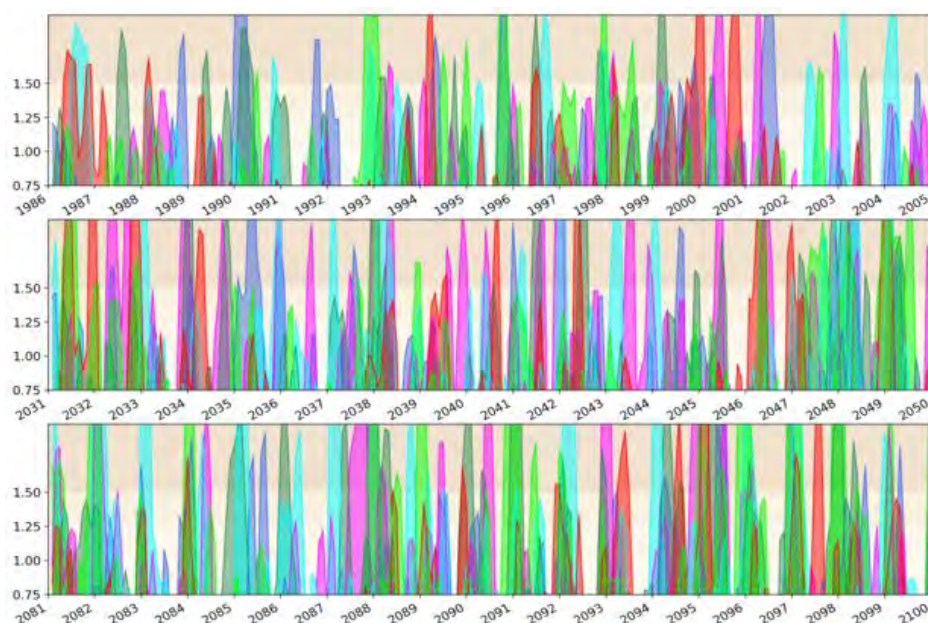


Figure 4-9: The 1990s (past, top) and the two future (2040s, middle; 2090s, bottom) time series of SPI60 for all NZ-CMIP5 ensemble members for the RCP8.5 emission scenario.

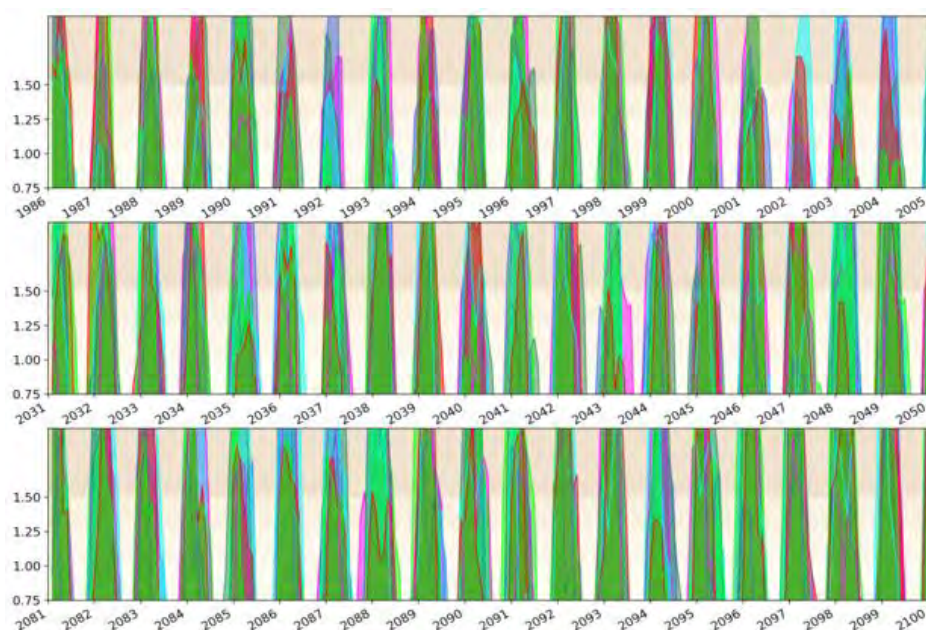


Figure 4-10: The 1990s (past, top) and the two future (2040s, middle; 2090s, bottom) time series of SMD for all NZ-CMIP5 ensemble members for the RCP8.5 emission scenario.

The drier soil conditions seen in Fig. 4-10 result from the combined effect of lack of precipitation and increased PET. The conditions become progressively drier over the century with nearly all models (coloured lines) in all seasons other than in winter indicating anomalously dry conditions (above 0.75) every year in the 2090s period, and the drought threshold (1.50) is crossed more frequently and for longer duration. Even though dry soil conditions are more or less an annual feature in the past 1990s

period (top panel), in the future periods the soil conditions are even drier with larger recharge required to break the drought. In contrast, the increased winter precipitation improves the potential to recharge soil moisture, with a resulting lower likelihood of winter drought.

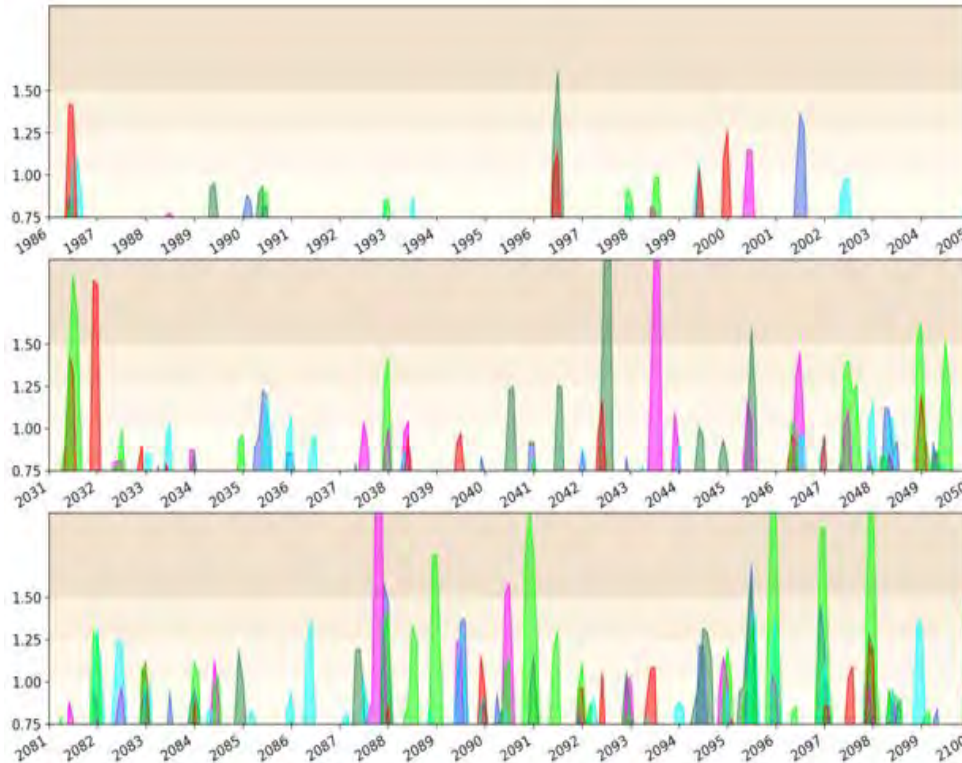


Figure 4-11: The 1990s (past, top) and the two future (2040s, middle; 2090s, bottom) time series of SMDA for all NZ-CMIP5 ensemble members for the RCP8.5 emission scenario.

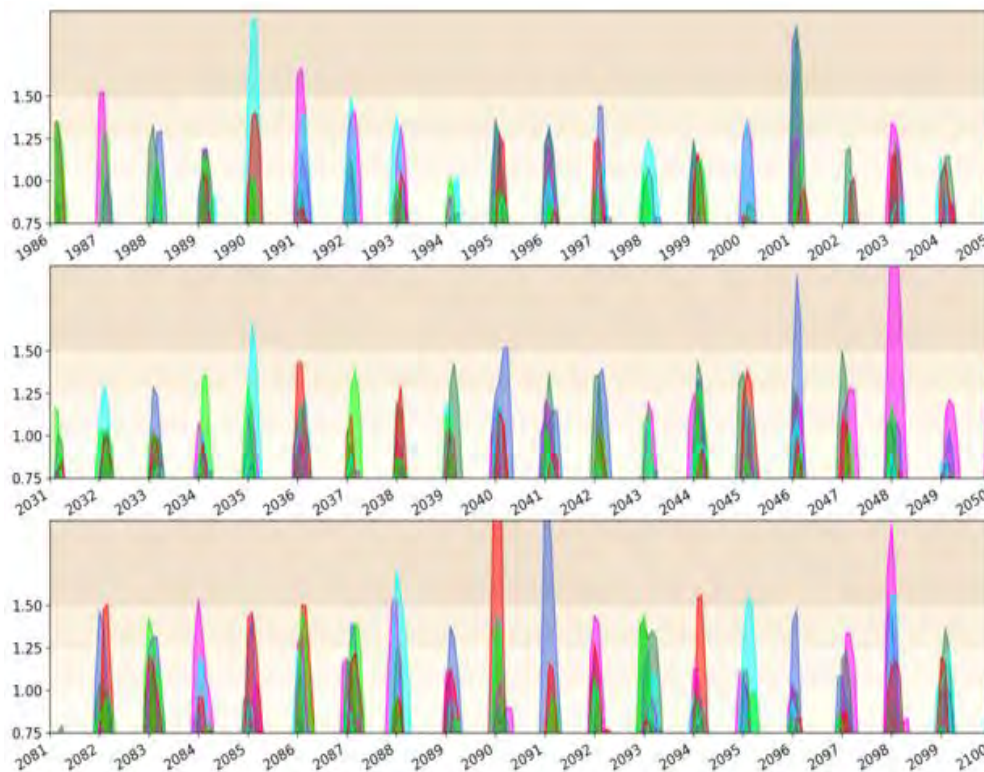


Figure 4-12: The 1990s (past, top) and the two future (2040s, middle; 2090s, bottom) time series of PED60 for all NZ-CMIP5 ensemble members for the RCP8.5 emission scenario.

The larger SMD and SMDA values in the future periods (Figs. 4-10 and 4-11, middle and lower panel) indicate future drier soil conditions are more prevalent at this location, but only in the late spring to early autumn seasons (PED60 goes to zero at the ends of each water-year), and again point to the need to distinguish the seasonal variations in regional change and how these may impact stakeholders in the primary sector. Despite increased winter precipitation, much higher temperatures lead to increased AET and thus higher SMD. Again, these changes are much smaller for the low emission scenario (RCP2.6) than for the higher emission projections.

The larger PED60 values in the future period (Fig. 4-12) almost reaching the “drought” threshold, are again indicative of much drier soil conditions not meeting “crop” water demand because of the combined effect of lack of precipitation and increased PET.

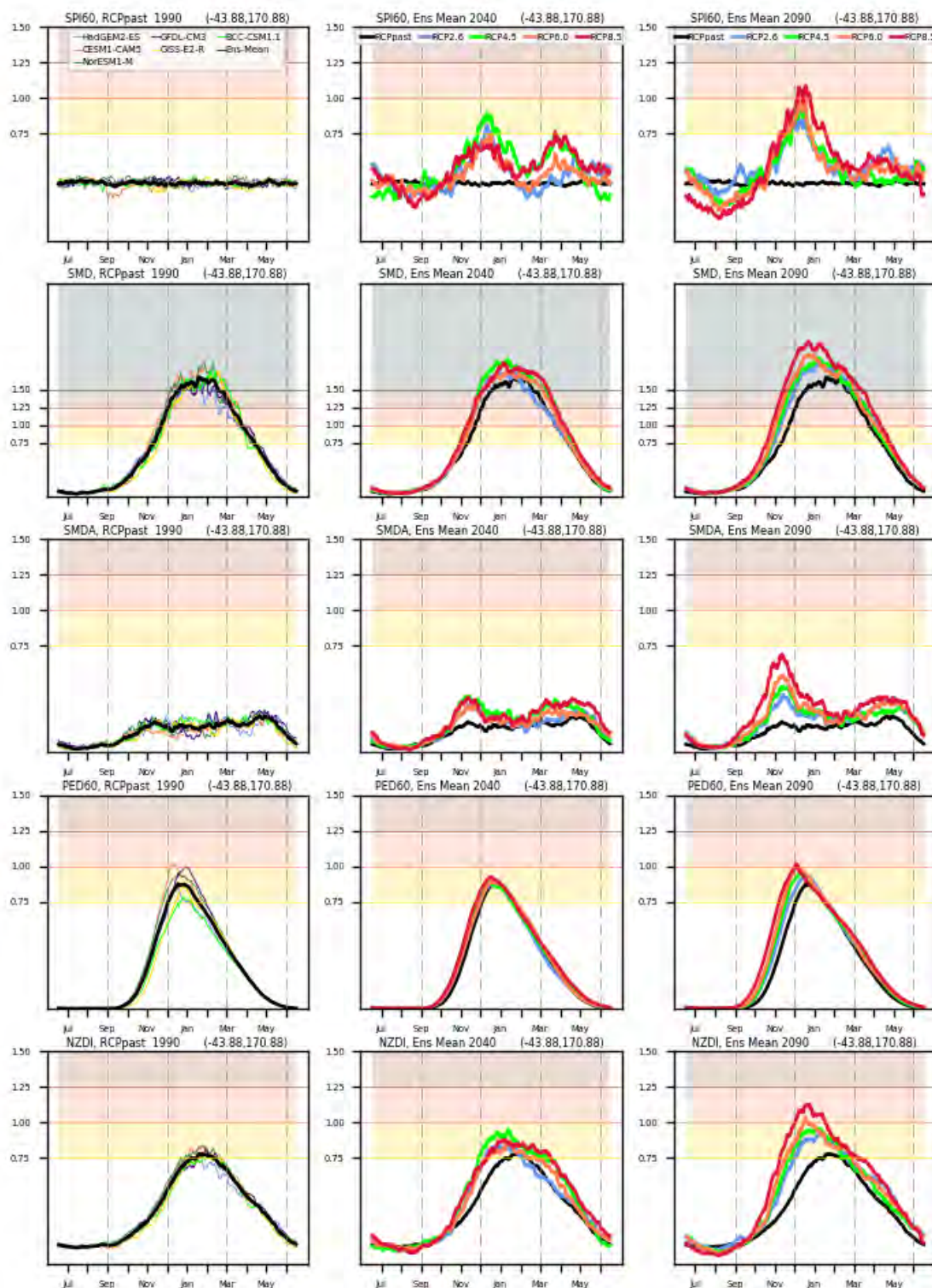


Figure 4-13: The mean annual cycle (July-June) with the drought classification (background colours) is presented above for the central Canterbury site. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black, thick) in the left column in the historic period are compared with the ensemble mean for the four RCP's at the middle (middle column) and the end of 21st century (right column)

Fig. 4-13 highlights the changes in the annual cycle of the Clim-NZDI and its constituent indices at the central Canterbury site. The large increase in Clim-NZDI occurs earlier in the season in the 2090s

relative to the historic period (Fig 4-13; bottom left column, black) and indicates higher risk of earlier drought. Lower values at the beginning and end of the annual cycle indicate lower risk of "back-to-back" droughts. The strongest signal is for the high emission scenario (RCP8.5, red) which is mostly due to the large increase in surface temperature increasing evapotranspiration and SMD (second row). The earlier increase in the 2090s relative to the historic period (left column, black) indicates a higher risk of earlier spring drought. Even the most optimistic low emission scenario (RCP2.6, blue) does not avoid an increase in spring and summer drought risk at this location.

4.2 Multi-region droughts

There were a few occurrences of multi-region drought in New Zealand in recent years, such as the 2013 severe North Island drought which led to imposed water restrictions in Wellington and also affected parts of South Island. A comprehensive analysis of concurrent drought occurring in each individual region is beyond the scope of this study and will be conducted separately. In the following Fig. 4-14, the percentage of New Zealand land surface under severe risk of drought (Clim-NZDI larger than 1) in the 20-year past reference period (the 1990s, black lines) and for end-of-century future period (the 2090s, red lines), are compared for one model (HadGEM2-ES) and the extreme emission scenario (RCP8.5).

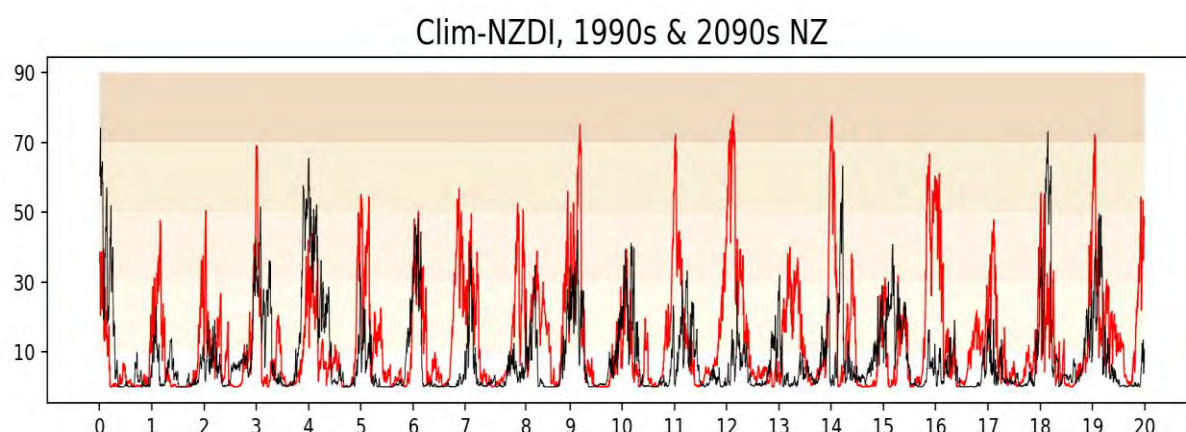


Figure 4-14: The total area (in %) at risk of drought (NZDI>1) for NZ-CMIP5 ensemble is shown in the top panel for one model (HadGEM2-ES. Larger area is under drought risk with Clim-NZDI > 1 more frequently in the 20-year time slice in 2090s (red) than in the reference past time slice, 1990s (black). The risk of 'back-to-back' multi year drought is low and confined to small regions below 10% nationally.

