The Bureau of Meteorology

A comparison of CMIP3 and CMIP5 climate projections across Western Australia

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Executive summary

The impacts of a changing climate on hydrological responses and subsequent water availability are evident in many catchments throughout Australia. Climate projections provide insights into a range of plausible futures as to how climate characteristics will change across the continent (CSIRO and Bureau of Meteorology 2015); (Wilson et al. 2022); Queensland (Skytus et al. 2020) – Long Paddock), New South Wales (DPIE 2020) - Narclim), Victoria (DELWP 2020 - VCP19), Tasmania (Corney et al. 2010) - Climate Futures), South Australia (DEW 2022), and Western Australia (WA:(Department of Water 2015 - DoW (2015)). Projections of changes in hydrological variables have also been produced, based upon the climate projections (DELWP 2020; Srikanthan et al. 2022; Turner et al. 2022; Wilson et al. 2022).

In 2015, Western Australia's then Department of Water published guidelines for assessing climate change impacts in five regions across the state (DoW 2015). Based on 12 Coupled Model Intercomparison Project Phase 3 (CMIP3) global climate models (GCMs) and a pattern scaling approach, the guidelines provided dry, medium and wet scenarios (based on 10th, 50th and 90th percentiles of change in regional mean annual precipitation). The scenarios guided assessment of the impacts of future climate change on groundwater and surface water availability. Recent updates to GCMs and advances in regional climate modelling, bias correction and water balance models have provided an opportunity for the 2015 guidelines to be updated and broadened in their scope. The Australian National Hydrological Projections (NHP), based on four CMIP Phase 5 GCMs, provide climate and hydrological projections from 2006 to 2099 across Australia (Srikanthan et al. 2022; Wilson et al. 2022). Regional assessments for northern, central and south-western Western Australia were conducted: respectively Srikanthan et al. (2022), Oke et al. (2022) and Turner et al. (2022). Currently the NHP provides a 16-member ensemble based on the four GCMs – with three different bias correction methods and one dynamical downscaling model – for two representative greenhouse gas emission scenarios. This results in 32 projections. Understanding the differences or similarities in precipitation changes projected by DoW (2015) and NHP has supported the Department of Water and Environmental Regulation to update the guidelines for Western Australia (DWER 2024). These guidelines will help water managers to ascertain when, or if, they need to update their water-resource risk assessments for long-term water planning throughout the state.

This study compares precipitation changes projected for 2050 in four regions of Western Australia by the NHP (Srikanthan et al. 2022) and DoW (2015). The GCMs (16 ensemble members) project a spread of drier (e.g. GFDL-ESM2M) and wetter futures (e.g. CNRM-CM5) across Western Australia. A storyline approach (Shepherd et al. 2018; Narsey et al. 2023) is used to select four NHP ensemble members in each region that represent a range of hydroclimate changes that have become evident in recent years, such as reductions in cool season precipitation in south-western Western Australia or increases in precipitation variability in the north. The storylines narrative enables a range of plausible climate projections to be compared and is recommended to assess the impacts of climate change on water resource management across the state (Schopf et al., 2023).

See Section 7 for a comparison of the NHP and DoW (2015). This study's key findings at the regional scale are:

1. Seasonality of monthly precipitation peaks is consistent between the NHP and DoW (2015) in all four regions. However, the NHP projects lower peak monthly precipitation in the South West region between May and October, and higher peak monthly precipitation in the Kimberley and Central West regions between November and March. In the Pilbara region, all projections represent the monthly precipitation climatology, although peak precipitation varies between ensemble members of the NHPs.

2. For all regions larger cool season precipitation reductions are projected by the NHPs compared with DoW (2015). In the Pilbara and Kimberley, an increase in cool season precipitation for a small group of projections highlights the need to investigate the range of seasonal changes and how they may differ at specific locations.

3. Very large increases and decreases in wet/warm season precipitation are projected by NHP ensemble members across Western Australia. Considerably larger than the spread of DoW (2015) projections, the spread of plausible futures under the NHP reflects uncertainty in the ability of models to simulate tropical processes that influence summer precipitation in north Western Australia. For regions outside the South West, historical inter-annual and decadal precipitation variability exceeds the climate trend of the wet, median and dry scenarios in DoW (2015), and thus long-term precipitation records are more appropriate to use in those regions. NHP allows the range of plausible futures to be explored across all regions of the state.