For the purposes of this report, we consider multiple regions to be affected if the land coverage exceeds 10%, and drought is experienced nationwide if it exceeds 70% with a few possible exceptions along South Island's west and east coasts. These thresholds are exceeded more often in the late 21st century (2090s) period (red), indicating higher risk of multi-region or even nationwide drought relative to the past period. Multi-region droughts are also likely to occur annually and last longer, unlike the less frequent ones in the past of shorter durations. However, an increase in the risk of multi-year or "back-to-back" droughts is not very evident in most regions because the Clim-NZDI falls below the dry threshold (0.75) in winter indicating improved recharge of the soils. Nevertheless, the annual low-risk drought period is of shorter duration, and there is an increased risk of drought to occur earlier in the following spring season especially towards the end of the 2090s.

The multi-region drought occurrence over 50%, and over 70%, of New Zealand's land surface is summarized in Table 4-1. The number of days in the past (1990s), and in the two future periods

(2040s and 2090s) with Clim-NZDI exceeding 1 (very dry) threshold, is shown in Table 4-1 for each of the six models. The number of years (out of 20) when these thresholds are exceeded is also presented. The mean duration of these droughts can now be derived as (number of days)/year. For example, for the HadGEM2-ES model and 70% areal coverage, the duration changes from 2 days in the past to 3 days in the 2040s and 6 days in the 2090s. There is considerable variability in these results between models (e.g., GISS-E2-R has low counts, and BCC-CSM1.1 has high counts), even showing a decrease in very large (70% coverage) of multi-year droughts in some instances. This variability may be related to multi-decadal climate variability and further investigation is required.

(Clim-NZDI>1)	HadGEM-ES1	CESM1-CAM5	NorESM1-M	GFDL-CM3	GISS-E2-R	BCC-CSM1.1
50% Area	days per period (years)	days per period (years)	days per period (years)	days per period (years)	days per period (years)	days per period (years)
RCPpast	120 (5)	139 (6)	95 (7)	109 (5)	148 (7)	233 (7)
RCP8.5-2040s	155 (11)	183 (10)	100 (10)	338 (17)	71 (6)	343 (11)
RCP8.5-2090s	285 (16)	340 (14)	323 (15)	647 (16)	108 (8)	716 (19)
70% Area						
RCPpast	4 (2)	5 (2)	19 (2)	0 (0)	33 (3)	44 (2)
RCP8.5-2040s	9 (3)	28 (1)	1 (1)	38 (4)	9 (1)	146 (6)
RCP8.5-2090s	43 (6)	36 (6)	19 (4)	197 (9)	2 (1)	201 (15)

Table 4-1: Number of days in the past, 1990s, two future, 2040s and 2090s periods and number of years (in brackets) where the “very dry” threshold is exceeded for Clim-NZDI for all six NZ-CMIP5 models and RCP8.5 emissions.

5 Drought Indicator Climatology Maps

In this section we present national maps for the model ensemble-mean of all the drought indices for all emission scenarios. The seasonal climatologies and the future change signal in the 2040s and 2090s with respect to past (1990s) period is shown to depict drought evolution with time over the century. However, there is considerable variability with the ensemble members of NZ-CMIP5 that are not captured by the ensemble mean, with some models in some regions even showing a decrease in drought conditions (e.g. NorESM1-M and GISS-E3-R).

5.1 SPI60

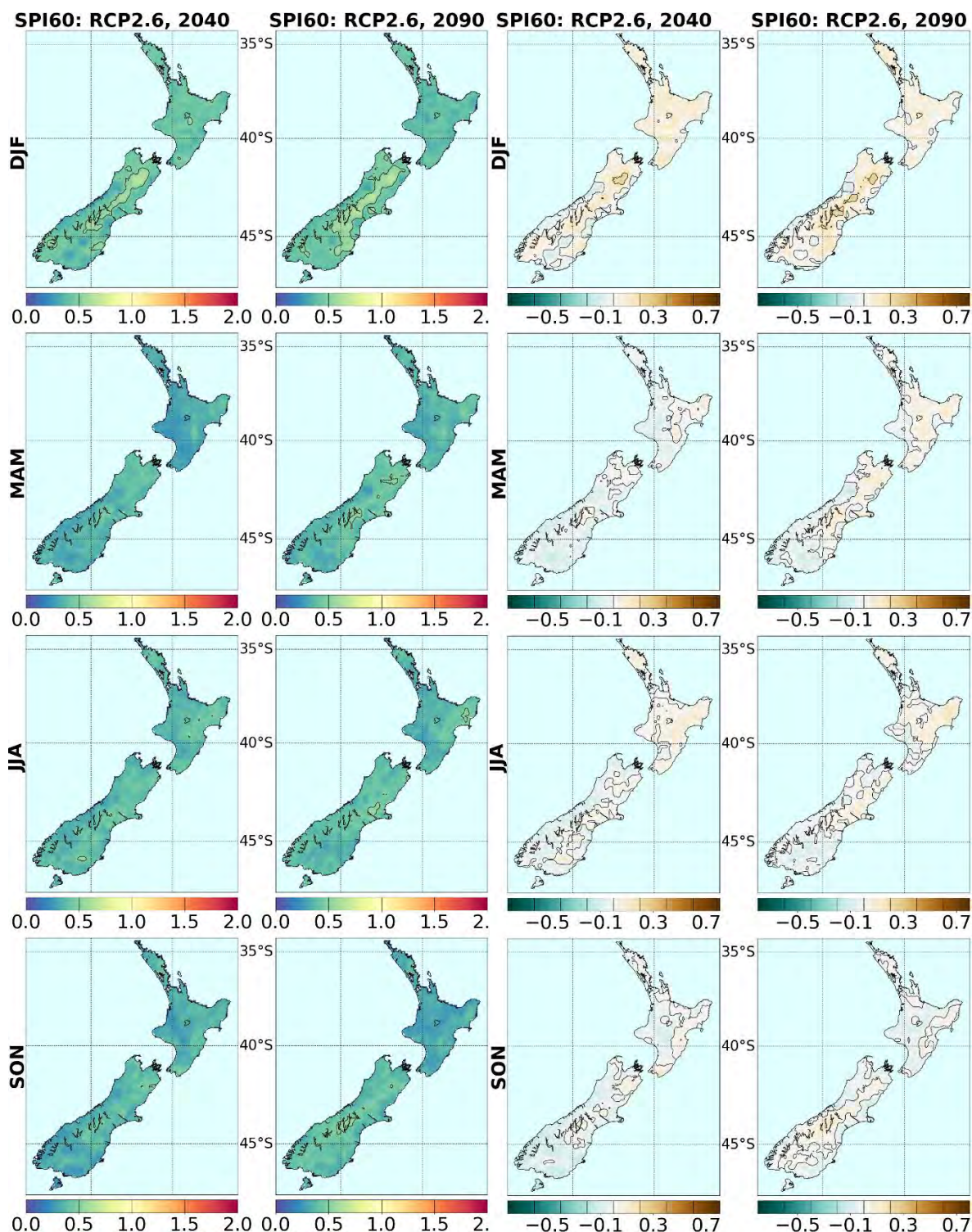


Figure 5-1: The seasonal climatologies (1. And 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of SPI60 (that is SPI with 60-day reference period) for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

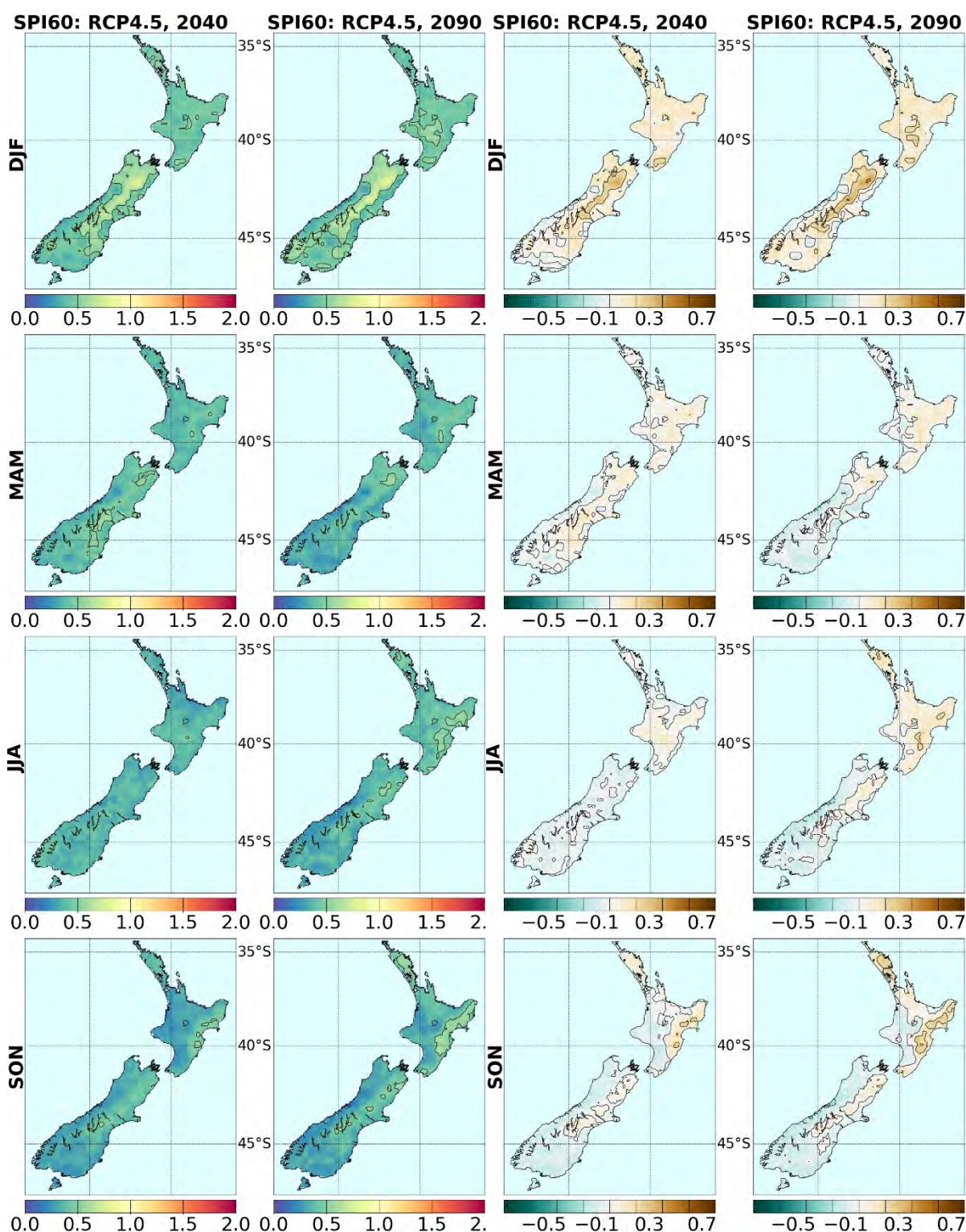


Figure 5-2: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of SPI60 (that is SPI with 60-day reference period) for RCP4.5 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4 columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

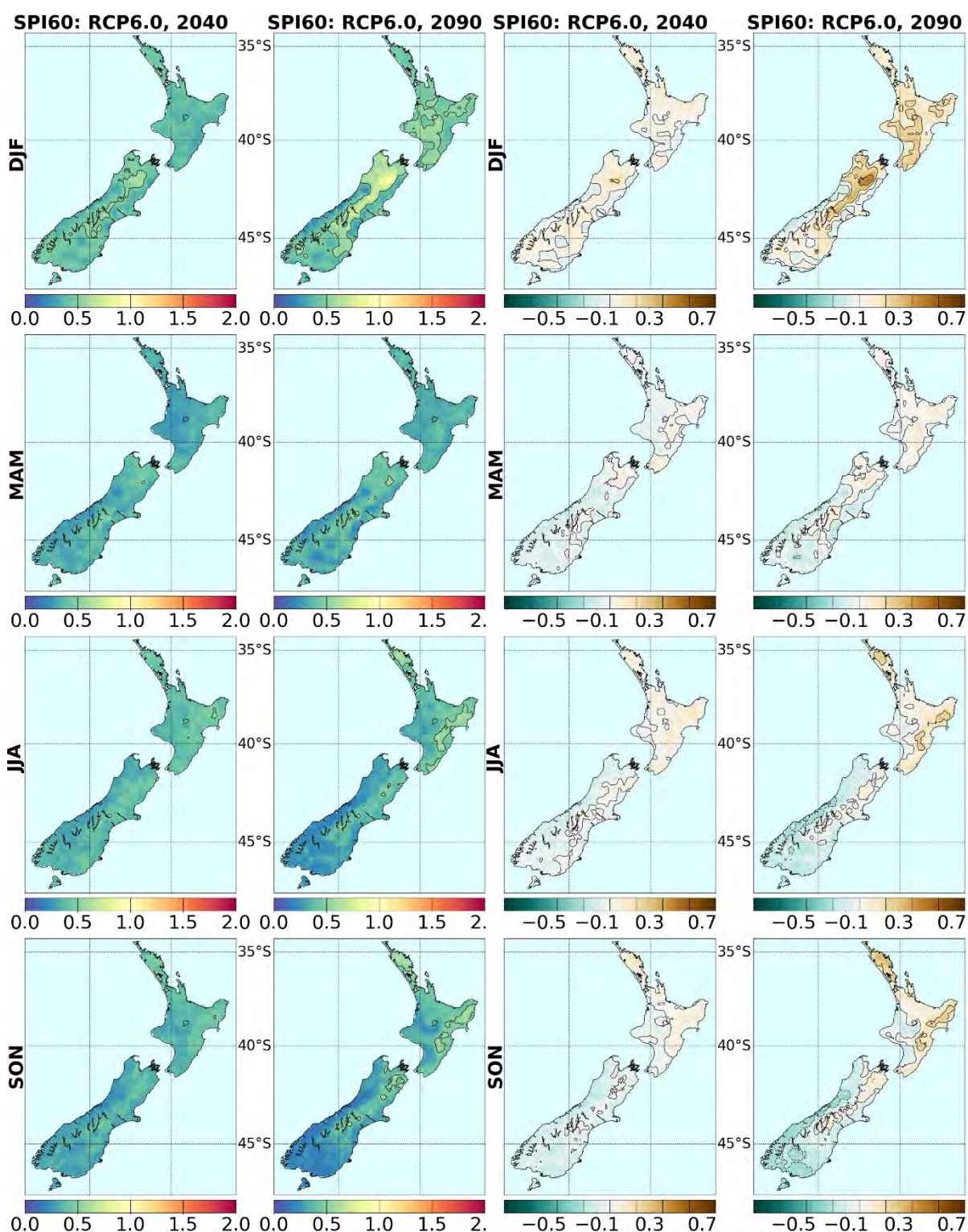


Figure 5-3: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of SPI60 (that is SPI with 60-day reference period) for RCP6.0 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate

project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

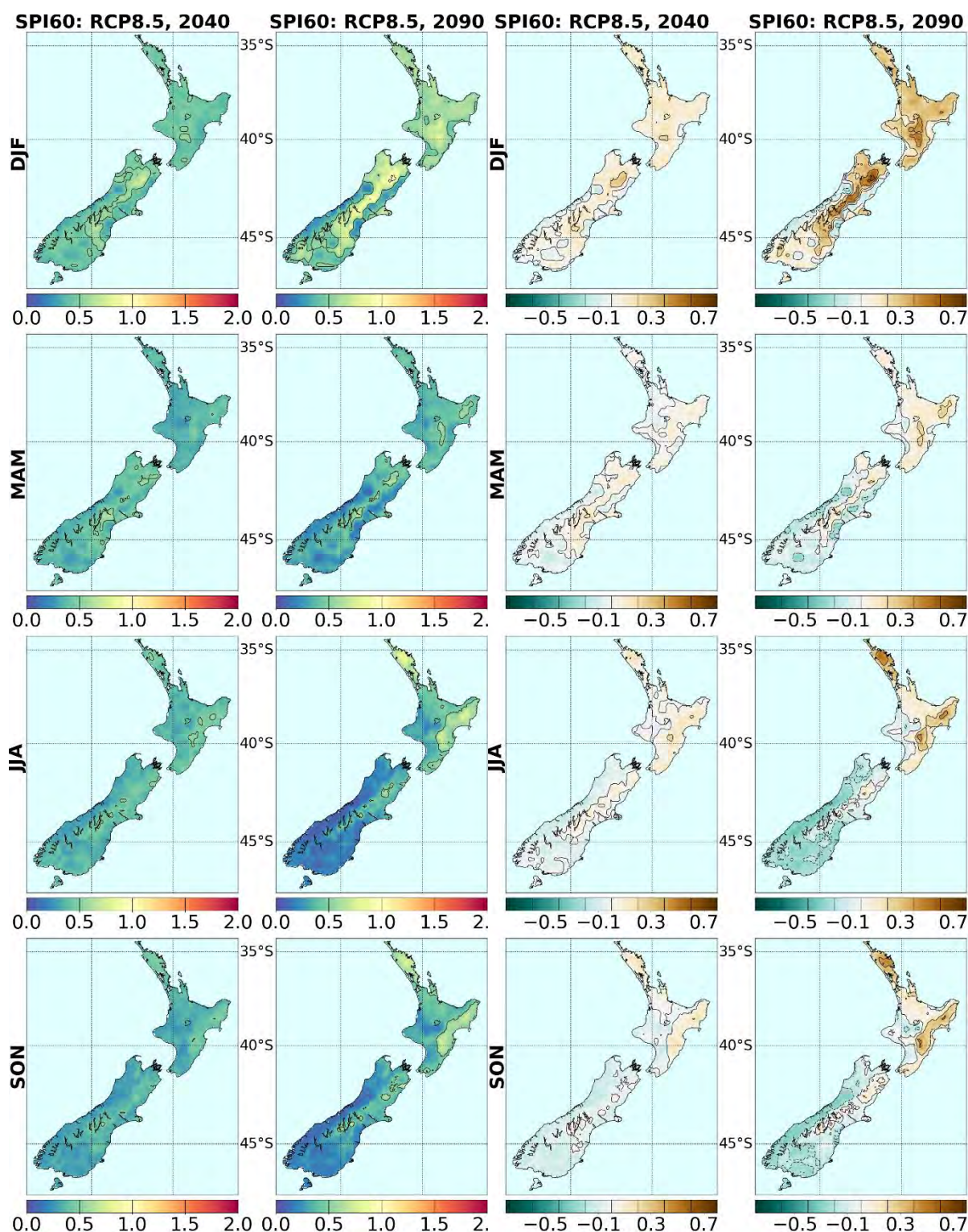


Figure 5-4: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of SPI60 (that is SPI with 60-day reference period) for RCP8.5 emission scenario for the 2040s (first and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

5.1.1 SMD

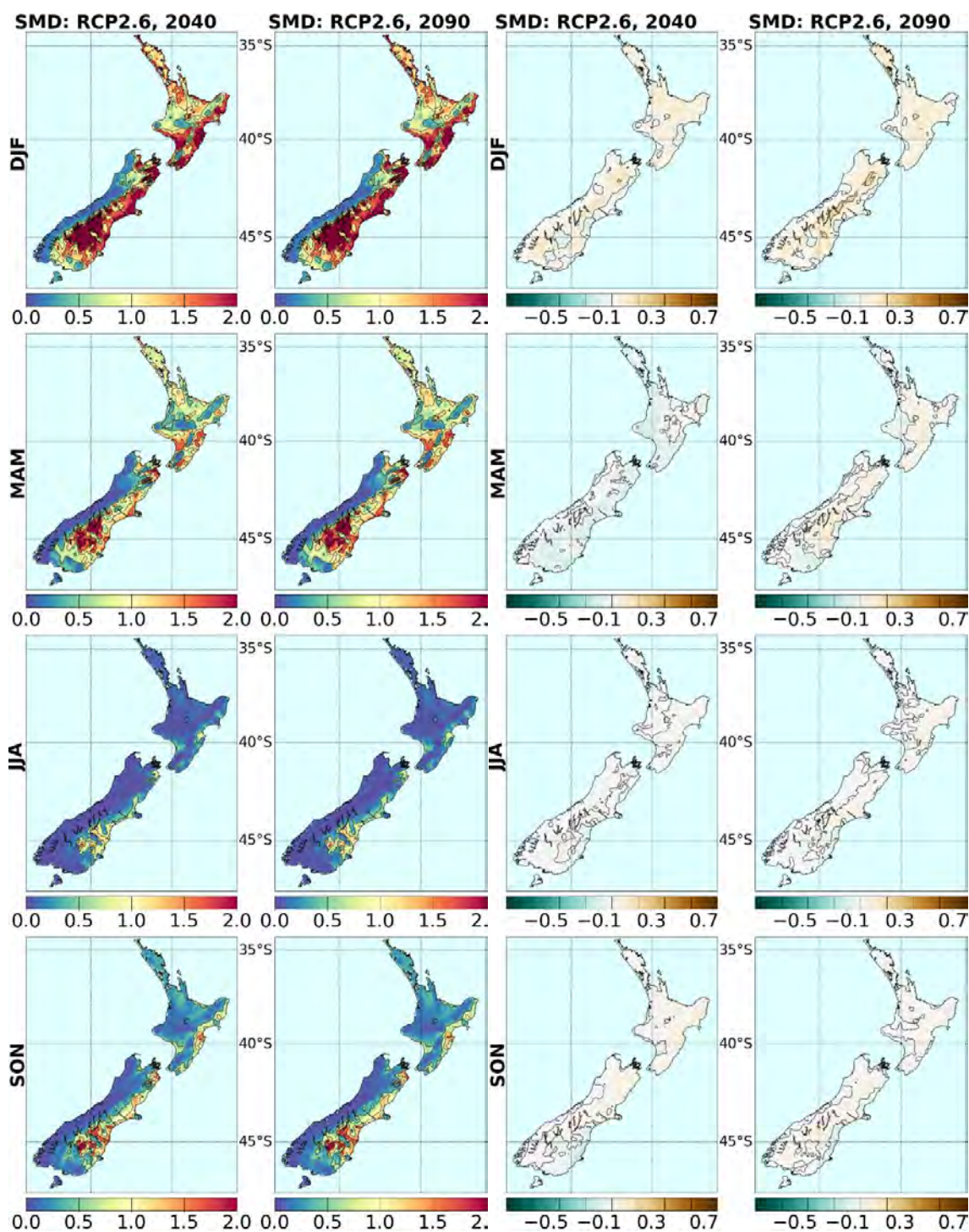


Figure 5-5: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMD for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours

indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

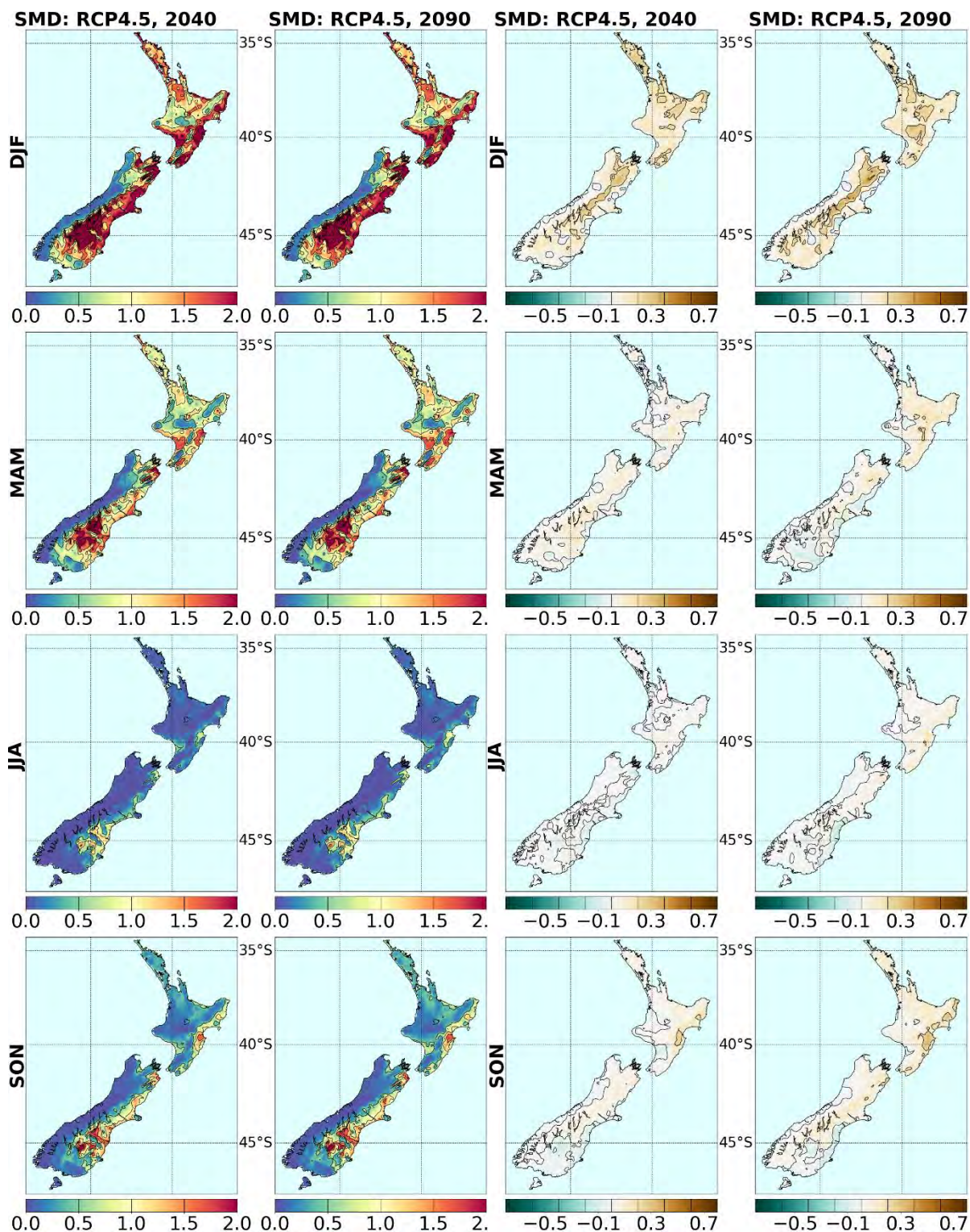


Figure 5-6: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMD for RCP4.5 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours

indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

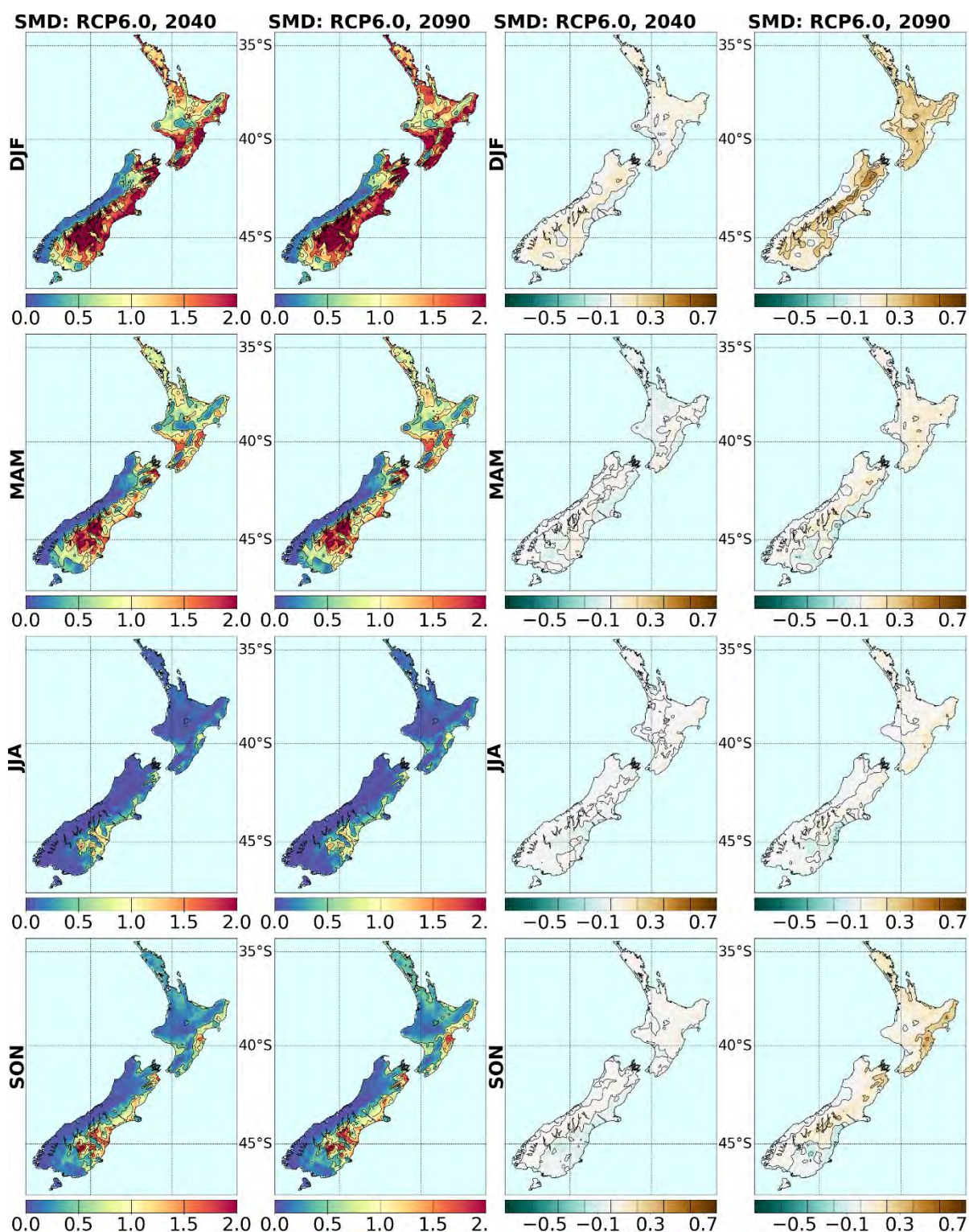


Figure 5-7: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMD for RCP6.0 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

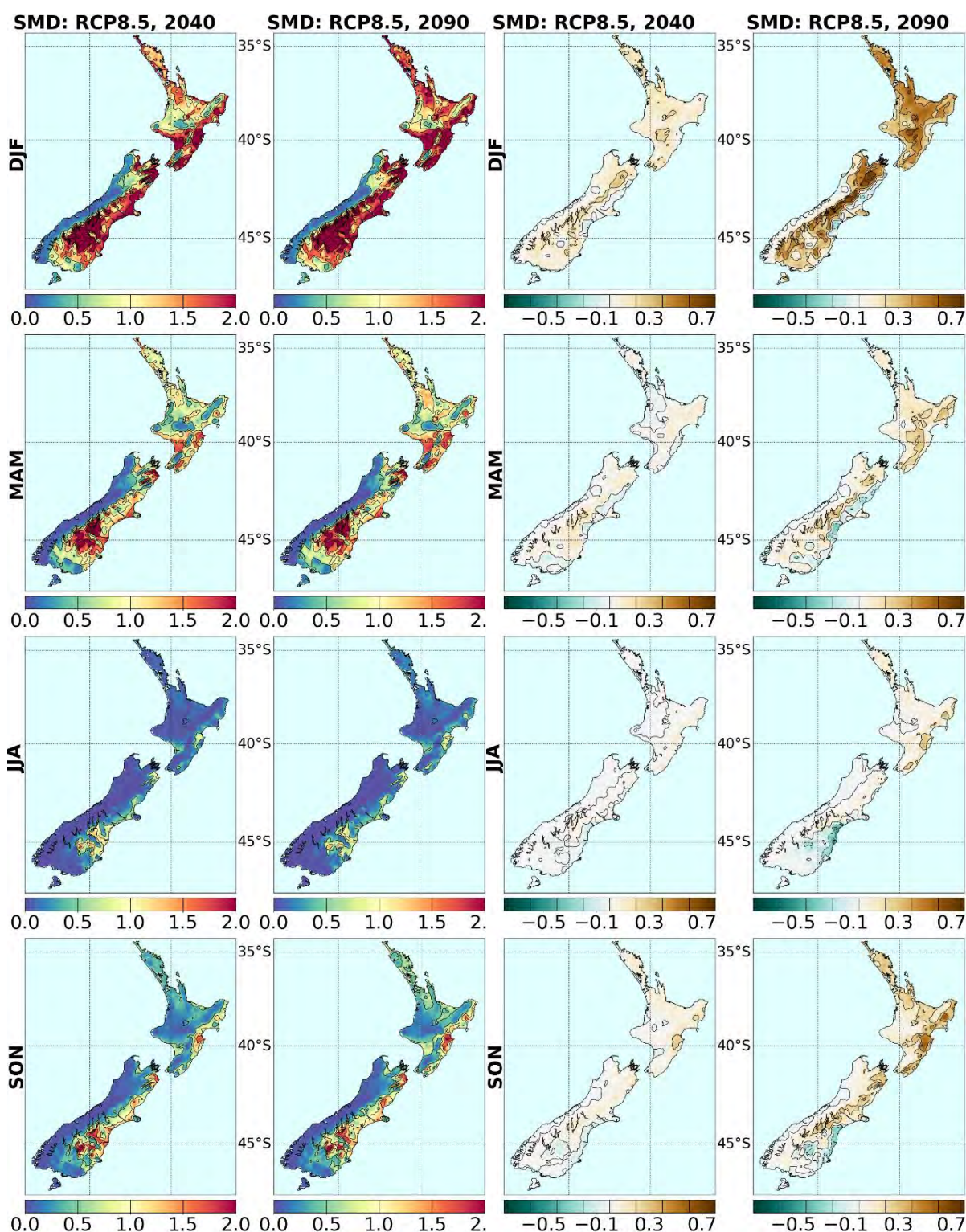


Figure 5-8: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMD for RCP8.5 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