4. NHP project larger precipitation peaks and troughs. The pattern-scaling approach used in DoW (2015) does not show differences in annual precipitation variability between the dry, median and wet scenarios as they simply use scaled observed variability. Large increases in warm season (November–April) variability are evident in the South West, although the warm season has low precipitation. Cool season (May–October) precipitation variability is projected to increase in the Kimberley region. In the Pilbara region, all NHP ensemble members project change in the variability of cool and warm season precipitation variability, although the direction and degree of change in not consistent between ensemble members.

5. Aridity index, meteorological, hydrological and agricultural drought indicators show the impact of projected precipitation changes on runoff and soil moisture in each region. For example, aridity (total annual precipitation divided by total annual potential evapotranspiration (PET)), is projected to increase in the South West and Central West regions. Drought duration (average number of months) is highest in the South West, both in magnitude and spread across ensemble members. The spread of projected change in drought intensity indicators varies between each region but is greatest in the South West for each of the ensemble members. Considering aridity and drought indicators across a region will help water resource planners to choose a subset of projections to undertake further investigations of hydrological and catchment processes.

DWER has released an updated guide to climate change projections for water resource management in Western Australia (DWER 2024). The guide provides a practical framework for water resource planners and decision-makers to use climate change projections in climate impact and risk assessments for water resources planning and decision-making in Western Australia. This is a scalable, practical, risk-based framework that guides how decision-makers in the water sector might choose climate projection datasets for water modelling and planning at the local scale. The guide recommends practitioners refer to this consistency assessment, as well as to similar assessments for the location of interest, before re-doing any climate assessments underpinned by DoW (2015) projections. Practitioners should consider whether previous water resource decisions may change based on the NHP and whether they need to be updated or not.

Another recommendation is for current practice to move away from using wet, median and dry scenarios, as outlined in DoW (2015), towards a ‘storyline approach’ that allows a risk-based assessment to investigate the range of plausible future projections with a subset of projections for detailed analysis. The results of this assessment show that when practitioners are choosing projections to represent plausible futures within a region, they should investigate the differences that may be evident in the climate characteristics that drive the water resource system. For example, annual totals, cool and warm season precipitation patterns, annual precipitation variability and changes in the aridity index within and between regions.

1. Introduction

1.1. Background

Many parts of Australia are experiencing a changing climate. Across Western Australia seasonal precipitation reductions, altered interannual variability and a continual decline in rainfall since the 1970s is impacting hydrological processes and subsequent water resource availability (Oke et al. 2022; Srikanthan et al. 2022; Turner et al. 2022). If greenhouse gases and global temperatures continue to increase hydroclimate characteristics will continue to change. Climate and hydrological projections provide a range of plausible futures to aid the assessment of potential risks of a changing climate and what planning is required to manage impacts to water availability, such as declines in water security and ecosystem health and increases in extremes such as droughts and floods.

Various research bodies and jurisdictions across Australia have been developing projection ensembles; as such, multiple sources of information have become available for elucidating the impact of climate change on water resources within a region (Wilson et al. 2022; Skytus et al. 2020; DPIE 2020; DELWP 2020; Corney et al. 2010). Understanding the differences among the projection ensembles aids interpretation of the range and uncertainty of the projected plausible futures. This allows for increased certainty around understanding the impact of projected climate change on water resource availability and management decisions. For instance, CSIRO & Bureau of Meteorology (2015) identified eight global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive (Taylor et al. 2012) that could represent key aspects of Australian climate characteristics. These included historical climate characteristics (ACCESS1-0), wet/dry extremes (El Niño/La Nina) (CNRM-CM5), hotter and drier regions (GFDL-ESM2M) and wetter conditions (MIROC5) (Table 1). As a result of the understanding of which models best represent Australia's climate drivers, global climate model (GCM) selection is replicated between some projection ensembles (e.g. CSIRO & Bureau of Meteorology 2015, DELWP 2020). However, there are additional GCMs unique to each ensemble that result in a greater number of plausible futures projected for regions across Australia. These include HadGEM2-CC and NorESM1-M (VCP19, CCiA, The long paddock (www.longpaddock.qld.gov.au/qld-future-climate/))), CanESM2 (The Long Paddock, CCiA, Narclim) and MPI-ESM-LR (The Long Paddock).

Table 1: Selected global climate models used in National Hydrological Projections (Srikanthan et al. 2022)

Climate model	Type	Institute	Country of origin	Reference
ACCESS1-0	Global	CSIRO & Bureau of Meteorology	Australia	(Collier & Uhe 2012)
CNRM-CM5	Global	Centre National de Recherches Météorologiques – Groupe d'études de l'Atmosphère Météorologique (CNRM-GAME) and Centre Européen de Recherche et de Formation Avancée	France	(Voldoire et al. 2013)
GFDL-ESM2M	Global	Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration (NOAA)	United States	(Dunne et al. 2012)
MIROC5	Global	Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	Japan	(Watanabe et al. 2010)
CCAM r3355	Regional	CSIRO	Australia	(Rafter et al. 2019)

The National Hydrological Projections (NHP) for Australia provide projected climate and hydrological variables from 1960 to 2099 across Australia (Srikanthan et al. 2022). Based on CMIP5 GCMs, the projections are underpinned by a nationally consistent ensemble derived from four GCMs (ACCESS1-0, CRNM-CM5, GFDL-ESM2M, MIROC5), a regional climate model (CCAM-r3355) and three bias correction methods (QME, ISIMIP2b and MRNBC) (Srikanthan et al. 2022) (Table 1). Climate projections are used to derive soil moisture, runoff, and potential as well as actual evapotranspiration projections, using the Australian Water Resources Assessment Landscape hydrological model (AWRA-L) (Frost et al. 2018). The GCMs included in the NHP modelling framework were chosen for their ability to represent key climate drivers around Australia (Wilson et al. 2022; Vogel et al. 2023). It includes a range of very wet to very dry plausible futures using a subset of the Climate Change in Australia projections suite (Srikanthan et al. 2021; CSIRO & Bureau of Meteorology 2015). This study uses the NHP, developed by the Bureau of Meteorology, to investigate projected changes in precipitation throughout Western Australia (Srikanthan et al. 2022; Turner et al. 2022).

Western Australia's Department of Water and Environmental Regulation (DWER) has used the NHP to update its climate change projection modelling and assessment processes. In 2015, DWER's predecessor, the Department of Water (DoW), published guidelines for assessing climate change impacts in five regions across the state (DoW

2015). Based on CMIP3 projections, this tool used a pattern-scaling approach to project dry, median and wet futures (based on 10th, 50th and 90th percentiles of change in regional mean annual precipitation) (Solomon et al. 2007). Using a change anomaly, the pattern-scaling approach does not allow for differences in temporal variability between scenarios. The understanding and application of the science that represents key climate drivers improves with every new GCM generation. Temperature and precipitation changes per degree of warming are comparable between CMIP3 and CMIP5 projections (CSIRO & Bureau of Meteorology 2015). However, it is the local-scale climate drivers and how they are represented in GCMs that cause variability between different generations of projection ensembles, resulting in local-scale differences between projections, such as for precipitation extremes (CSIRO & Bureau of Meteorology 2015; Moise et al. 2015; Hope et al. 2015).

This study compares the DoW (2015) CMIP3 projections to those of the NHP in four regions of Western Australia. It explores the impacts on regional hydrological processes including aridity (calculated as total annual precipitation divided by total annual potential evapotranspiration) and drought (duration, frequency and intensity of precipitation, runoff and soil moisture conditions). This comparison supports DWER to use the NHP in groundwater and surface water modelling to assess the impact of climate change on water supply availability and reliability throughout Western Australia.

1.2. Scope and structure

This study investigates the projected impact of climate change on the climate and hydrological features of the Kimberley, Pilbara, Central West and South West regions of Western Australia. The methods for this study are outlined in sections 5 and 6. In brief, the scope of this study includes:

1. The change in seasonal precipitation projected by the NHP in each region as outlined in Section 4.
2. A comparison of the NHP to previous projections DoW (2015), undertaken in two parts:

    a. Scaling anomalies derived for DoW (2015) are used to compare monthly climatology projected by the NHP and DoW (2015) projections (Section 5).

    b. A storyline approach is used to identify and select four ensemble members that represent the spread of plausible 2050 futures in each region. The four ensemble members are than used to compare the projected change in annual and seasonal precipitation (total and variability) by the NHP and DoW (2015) (Section 7).
3. Finally, hydrological projections are used to investigate aridity and drought conditions within the Pilbara, Kimberley, Central West and South West (Section 8).