5.1.2 SMDA

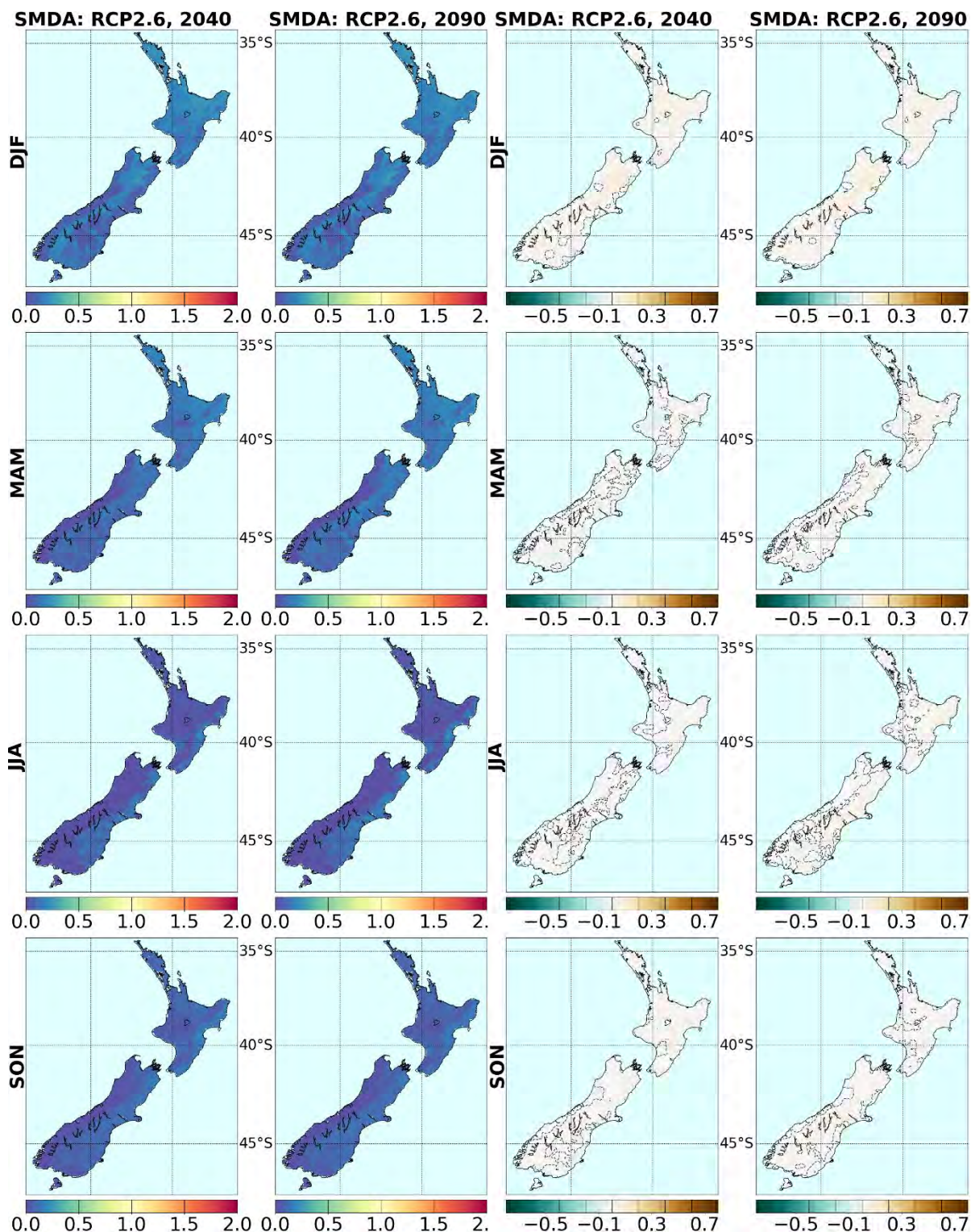


Figure 5-9: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

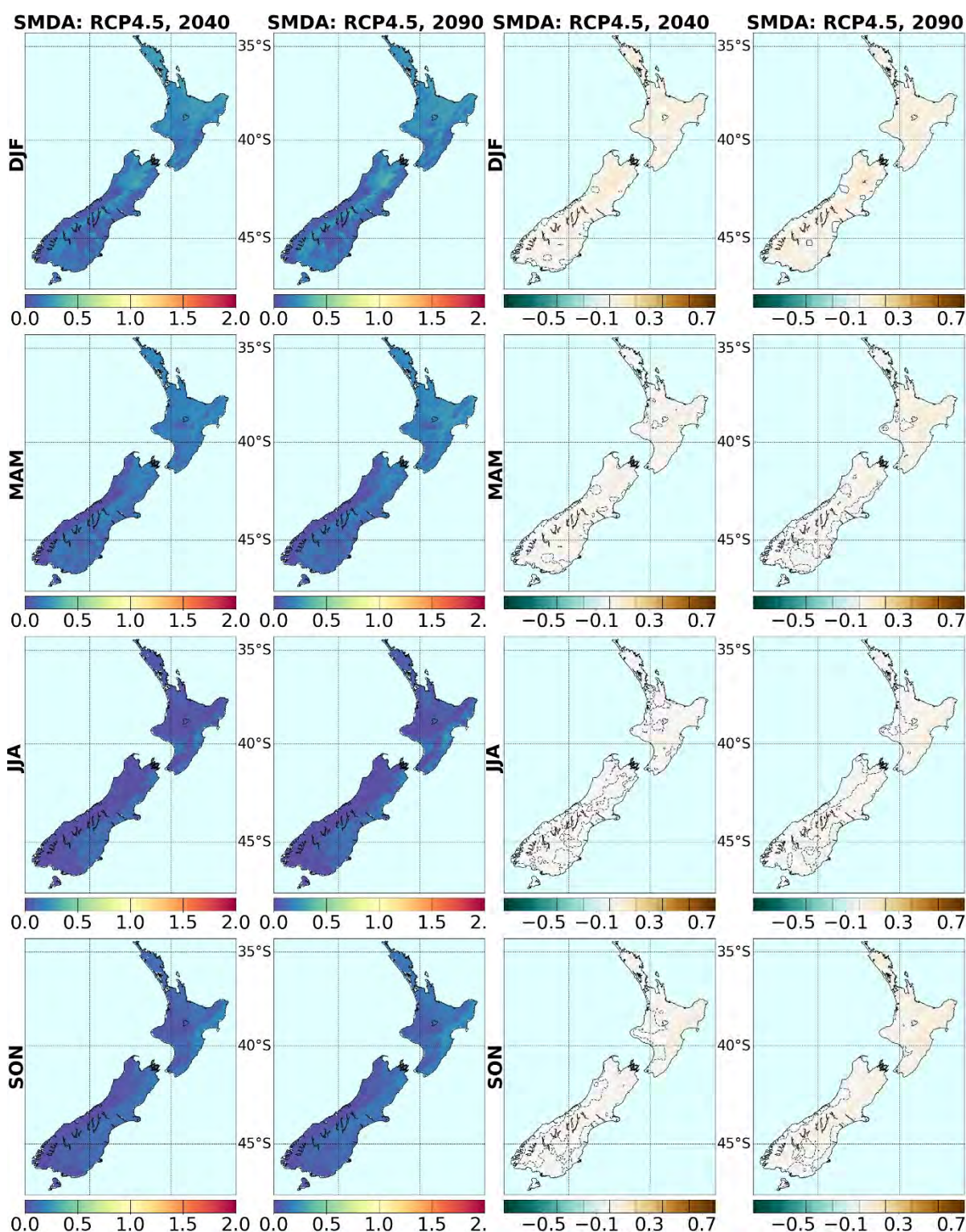


Figure 5-10: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

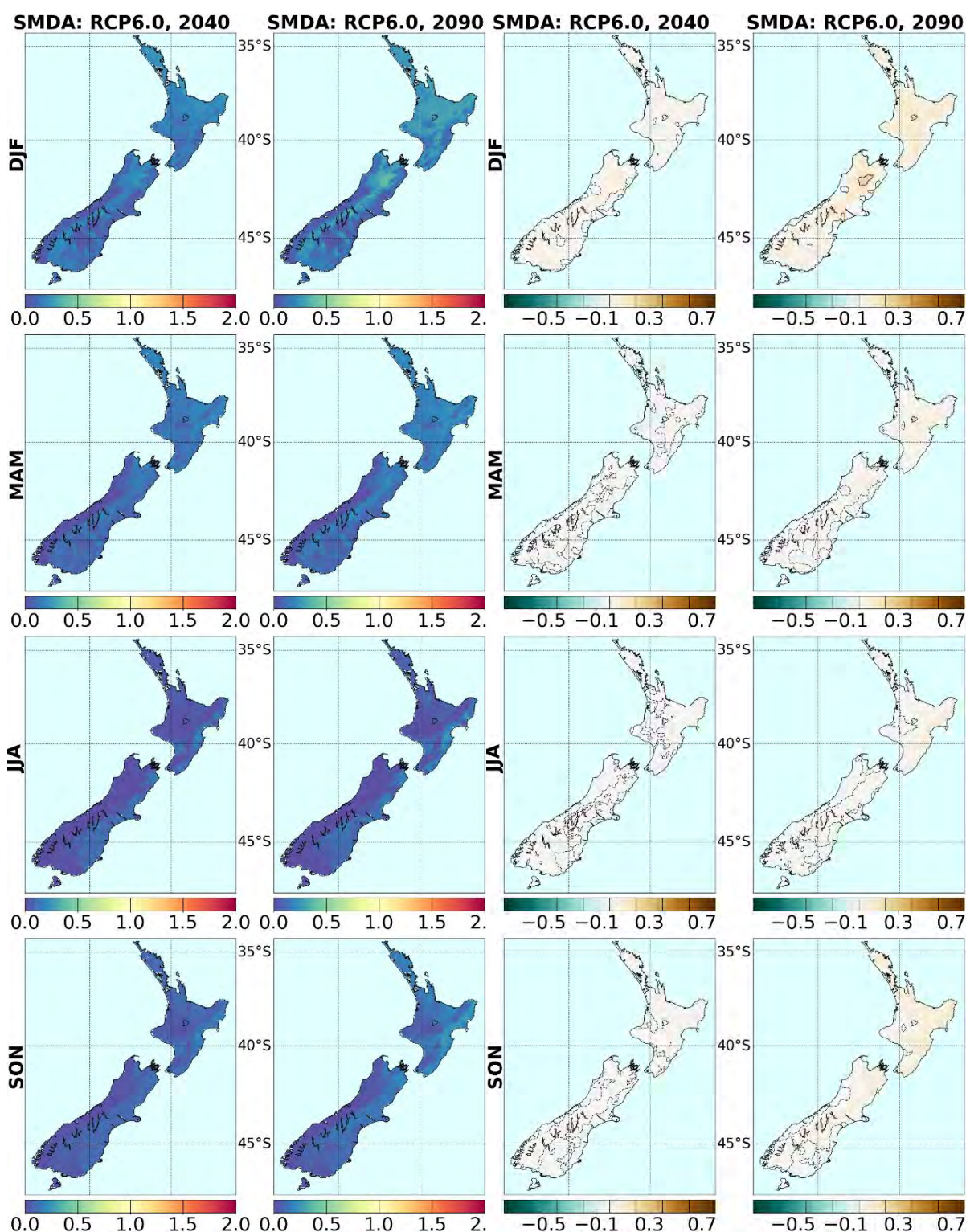


Figure 5-11: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

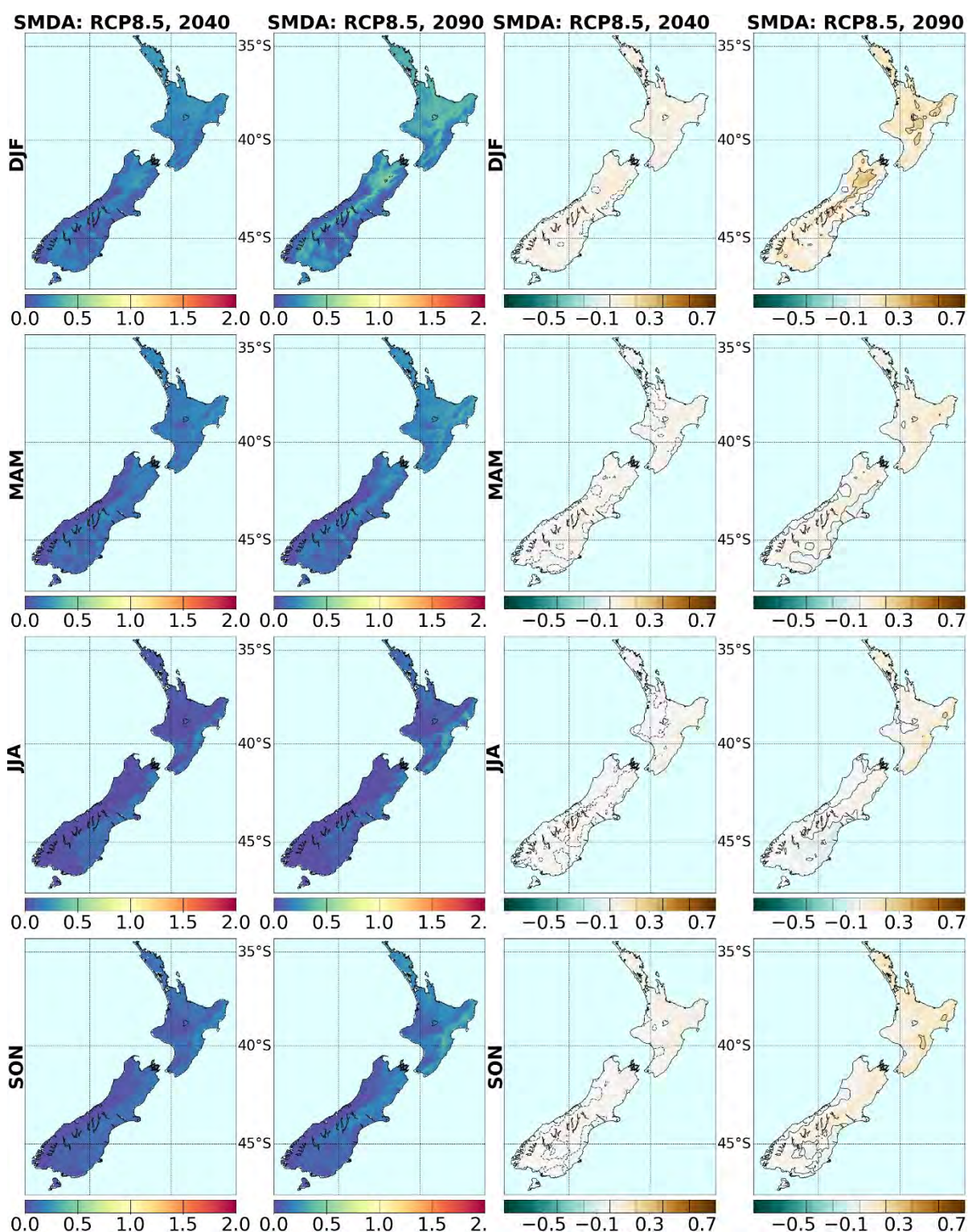


Figure 5-12: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

5.1.3 PED60

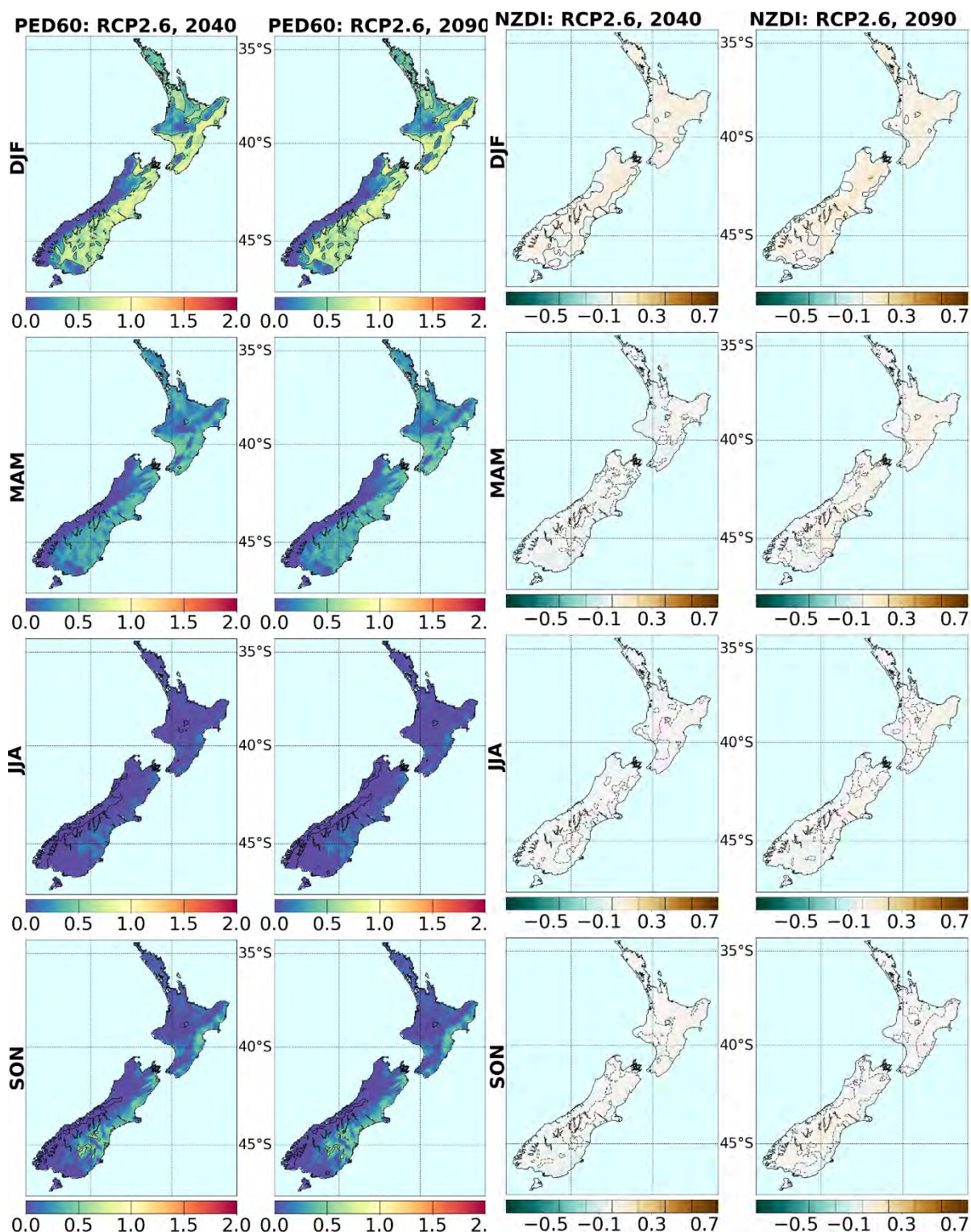


Figure 5-13: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

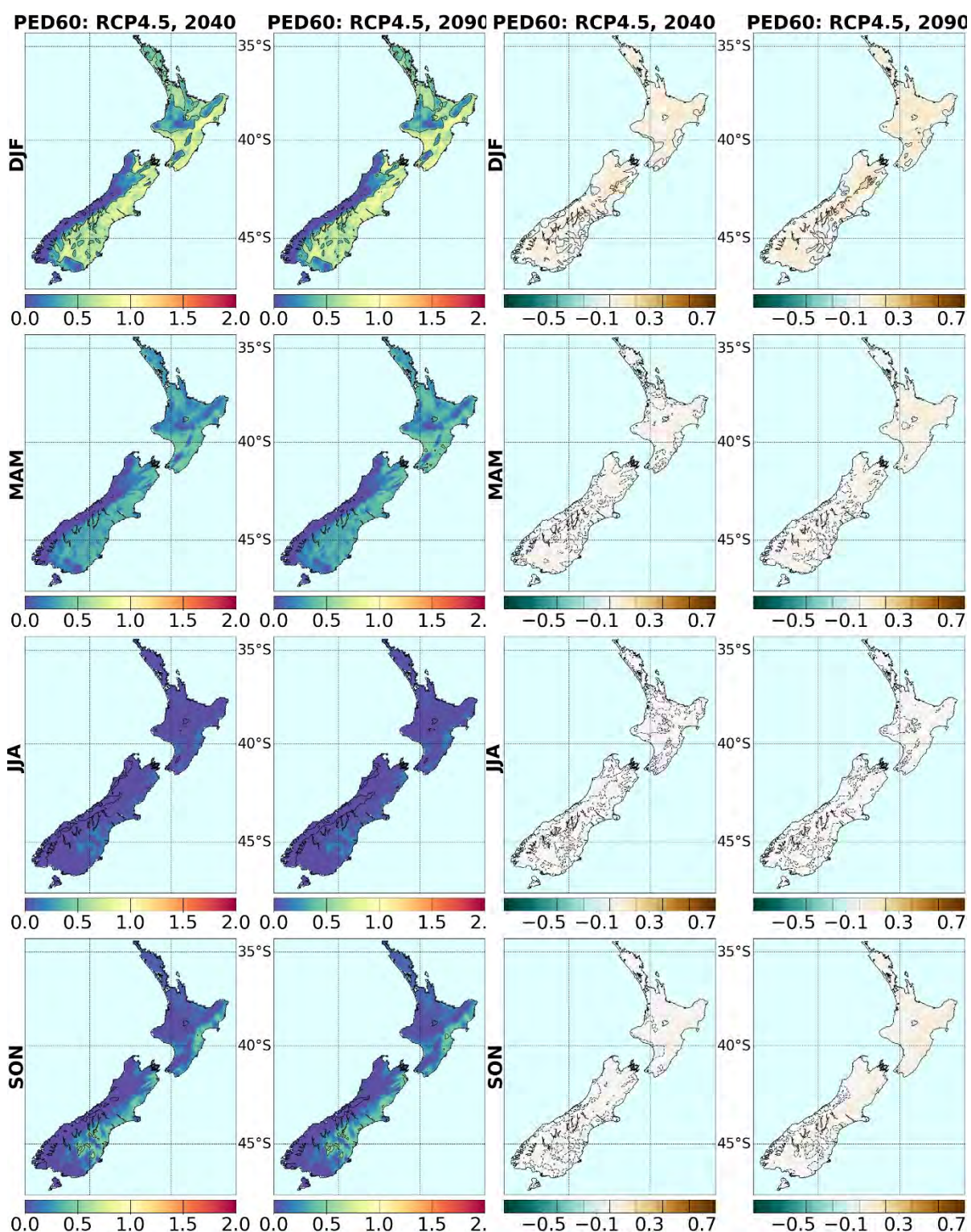


Figure 5-14: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

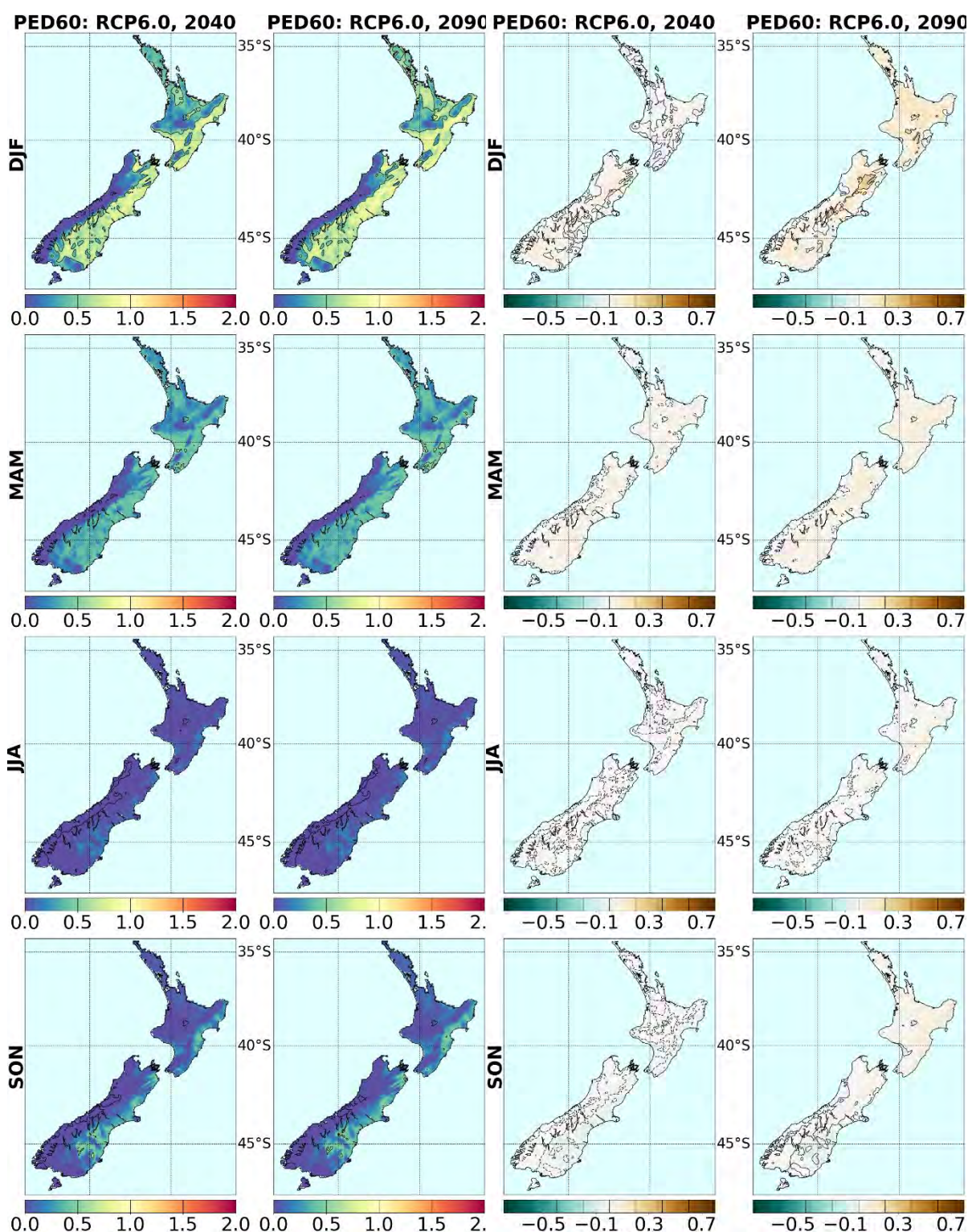


Figure 5-15: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

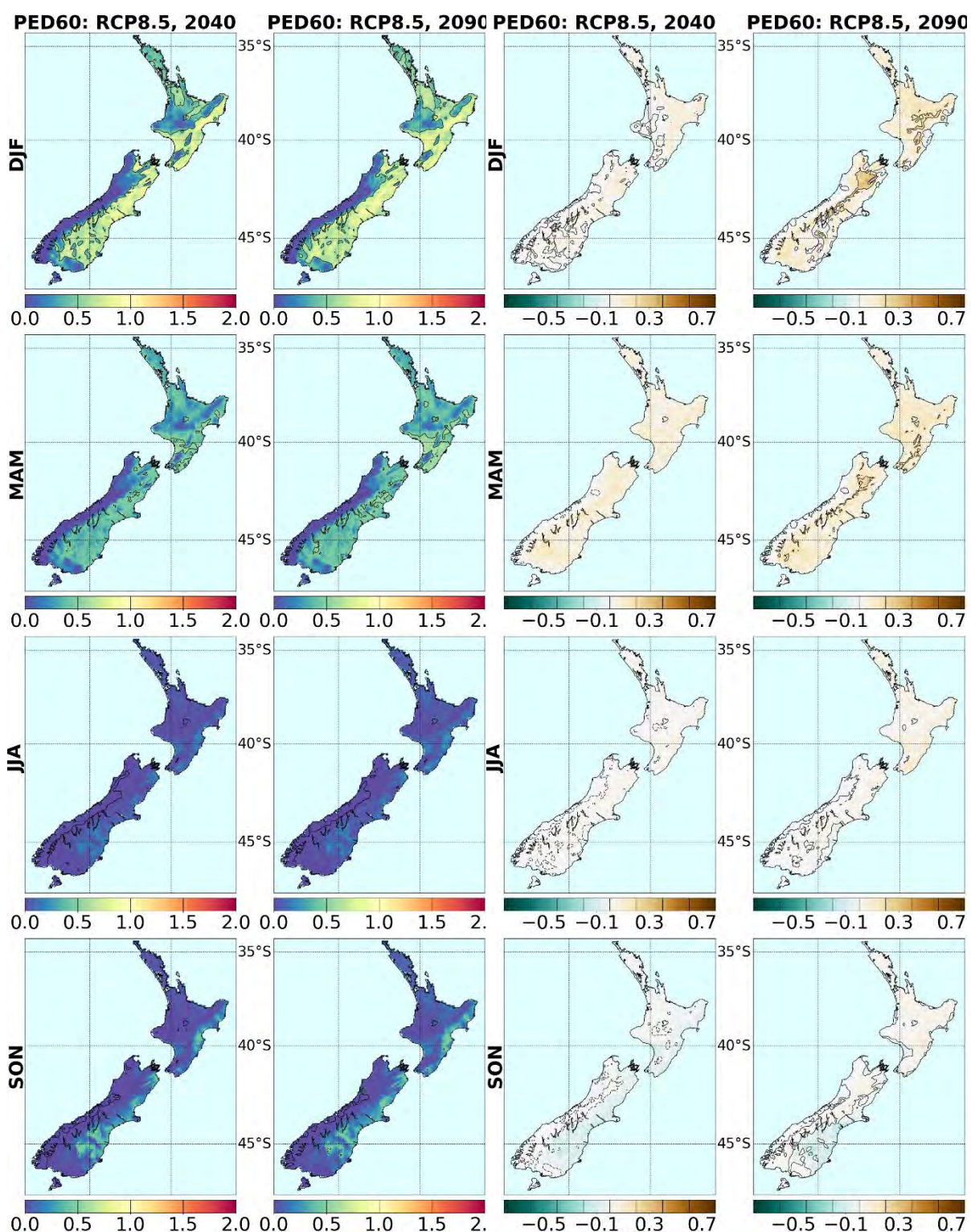


Figure 5-16: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

5.1.4 Clim-NZDI60

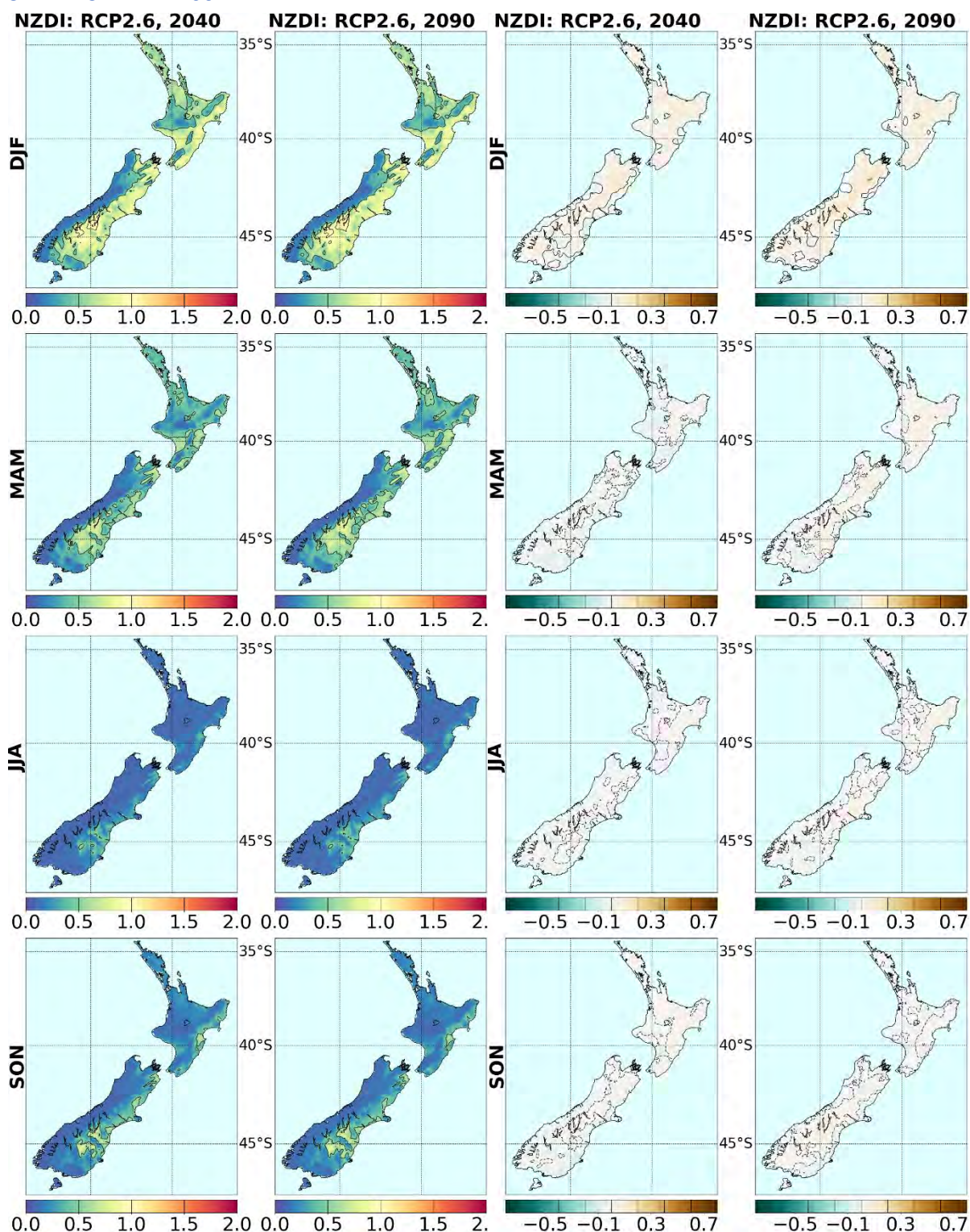


Figure 5-17: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

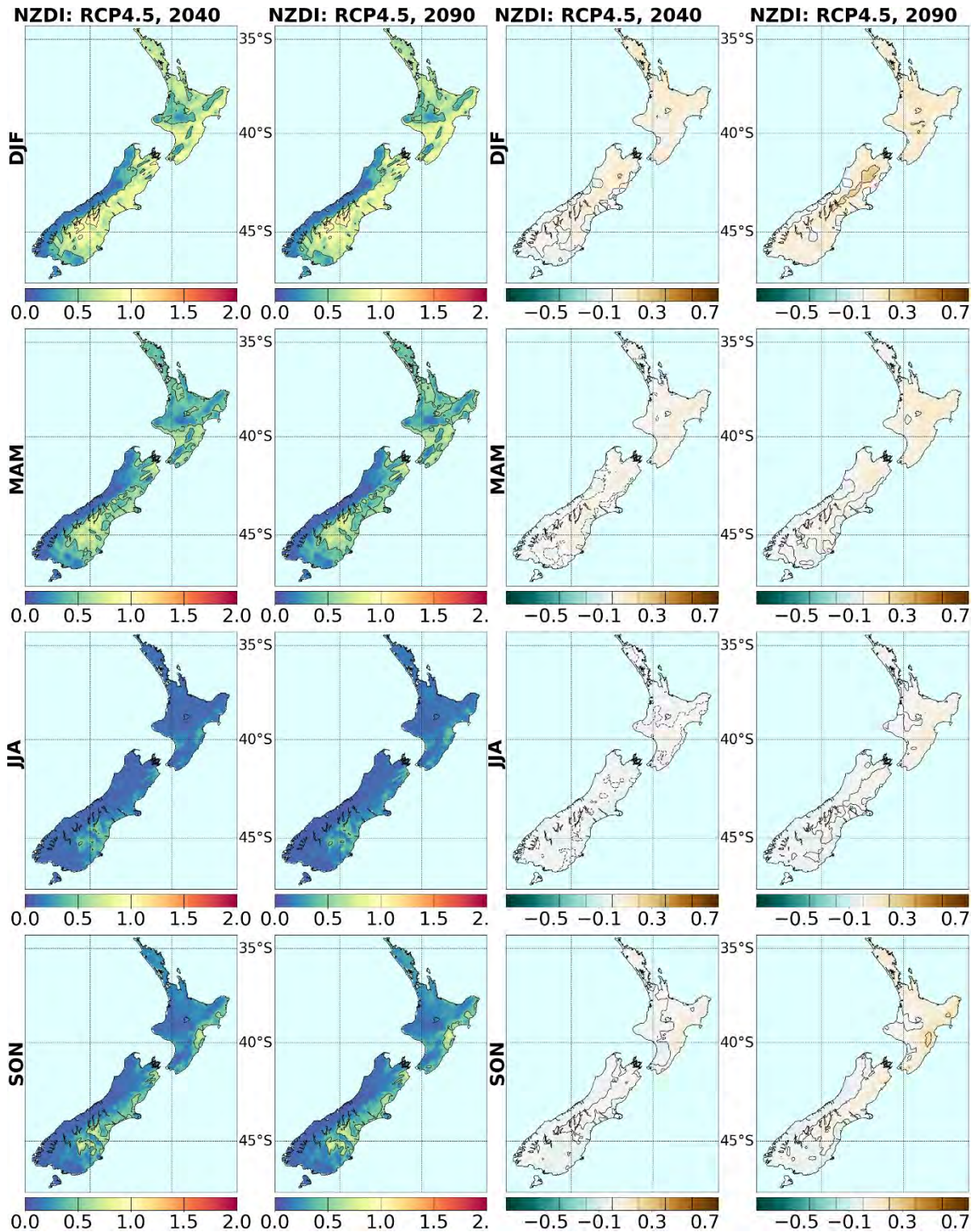


Figure 5-18: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

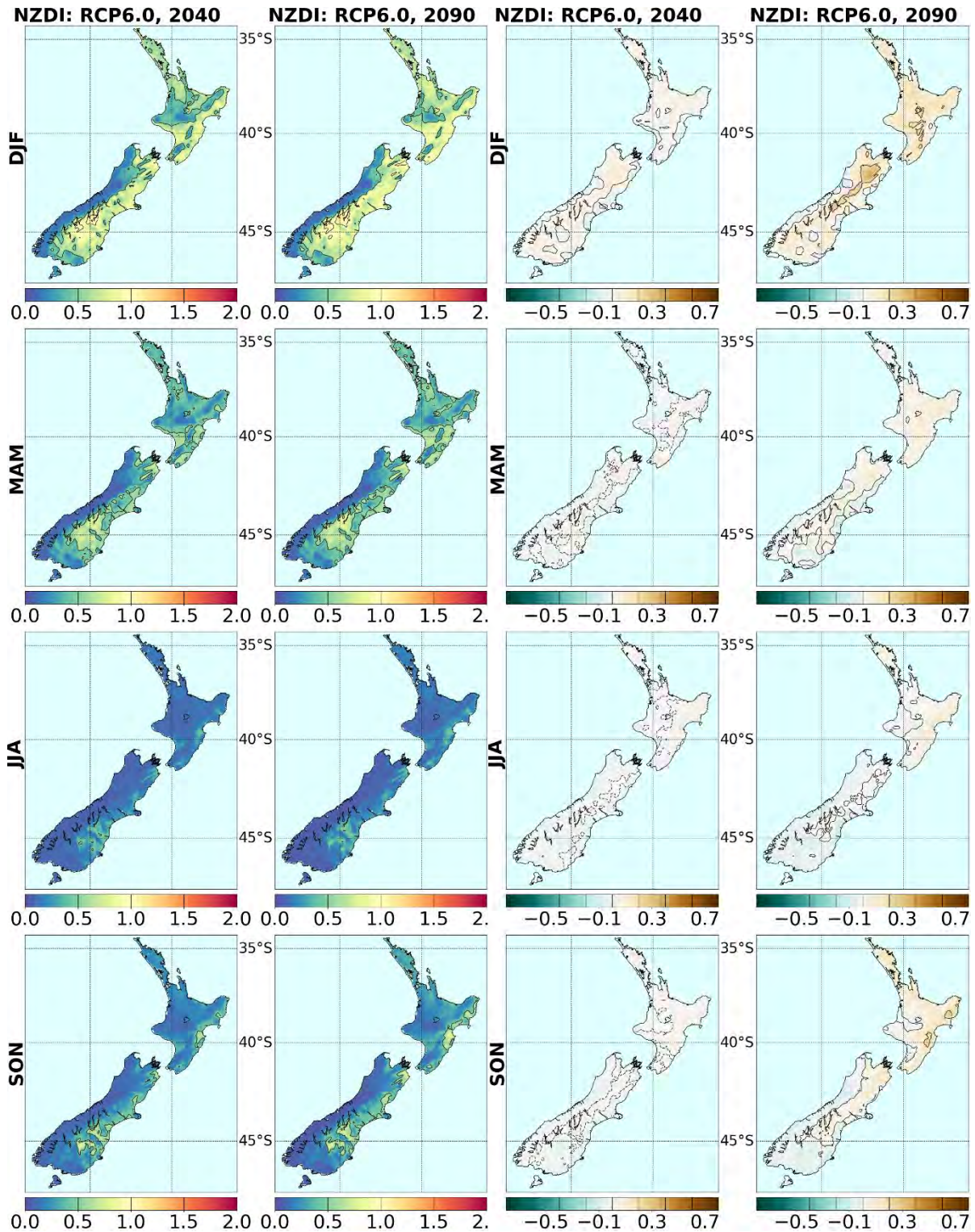


Figure 5-19: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

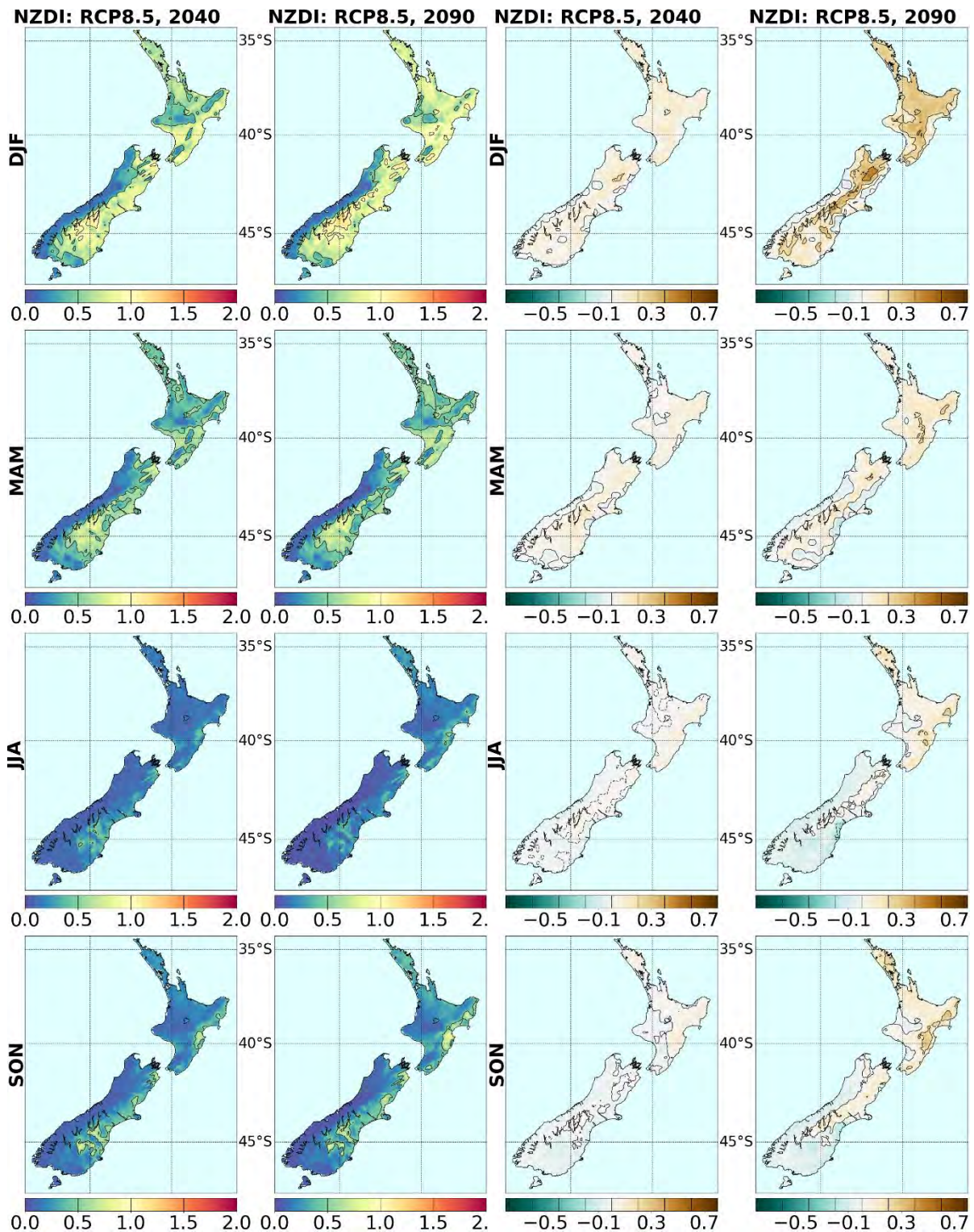


Figure 5-20: The seasonal climatology (1. and 2. columns) and the climate change signal (3. and 4. columns) of the model ensemble mean of daily SMDA for RCP2.6 emission scenario for the 2040s (1. and 3. columns) and 2090s (2. and 4. columns) time slices based on NZ-CMIP5 climate project data. The yellow to red colours indicate dry conditions in seasonal climatologies and brown shades indicate increased drier conditions with respect to 1990s reference past period.

6 Changes in intensity and duration of drought at study sites

The diverse range of changes in drought characteristics across New Zealand are summarized in Table 6-1, and illustrated as annual time series in Figs. 6-1 to 6-7, for all the sites used in the Tonkin and Taylor study to assess potential risks to drinking water potential.

Study Sites	Location	Precipitation (SPI60)	Temperature (SMD/SMDA/PED60)	Clim-NZDI
Northland sites: Wairoro Stream Punakitere River Lake Omapere	(Fig. 4-7) 173.827E 35.458S 173.797E 35.465S 173.769E 35.362S	Significant deficit in all seasons other than in autumn	SMD higher in mid-spring to late summer with SMDA peak in Dec. Increase in drought risk period with earlier onset by a month (PED60) for all RCPs other than RCP2.6	Drier conditions in all seasons with higher risk of “back-to-back” droughts due to drier winters and a peak risk in summer.