2. Observed climate and hydrological trends in the South West, Central West, Pilbara and Kimberley

DoW (2015) used a seasonal precipitation classification to define four regions based on distinct climate zones throughout Western Australia. This comparison of the NHP and DoW (2015) projections uses the same four regions, namely:

- The **South West**, including Perth, Geraldton, Esperance and the Wheatbelt, which extends inland to Kalgoorlie and north to Shark Bay. This region has winter-dominant precipitation (marked wet winter and dry summer), with some summer precipitation in the eastern portion.
- The **Central West**, which extends north from the South West region to Coral Bay and inland to Mount Magnet. This region is classified as arid (low precipitation).
- The **Pilbara**, which extends from Exmouth to around 300 km east of Port Hedland and inland to Newman. This region is classified as arid. Summer precipitation contributes most to the annual total though rain may also fall in winter.
- The **Kimberley**, which extends from south of Broome to the state border with the Northern Territory. Summer precipitation is dominant (marked wet summer and dry winter) because of monsoonal weather systems.

Throughout these regions, this assessment uses six sites for comparison: Perth Airport, Morowa and Scaddan (South West), Gascoyne Junction (Central West), Marble Bar (Pilbara) and Fitzroy Crossing (Kimberley).

Precipitation in the South West has declined by 20% since 1970 and by 28% between 2000 and 2020 (CSIRO & Bureau of Meteorology 2020; Hope et al. 2006). Interannual variability in cool season rainfall peaks decreased after the 1960s, with very wet years becoming less frequent (Rauniyer et al. 2023). Another decline, or step change, in rainfall was evident in the 1990s (Rauniyer et al. 2023). There are now fewer days of rain and the intensity and frequency of extreme precipitation events has decreased (Gallant et al. 2007). The average annual temperature has increased by 1.1°C in the South West between 1910 and 2013 (Hope et al. 2015a; Moise et al. 2015). This warming has seen an increase in the frequency of extreme heat events (Alexander et al. 2007). The trend of the past 50 years toward a drier and hotter climate is reflected in the lower average annual runoff since the 1970s (Turner et al. 2022). Reduced runoff generation caused by decreasing rainfall since 1975 – and the associated decline in streamflow – has been widely reported (Fu et al. 2007; Bates et al. 2010; Petrone et al. 2010; Silberstein et al. 2012; CSIRO & Bureau of Meteorology 2015; Zhang et al. 2016; Wasko et al. 2021). Reductions in runoff will also be influenced by changes in catchment characteristics (such as vegetation cover and soil properties), prolonged warmer temperatures, increased evapotranspiration, as well as reduced soil moisture groundwater replenishment – all of which support a disproportional decline in runoff.

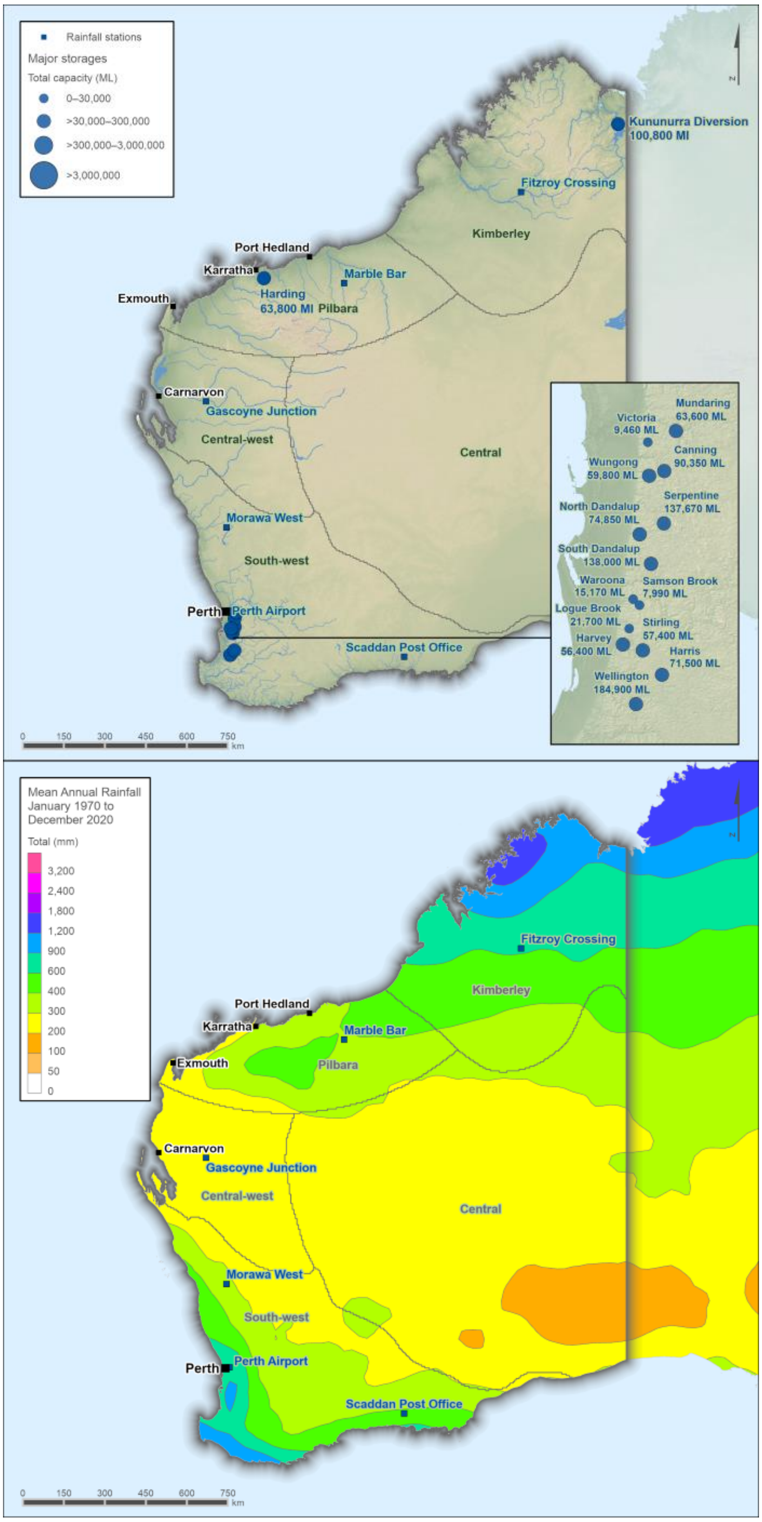


Figure 1: Western Australia regions defined by DoW (2015) (top) and mean annual precipitation 1970 to 2020 (bottom).

Precipitation in the Central West is influenced by winter fronts as well as tropical processes in the summer, including tropical cyclones. The Central West and Pilbara fall within the Rangelands NHP assessment region, with similarities in their recent trends. There is high year-to-year and interdecadal variability in the Rangelands region, particularly since the 1970s (Oke et al. 2022). There has been a shift towards wetter years from the 1970s, resulting in a corresponding increase in runoff and soil moisture. Precipitation in the Rangelands has increased (43%) between 1911 and 2020 (Oke et al. 2022), which has seen a large increase in runoff throughout the region. Potential evapotranspiration has become more variable since the 1970s. Precipitation increases are most notable in the Pilbara during the northern wet season (November–April) (Oke et al. 2022).

Climate trends in the Kimberley are influenced by monsoonal weather systems. Trends are reflected in those found in the larger Monsoonal North NHP assessment region. In recent decades, the Monsoonal North region has seen above-average precipitation and runoff (Srikanthan et al. 2022). The Monsoonal North receives most of its precipitation during the summer monsoonal wet season (December–April). This is reflected in highly seasonal runoff patterns, with 95% of annual runoff occurring during the wet season. Increases in precipitation are associated with increased early monsoonal precipitation intensity and a possible extension of the wet season. However, year-to-year precipitation is highly variable in this region. For example, in 2018–19, north-western Australia had a delayed start to the monsoon, which was the driest wet season in the Northern Territory since 1992–93, and total precipitation was 34% below the long-term average.

During the dry season (May–October) in the Monsoonal North, low precipitation combines with high evapotranspiration and leads to the region’s soil becoming very dry (Srikanthan et al. 2022). Over much of the Monsoonal North region, potential evapotranspiration exceeds 2,000 mm/year and it can approach 360 mm/year during the wet season (Srikanthan et al. 2022). High precipitation is reflected in high runoff in the region. However, large precipitation variability and high evapotranspiration rates in this region can limit runoff into rivers and storages at times (Srikanthan et al. 2022).

3. Climate and hydrological projections modelling

3.1. The Australian National Hydrological Projections

The modelling framework for the NHP is shown in Figure 2. The chosen CMIP5 climate models are a subset of the models used in the Climate Change in Australia (CCiA) assessment (see Chapter 5 in CSIRO & Bureau of Meteorology 2015). ACCESS1-0, CRNM-CM5, GFDL-ESM2M and MIROC5 model key climate drivers around Australia, such as El Niño Southern Oscillation (ENSO), the Southern Annular Mode (SAM) and monsoonal precipitation patterns (CSIRO & Bureau of Meteorology 2015), quantifying a range of plausible very wet and very dry futures. The four GCMs provide all the necessary climate inputs for the AWRA-L (version 6.1) (Frost & Wright 2018). A dynamical downscaling climate model (CCAM-r3355) was used to bring each of the four selected GCMs to a finer resolution output of about 50 km^2 over Australia. Termed a regional climate model (RCM) for ease of discussion, it accounts for regional climatic influences, such as local topography.