Auckland site: Cosseys Dam	(Fig. 6-1) 175.103E 37.063S	Significant deficit in late spring-summer and in early winter	SMD higher in mid-spring to early autumn in the 2090s with SMDA peak in Dec. Increase in drought risk period with earlier onset by a month (PED60) for all RCPs other than RCP2.6	Earlier onset of drier than past conditions in mid-spring to early autumn. More intense summer drought risk.
Waikato site: Te Miro Reservoir	(Fig. 6-2) 175.587E 37.790S	Significant deficit in late spring-summer	SMD considerably higher in mid-spring to early autumn with SMDA peak in Dec. Increase in drought risk period with earlier onset by a month (PED60) for all RCPs other than RCP2.6	Earlier onset of drier than past conditions in mid-spring to early autumn. More intense summer drought risk.
Taranaki site: New Plymouth	(Fig. 6-3) 174.093E 39.156S	Significant deficit is mostly in mid-spring to mid-summer and much wetter winter conditions	SMD a slightly higher in summer with SMDA peak in Jan. Slight increase in drought risk period with earlier onset by a month (PED60) mostly for RCP8.5	Slight increase in drought risk mostly for RCPs 6.0 and 8.5 in the 2090s and decreased risk of “back-to-back” droughts due to wetter winters.
Gisborne site: Te Arai River	(Fig. 6-4) 177.789E 38.824S	Significant deficit in all seasons with least change in RCP2.6	SMD higher in mid-spring to early autumn in the 2090s with SMDA peak in late Nov. Increase in drought risk period with earlier onset by a month (PED60) for all RCPs other than RCP2.6	Drier conditions in all seasons indicating higher risk of “back-to-back” droughts and a peak in summer.
Manawatu-Whanganui site: Turitea Dam	(Fig. 6-5) 175.661E 40.430S	Significant deficit in the 2090s mostly in summer and wetter conditions in winter to mid-spring	SMD higher in summer with SMDA peak in Dec. Slight increase in drought risk period with earlier onset by nearly a month (PED60) for all RCPs other than RCP2.6	Wetter winter and early spring are followed by dry conditions in all seasons indicating lower risk of “back-to-back” droughts and a peak in summer.
GWRC sites: Masterton East Masterton West	(Fig. 6-6) 175.587E 40.873S 175.542E 40.897S	Significant deficit mostly in summer and late autumn to early winter with slightly wetter spring conditions	SMD higher in 2090s in the summer and considerable increase in SMDA with a peak in Dec-Jan. A corresponding increase in PED60 indicates increased dryness and drought risk	The increase in drought risk is from early summer to late autumn but recovery in winter implies lower risk of “back-to-back” droughts.