Climate outputs from the GCMs and RCM were re-gridded to a 5 km scale before being bias corrected. After the re-gridding process, three bias correction methods were applied to modelled climate data to correct biases in the GCMs and RCM forcing against observations. The 16-member ensemble per selected representative concentration pathway (RCP) includes: 12 ensemble members comprising each of the four GCMs corrected with three different bias-correction methods and four ensemble members comprising each of the four GCMs, downscaled and adjusted to a finer resolution as an RCM and corrected with one bias-correction method (Figure 2). The 16-member ensemble provides a spread of plausible futures, from very dry to very wet, which varies depending on the location in Australia (discussed further in Section 4). ACCESS1-0 and GFDL-ESM2M generally show a drying signal, whereas CNRM-CM5 and MIROC5 show increased precipitation (Peter et al. in prep; Turner et al. 2022).

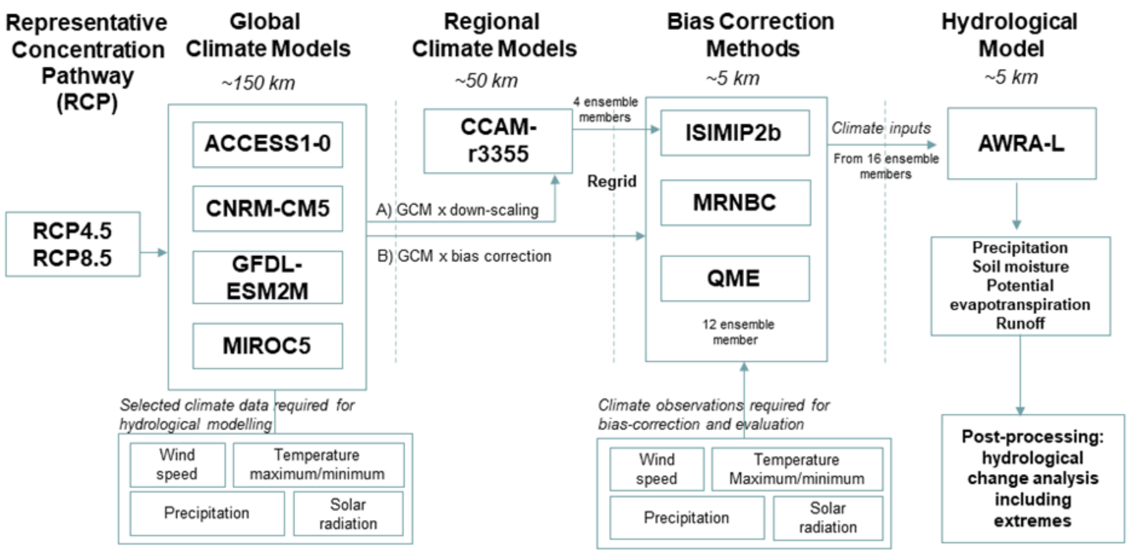


Figure 2: National Hydrological Projections modelling framework (See Wilson et al.2022 for further detail).

Using bias-corrected climate inputs of precipitation, temperature, wind and solar radiation from the 16-member ensemble, the hydrological AWRA-L model produced daily model outputs of soil moisture, runoff, and potential and actual evapotranspiration over Australia. A description of the AWRA-L model used for NHP and how these processes were modelled can be found in Frost et al. (2018). An evaluation of the modelled processes is included in (Srikanthan et al. 2022). Use of two representative greenhouse gas emission scenarios – RCP 4.5 and RCP 8.5 – results in a 32-member ensemble.

To assess hydrological changes, temporal results are aggregated in 30-year periods centred around 2030, 2050, 2070 and 2085 for annual and seasonal timescales, the latter comprising summer (December–February), autumn (March–May), winter (June–August), spring (September–November), cool (May–October) and warm (November–April). Each step of the NHP modelling chain is carefully evaluated to understand the uncertainties associated with the modelling process (Arzanivand et al. 2022; Srikanthan et al. 2022). Uncertainties in hydroclimate change analysis can come from multiple sources, including how greenhouse gas emissions will change into the future, the processes represented in the climate models, the effect of bias-correction and downscaling processes and the hydrological modelling itself (Srikanthan et al. 2022; Arzanivand et al. 2022).