Tasman site: Lee River	(Fig. 6-7) 173.157E 41.423S	Significant deficit mostly in summer, with much wetter winter and spring conditions	SMD higher in late spring to summer and considerable increase SMDA with a peak in Dec. A corresponding increase in PED60 in summer indicates increased dryness and drought risk	The increase in drought risk is in summer but recovery in winter and spring implies lower risk of “back-to-back” droughts.

Study Sites	Location	Precipitation (SPI60)	Temperature (SMD/SMDA/PED60)	Clim-NZDI
Canterbury sites: central Canterbury Pukaki Dam	(Fig. 4-13, 6-8) 170.875E 43.875S 170.147E 44.193S	Significant deficit mostly in summer and late autumn and wetter conditions in winter to mid-spring	SMD much higher in mid-spring to early autumn with SMDA peak in mid- to late summer. Anomalous conditions in Oct-Dec even for RCP2.6 in the 2090s (central Canterbury). Earlier onset of drier conditions by about one month in PED60 for central Canterbury and little change at the Pukaki Dam site	Wetter winter conditions are followed by much drier conditions in spring which results in higher drought risk in the summer which remains high until mid-winter and lower risk of “back-to-back” droughts
Southland sites: Gore	(Fig. 6-9) 168.101E 46.101S	Slight deficit only in summer and wetter conditions in most of the year	SMD is slightly higher in summer with SMDA peak in summer. Highly anomalous conditions in Nov-Dec even for RCP2.6 in the 2090s (central Canterbury).	Wetter winter conditions are followed by drier conditions in summer results in higher drought risk in the summer but lower risk of “back-to-back” droughts

Table 6-1: The details of changes in drought characteristics across sites at the North and South Island as depict in Figs. 4-7, 4-13 and 6-1 to 6-7. The drought risk progressively increases over the century for all RCPs with lowest impact in the low emission scenario RCP2.6 and the highest in RCP8.5 unless otherwise stated.

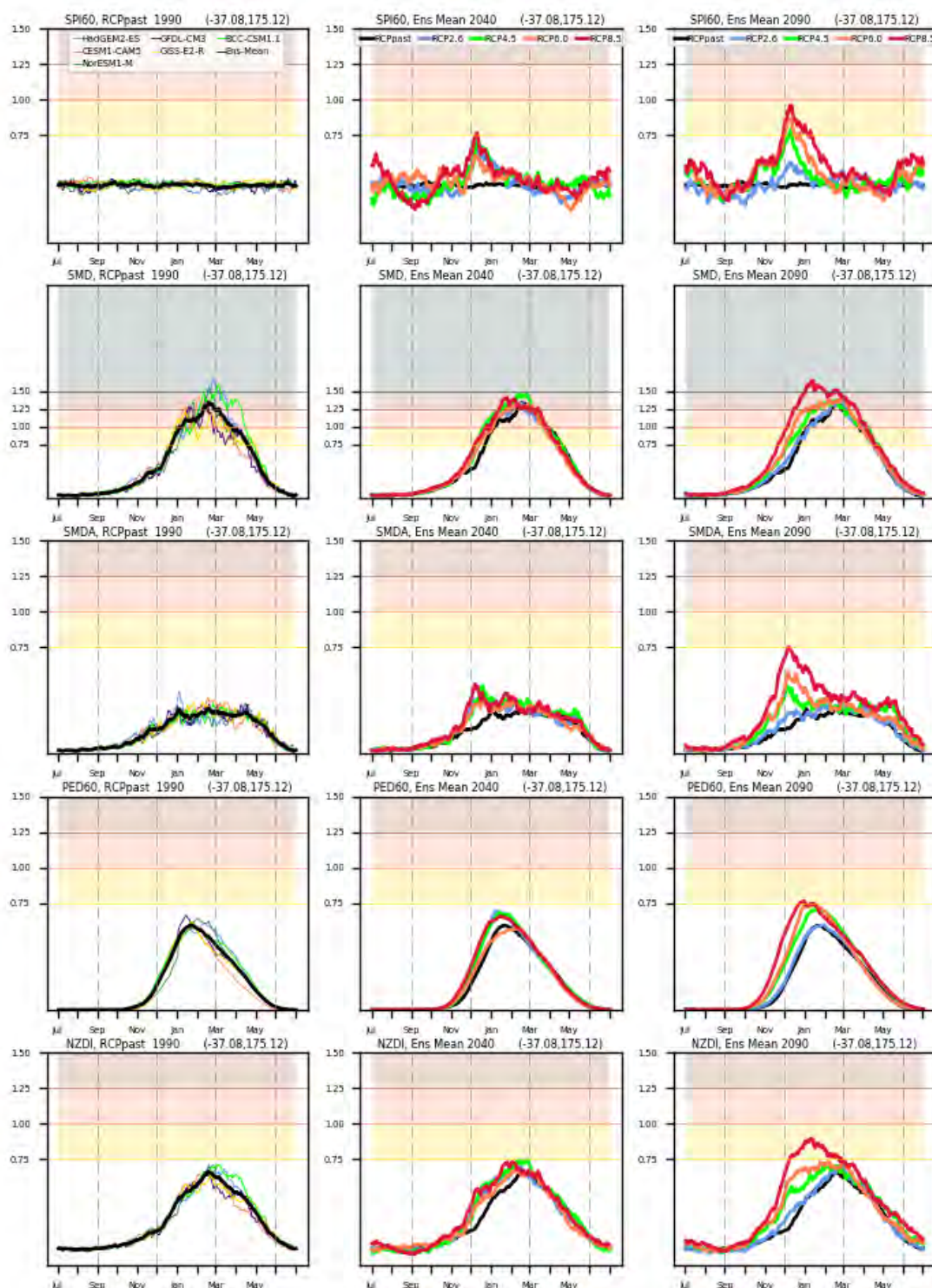


Figure 6-1: The mean annual cycle (July-June) with the drought classification (background colours) is presented for Cosseys Dam, Auckland. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black) in the left column in the historic period are compared with the ensemble mean for the four RCPs at 2040s (middle) and 2090s (right). This location experiences a drier winter, slightly wetter (or no change) spring and much drier summer (top row) which results in significant drier conditions throughout the summer already in the 2040s which intensify in 2090s relative to the historic period (left column, black) in the summer and winter seasons. The Clim-NZDI (bottom row) indicates higher risk of earlier onset in the late spring, but negative values or no change in the SPI at the beginning of the annual cycle due to increased rainfall indicate lower risk of "back-to-back" droughts.