3.2. Selection of future climate projections for Western Australia

As discussed previously, the guidance in *Selection of future climate projections for Western Australia* (DoW 2015) was based on CMIP3 climate models. Twelve GCMs were chosen for their ability to reproduce observed climate conditions. Combined with four special report emission scenarios (SRES), 48 scenarios were ranked in each region. Wet, median and dry scenarios were identified. Constant pattern scaling using monthly anomalies applied to daily baseline series derived the projected changes in precipitation, evapotranspiration and temperature.

A comparison of the modelling methodologies is shown in Table 2. The NHP and DoW (2015) modelling methodologies use different baselines: 1976 to 2005 and 1961 to 1990 respectively. When projected changes by the methods are discussed throughout this assessment, the relevant reference period will be noted.

Table 2: National Hydrological Projections and DoW (2015) modelling methodologies and components

Modelling components	DoW (2015)	BoM (2021)
Spatial coverage	Western Australia	National
CMIP models	CMIP3 models	CMIP5 models
Global climate models selection	Twelve GCMs chosen for skill in reproducing observed climatic conditions	Four global climate models that represent the spread of wet and dry futures (CCiA 2015) and Australian climate drivers
Downscaling/bias correction methods	Constant (pattern) scaling – monthly anomalies applied to daily baseline to generate projections	Regional model: CCAM (50 km) Bias correction: QME, ISIMIP, MRNBC (5 km) GCM re-gridding
Emission scenarios	Special report on emission scenarios (SRES) – four chosen to represent a range of potential global warming SRES (A1F1, A2, A1B, B2) 1.4°C to 5.4°C by 2100	RCP 4.5 (1.7°C to 3.2°C by 2100) RCP 8.5 (3.2°C to 5.4°C by 2100)
Ensemble	48 scenarios – change ranked in each region by mean annual precipitation. Wet, median and dry scenarios identified	Sixteen-member ensemble per RCP (32 ensemble members in total)
Baseline/reference period	1961 to 1990 (monthly anomalies applied to baseline period) Observation data sourced from SILO	1976 to 2005 AWAP data for climate variables Modelled data for hydrological variables
Hydroclimate parameters	Precipitation, evaporation, temperature (min, max, mean), radiation, reference ET-FOA56, relative humidity	Precipitation, potential evapotranspiration – Penman, runoff, soil moisture, temperature (min, max), solar radiation, wind speed
Time slices	2030, 2050, 2070, 2100	2030, 2050, 2070, 2085 Continuous data from 2006 to 2100

4. NHP projected precipitation in Western Australia

Precipitation changes projected by the NHP ensemble median in each region and by each ensemble member are shown in Figure 3 and Figure 4 respectively. Precipitation (ensemble median) in the cool season (May–October) is projected to decrease in the South West, Central West and Pilbara for the 2030, 2050 and 2070 time slices under the RCP 8.5 emissions scenario (Figure 3). There is high agreement between ensemble members on the precipitation decrease, particularly in the South West and Central West (Figure 4). The median precipitation change is projected as small increases and/or decreases at most time slices across the Kimberley (Figure 4). Spatial variability in projected precipitation changes is evident in the Kimberley despite significant decreases projected for the southern part of the region (Figure 3). This is reflected in the wide spread of precipitation increases and decreases projected by the NHP ensemble members (Figure 4). In the warm season (November–April), the median change in precipitation projects increased precipitation in most regions, with exceptions in 2070 in the South West, Central West, and Pilbara (Figure 3). The extent of increased precipitation projected is evident across the Kimberley (Figure 3), although the ensemble members show a spread both of large increases and decreases in the warm season across all regions (Figure 4) (Srikanthan et al. 2022). The spread of projected precipitation in the warm season results from uncertainty in ability of models to simulate tropical processes (Turner et al. 2022).

While projected median change in precipitation provides an indicator of the drying and wetting trends within a region, it is important to understand the range of precipitation within each GCM and ensemble member as they are all considered equally plausible. The largest decreases are projected by GFDL-ES2M ensemble members for the South West (all Bias Correction members) and Central West (CCAM-ISIMIP and ISIMIP). GDFL-ES2M–CCAM-ISIMIP and MIROC ensemble members (MIROC–CCAM-ISIMIP2b) also project large decreases in the Kimberley and Pilbara, particularly at the 2070 and 2085 time slices (Figure 4). Under the RCP 8.5 emission scenario, large increases in precipitation are projected in the South West and Central West by CNRM-CM5 (MRNBC, CCAM-ISIMIP, QME) and MIROC (all) ensemble members (Figure 4). The CNRM-CM5 and MIROC GCMs also project large precipitation increases in the Kimberley and Pilbara, but those increases include MRNBC and QME ensemble members. Further details on the projected hydroclimate changes across Western Australia and the differences between models are discussed in the Southern and South-Western Flatlands, Rangelands and Monsoonal North NHP assessment reports (Oke et al. 2022; Srikanthan et al. 2022; Turner et al. 2022).