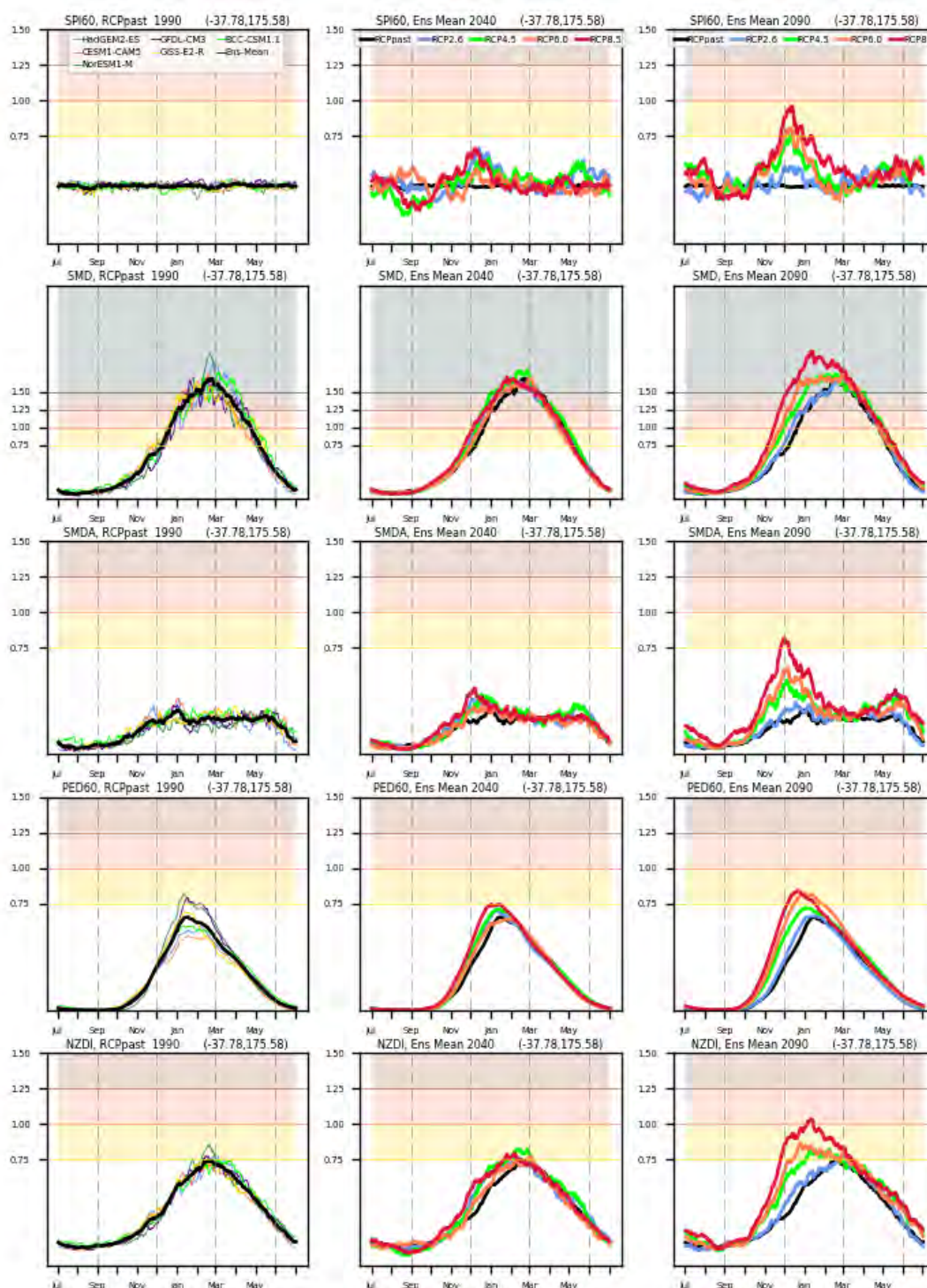


Figure 6-2: The mean annual cycle (July-June) with the drought classification (background colours) is presented for Te Miro reservoir, Waikato. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black) in the left column in the historic period are compared with the ensemble mean for the four RCPs at 2040s (middle) and 2090s (right). Despite similar change of precipitation index (top row) to the Auckland site, there is a larger increase of drought risk (bottom row) with the onset earlier in early summer in the already evident in the 2040s but intensifies in 2090s relative to the historic period (left column, black) and onset in mid spring.

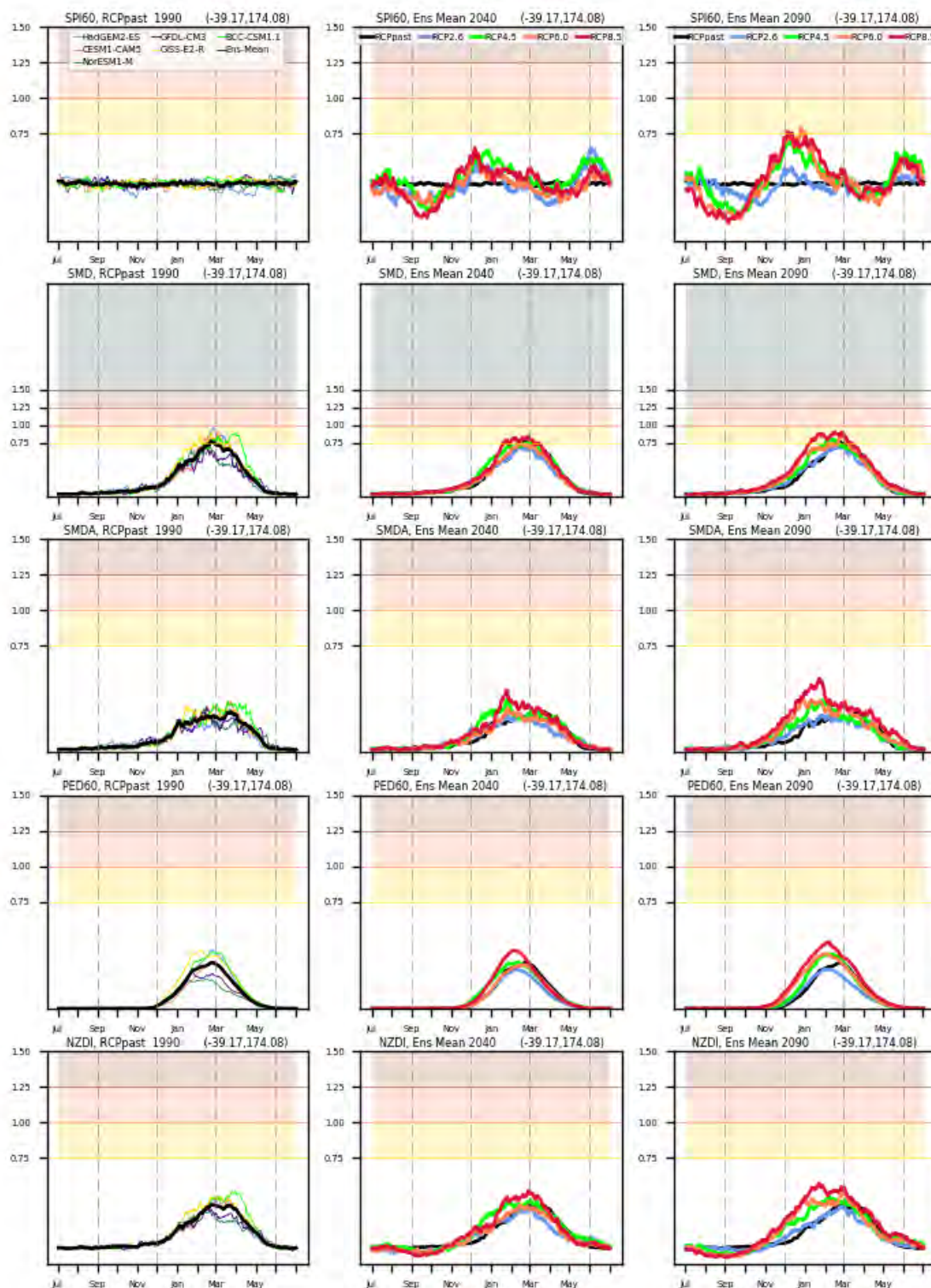


Figure 6-3: Same as Fig 6-1, but for New Plymouth, Taranaki. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black) in the left column in the historic period are compared with the ensemble mean for the four RCPs at 2040s (middle) and 2090s (right). Much wetter late winter and early spring delay but not avoid early onset and intensification of drought conditions for all emission scenarios other than RCP2.6. The risk of “back-to-back” droughts is low.

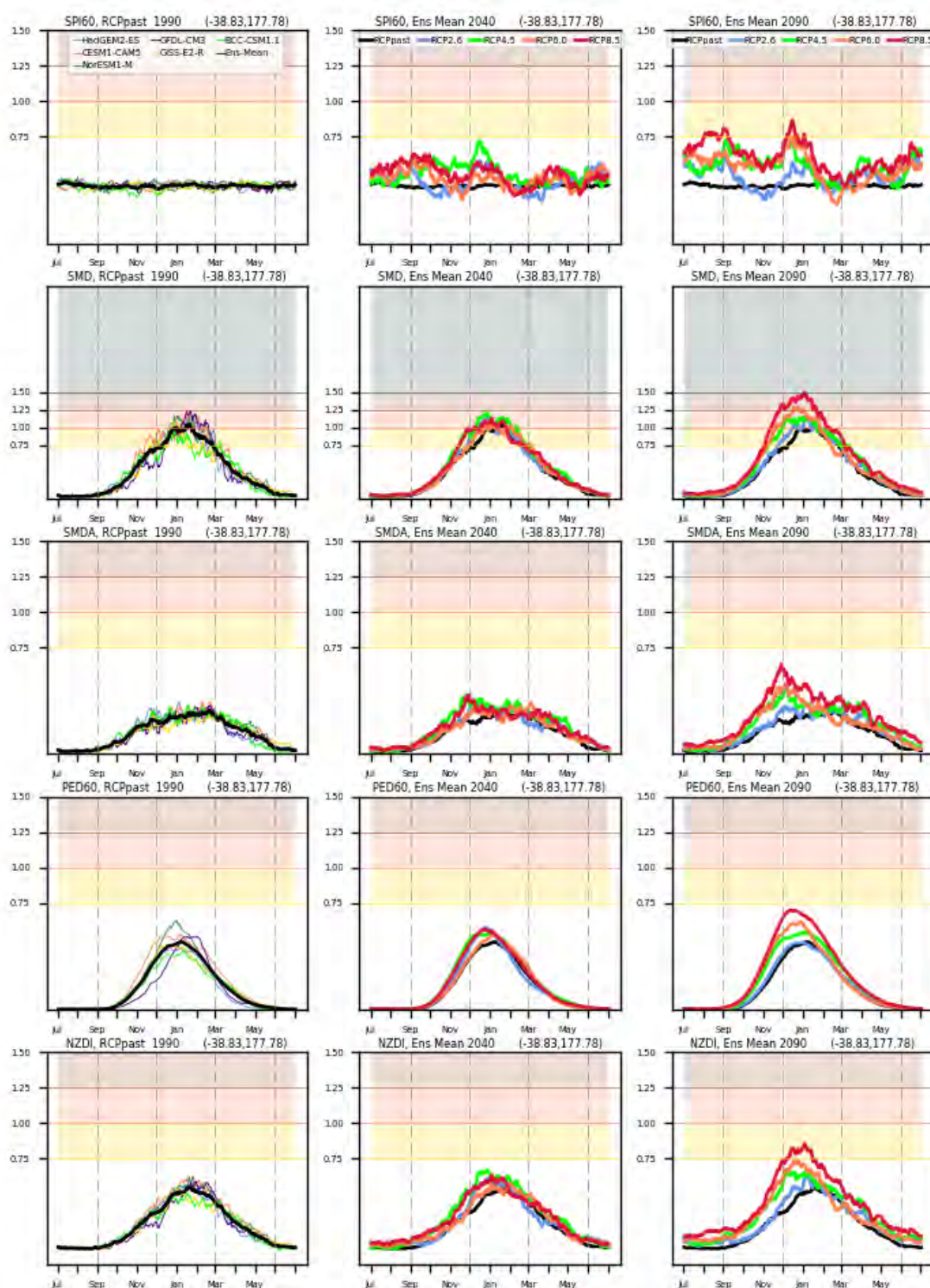


Figure 6-4: The mean annual cycle (July-June) with the drought classification (background colours) is presented for Te Arai River, Gisborne. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black) in the left column in the historic period are compared with the ensemble mean for the four RCPs at 2040s (middle) and 2090s (right). Similar to Northland locations, all seasons are drier which results in significant increase of drought risk onset earlier in mid spring to summer in the already in the 2040s but intensifies in 2090s relative to the historic period (left column, black). The Clim-NZDI (bottom panels) indicates higher risk of earlier onset and the higher values at the beginning and the end of the annual cycle pointing towards higher risk of "back-to-back" and more intense droughts

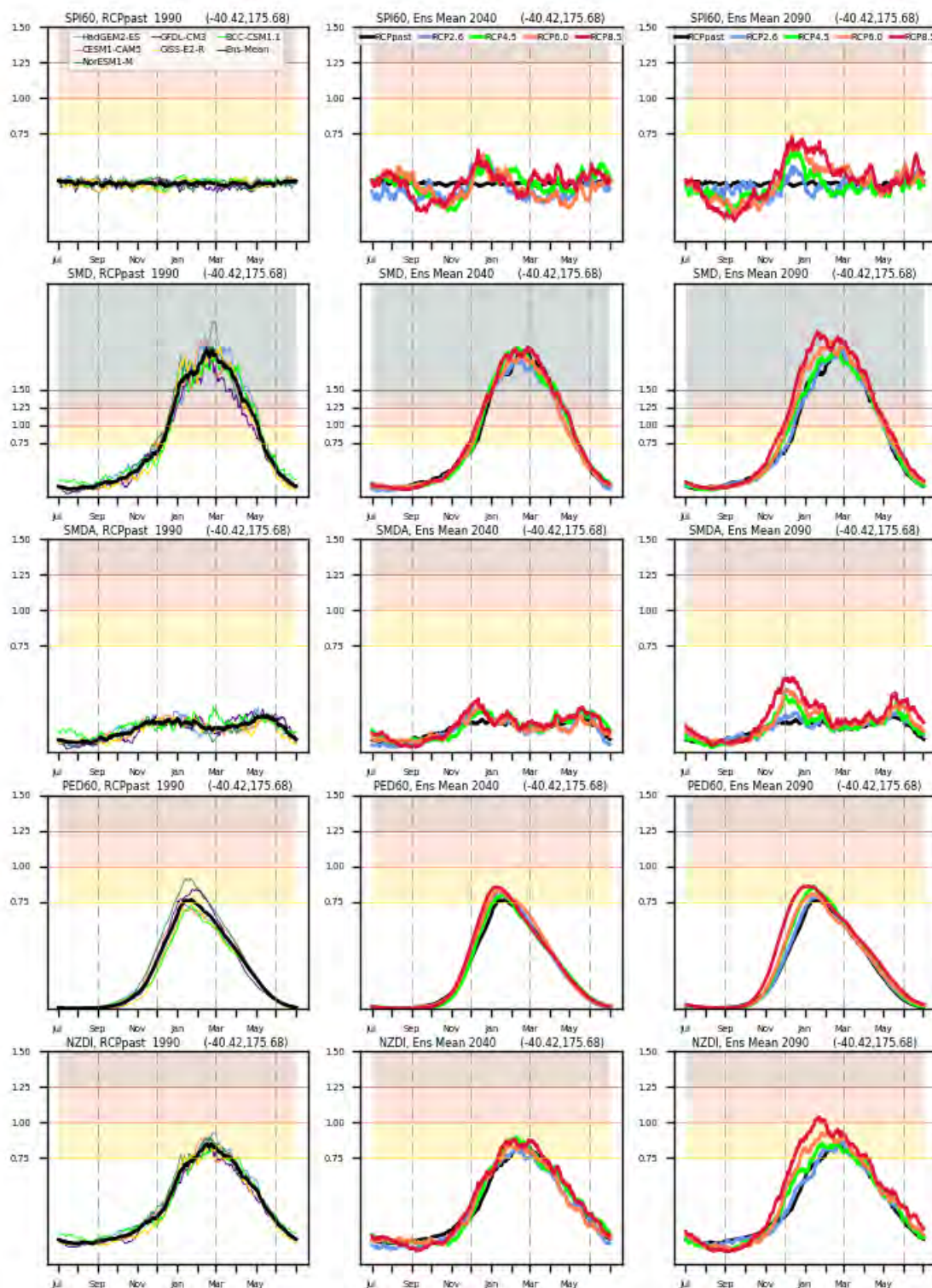


Figure 6-5: Same as Fig 6-3, but for Turitea Dam, Manawatu-Whanganui. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black) in the left column in the historic period are compared with the ensemble mean for the four RCPs at 2040s (middle) and 2090s (right). Despite wetter late winter and early spring, the drought risk onset in the 2090s is earlier in late spring and lasts longer progressively over the 21st century but “back-to-back” drought conditions are avoided.

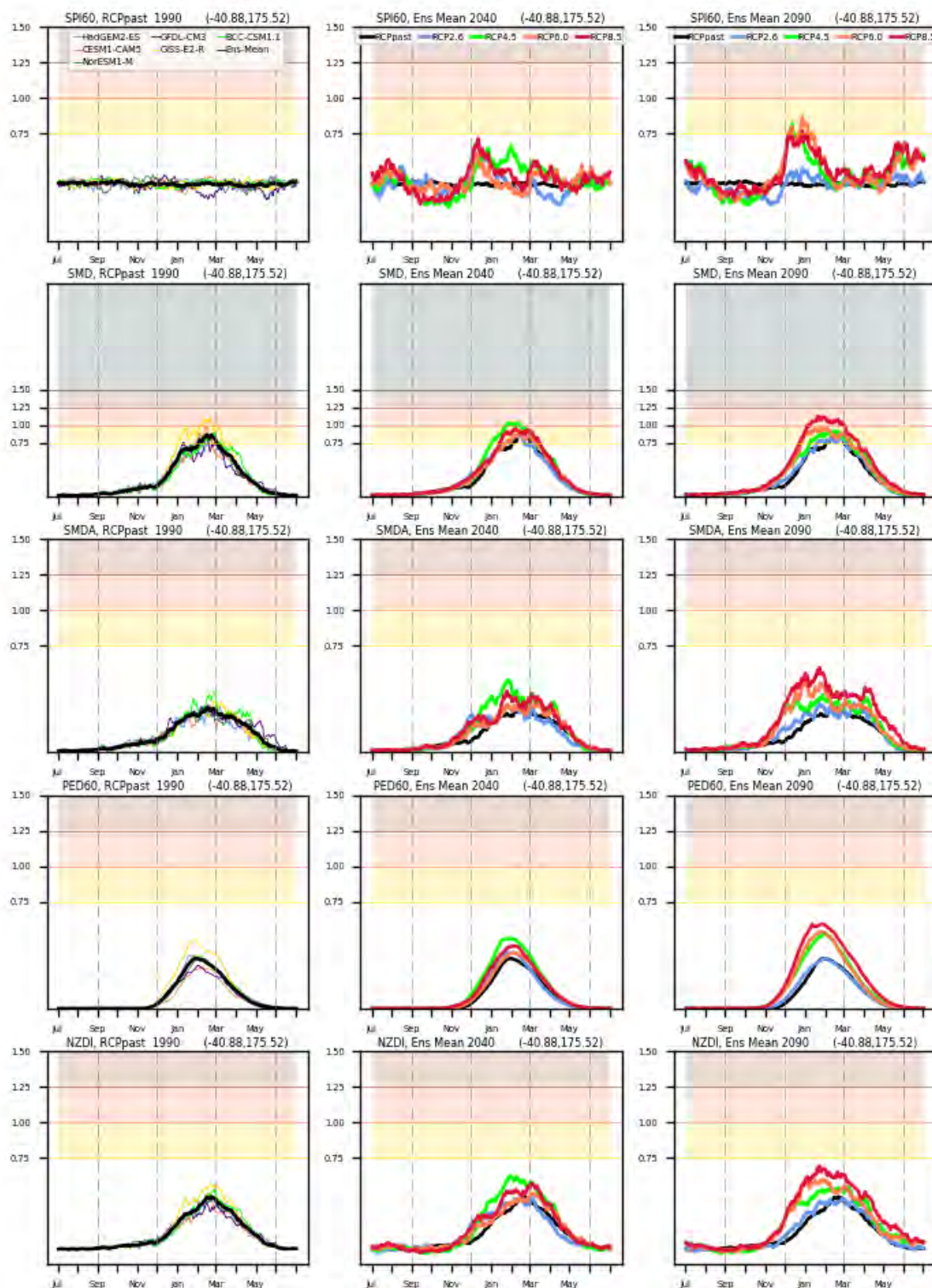


Figure 6-6: Same as Fig 6-3, but for Masterton East, Wellington. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black) in the left column in the historic period are compared with the ensemble mean for the four RCPs at 2040s (middle) and 2090s (right). Somewhat drier winter and wetter spring conditions does not hinder earlier onset of drought conditions. The summer drought is longer and more intense especially for RCP8.5 emission scenario but little change is experienced under RC2.6 conditions.

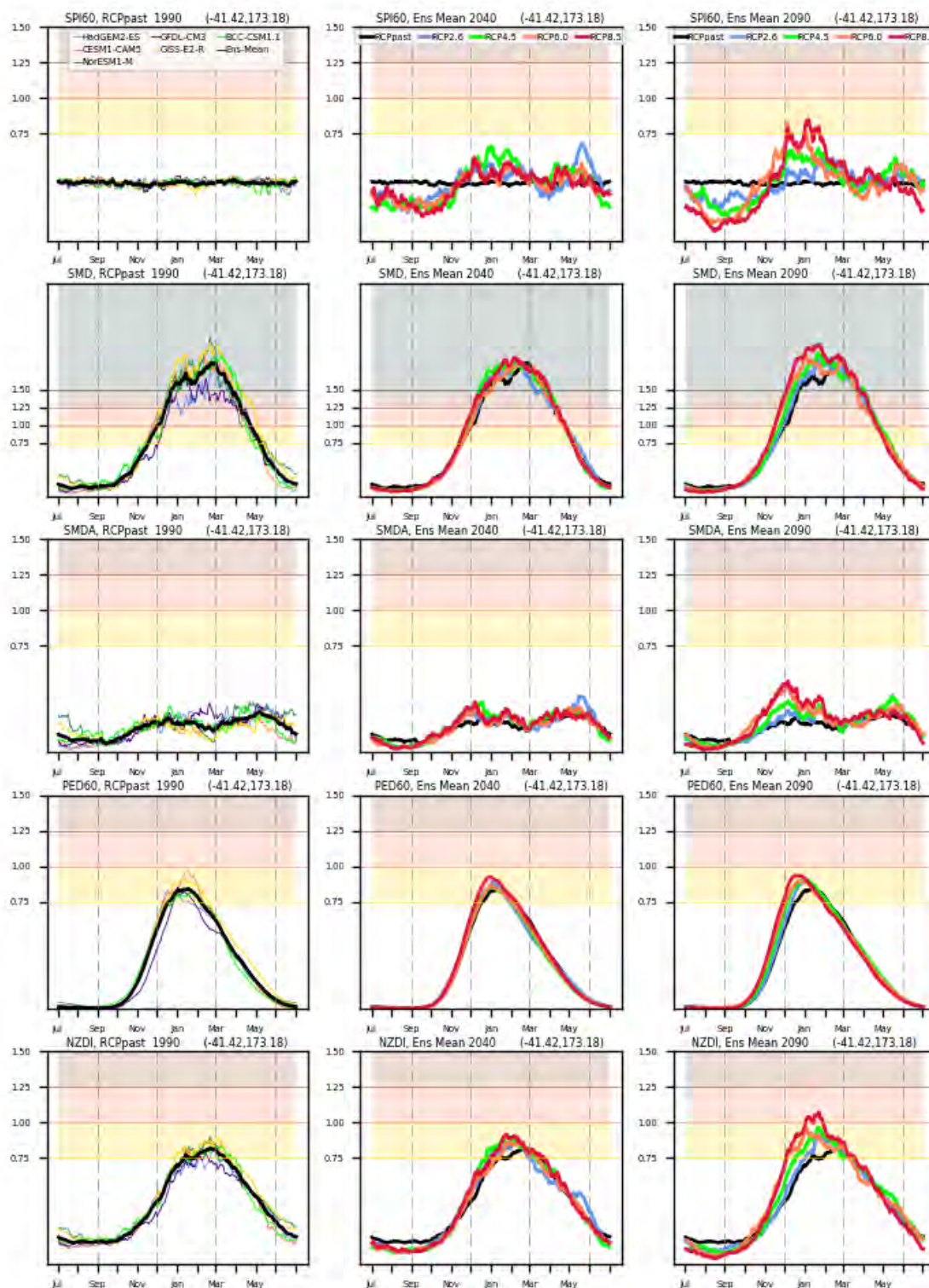


Figure 6-7: Same as Fig. 4-13, for Lee River, Tasman. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black) in the left column in the historic period are compared with the ensemble mean for the four RCPs at 2040s (middle) and 2090s (right). This location experiences much wetter winter and spring and much drier summer (top row) which results in little change of drought risk in the 2040s but significant increase in 2090s relative to the historic period (left-bottom column, black). The Clim-NZDI (bottom panels) indicates higher risk of earlier onset and a more intense drought. increased rainfall in the winter result in lower risk of "back-to-back" droughts.

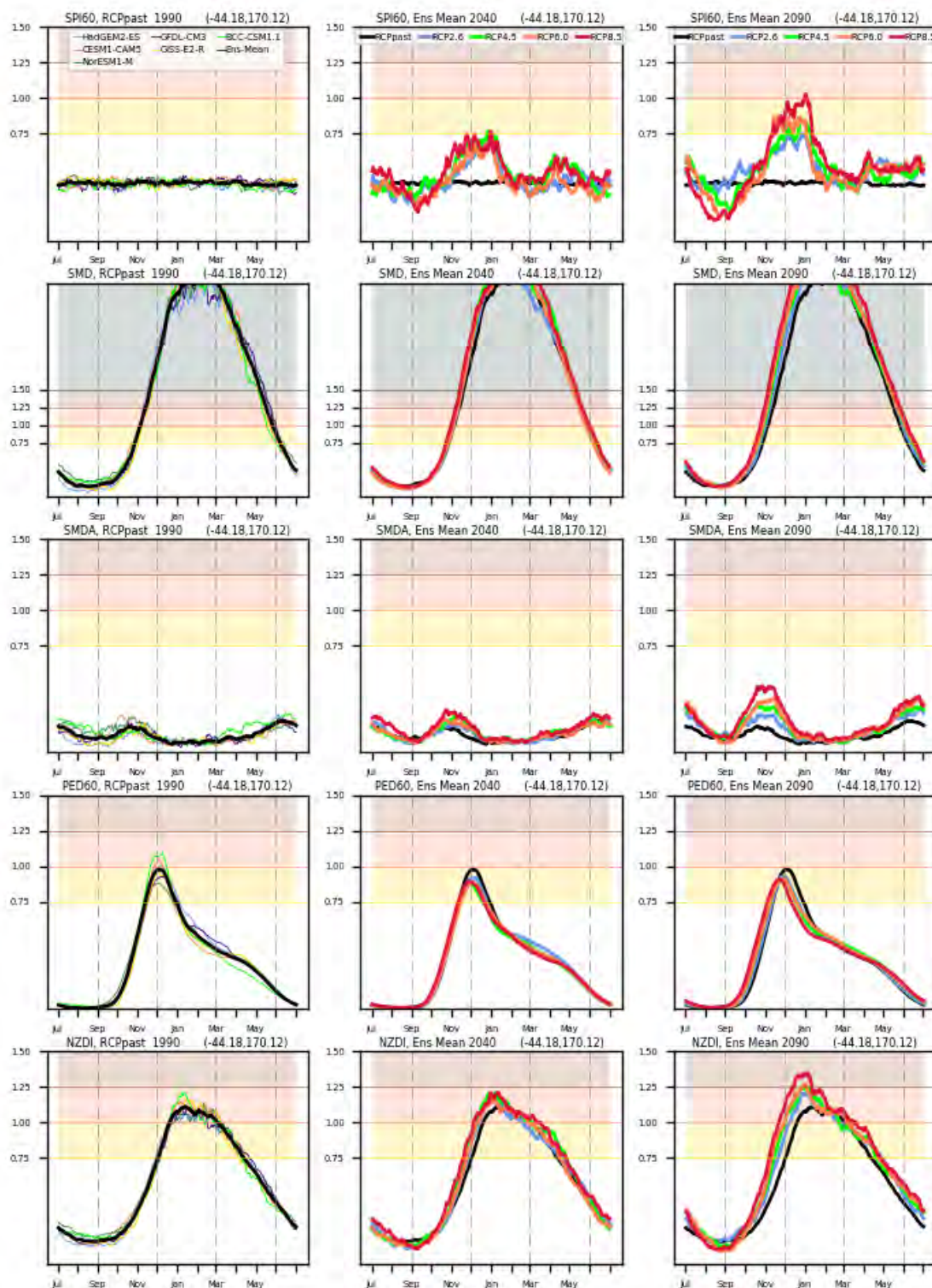


Figure 6-8: Same as Fig 4-17, but for Pukaki Dam, Canterbury. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black) in the left column in the historic period are compared with the ensemble mean for the four RCPs at 2040s (middle) and 2090s (right). This location experiences a similar but more intense signal of change than at the central Canterbury site (Fig. 4-17), with earlier, longer and more intense drought.

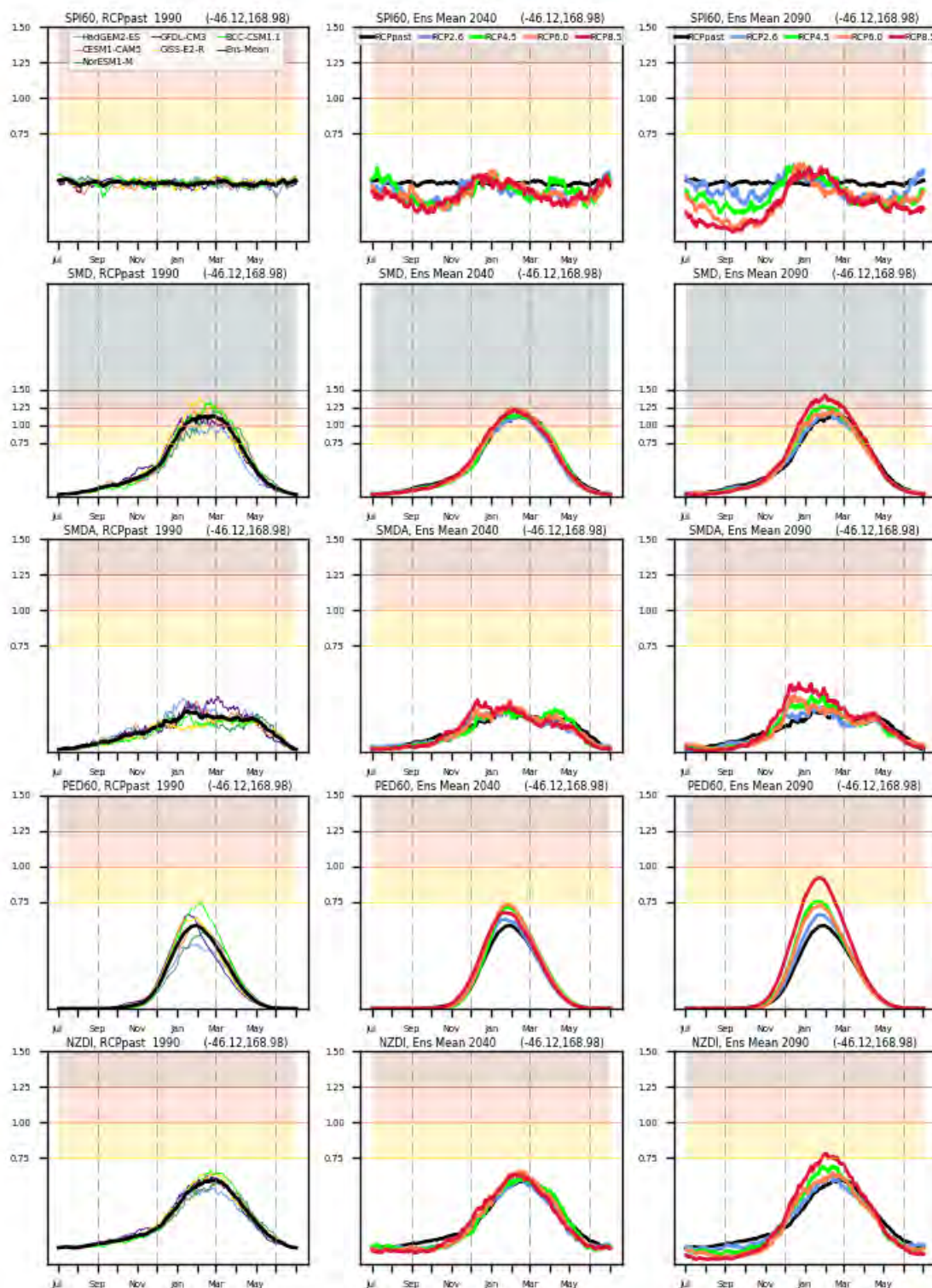


Figure 6-9: Same as Fig 6-1, but for Gore, Southland. The 20-year mean annual cycle for the six models (coloured, thin) and their ensemble mean (black) in the left column in the historic period are compared with the ensemble mean for the four RCPs at 2040s (middle) and 2090s (right). This location experiences wetter conditions in all seasons other than in the summer (top row) with slightly longer and more intense drought periods.

7 Discussion

These new drought estimates bring into sharp focus the need to assess the vulnerability and sustainable management of New Zealand's drinking water resources, as this will be a key drought management tool in the future. Resilience-based research focussing on adaptation is a much broader undertaking than the climate-focussed work undertaken here. Nevertheless, efforts in this study to estimate nationwide spatial patterns of expected change in drought incidence, duration and their spatial cover, sometimes impacting multiple regions simultaneously, improve understanding of drought within this broader framework and are required to support the planning effort.

Increasing capability of the climate models to simulate important properties of meteorological and agricultural droughts for the past period with historic climate forcings (greenhouse gases, ozone, solar and others), has led to increased confidence in using the same models to determine drought projections for the future period.

Development and application of the appropriate drought indices is a key requirement for developing regionally optimized "best" drought monitoring practice. Several different indices have been widely used in drought monitoring at global and regional scales. The NZDI is designed for New Zealand stakeholders' requirements to support a diverse range of applications [Mol et al., 2017]. The projections of the related Clim-NZDI, derived on a daily scale using NZ-CMIP5 data, helps us to more comprehensively identify and characterise past and future drought-prone regions in New Zealand. Additionally, the changes in the four constituent DIs and Clim-NZDI enables us to anticipate the cause and scope of future droughts and help estimate bottlenecks in water resource availability for drinking water or irrigation compared with past (baseline) conditions. The changes in regional and seasonal precipitation (SPI60), and increasing temperatures impacting PET all year around and nationwide, are the main drivers of changes in regional drought characteristics. Since all DIs calculated in this study are on a daily scale, it is possible to more accurately identify the onset and evolution of droughts in a more direct and explicit way. Nevertheless, the limitations and simplification in this analysis affect the broader application of these results. Some of the major current concerns are:

- Using a single soil type and vegetation type (short grass) in the simple single-layer soil model limits the reliability of the application to typical pasture sites and relatively homogeneous land use. [Porteous et al., 1994].
- The limited number (six) of simulations available for the four emission scenarios allows us to get a coarse estimate of variability, but not a more accurate probabilistic estimate. However, considering the uncertainty due to model error and model simplifications, more comprehensive probabilistic estimates at this stage without increasing confidence in the individual drought estimates may be premature.
- Verification, evaluation and further optimization of DIs and Clim-NZDI based on historic observed data and drought classification is required to achieve more confidence in the drought estimates.

Some of these concerns will be addressed in ongoing MPI (Ministry of Primary Industries) and MBIE projects in order to further increase confidence in the derived and optimized products. It is also of concern that the climate warming signal in the latest CMIP6 models is, in general, significantly larger than in the current assessment using CMIP5 models [Zelinka et al., 2019]. With temperature being a major driver for New Zealand droughts (Table 7-1), the impact on the future drought estimates using these new data is anticipated to be considerable.

8 Acknowledgements

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9 Glossary of abbreviations and terms

RCP	Representative Concentration Pathways: A concentration scenario identified by its approximate total radiative forcing at 2100 relative to 1750.
IPCC-AR5	5th Assessment (AR5) report for the Intergovernmental Panel on Climate Change (IPCC) (see http://cmip-cmdi.llnl.gov/cmip5/)
CMIP5	Coupled Model Intercomparison Project Phase 5 (CMIP5) climate data repository
GCM	Generalized Circulation Model of the climate system. The coupled GCM includes atmosphere, ocean and sea ice components and land surface component provides surface boundary conditions (temperature, wind, moisture) to the overlying atmosphere.
RCM	Regional Climate Model is the limited area version (here over New Zealand) of the atmospheric only GCM.
NZ-CMIP5	CMIP5 climate projections dynamically downscaled for New Zealand using RCM (HadRM3) and subsequently bias-corrected and semi-empirically downscaled to 5km grid for climate impact studies
ESM	Earth System Models include biogeochemistry of the oceans and atmospheric components in coupled GCM
PET	Potential evapotranspiration
NZDI	New Zealand Drought Index
Clim-NZDI	Climate New Zealand Drought Index
SPI	Standardized Precipitation Index
PED	Potential Evapotranspiration Deficit
SMDA	Soil Moisture Deficit Anomaly
SMD	Soil Moisture Deficit

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