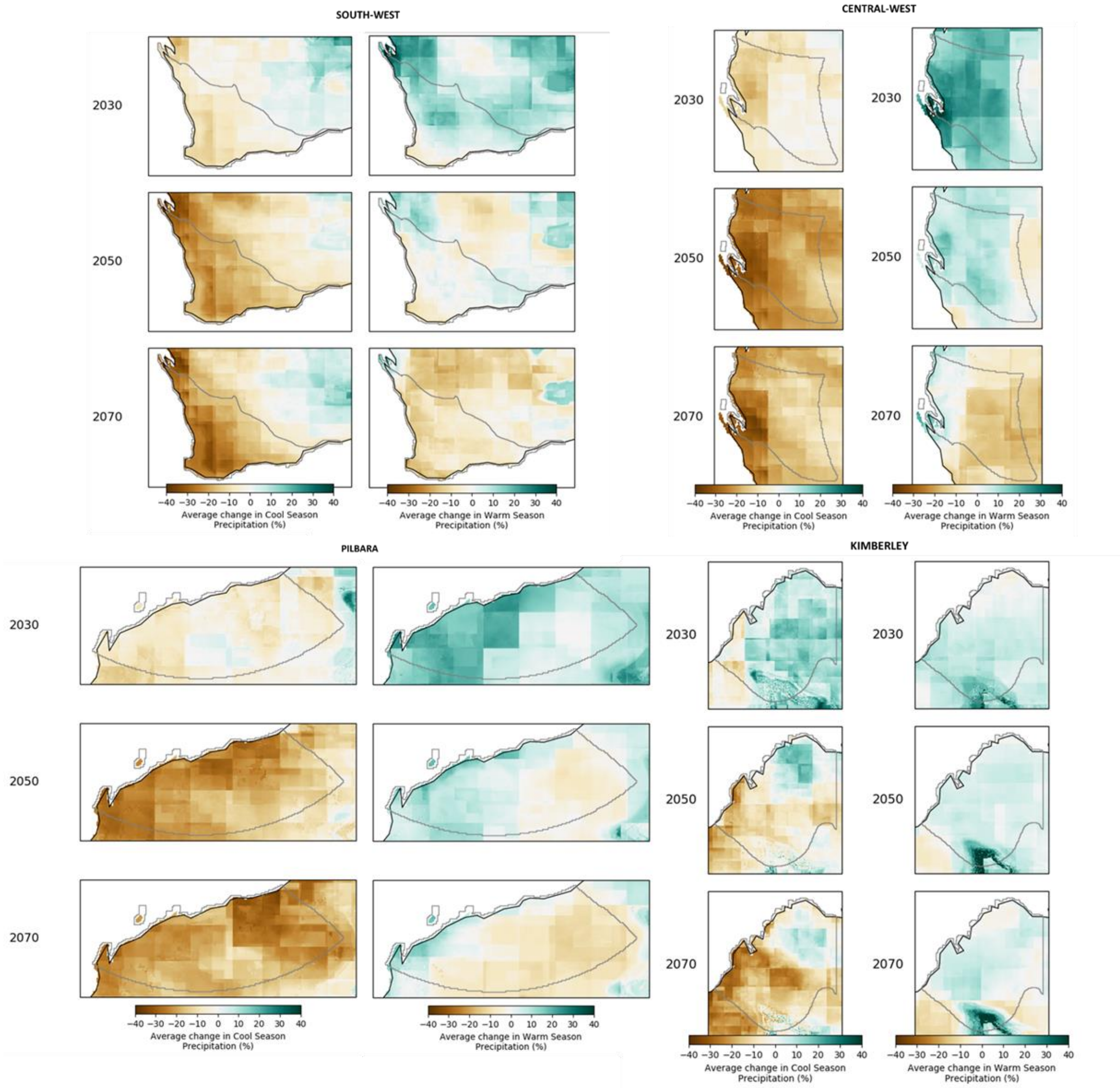


Figure 3: Relative change (%) in median precipitation projected by NHP under RCP 8.5 emissions scenario for the cool season (May–October) (left panel for each region), and warm season (November–April) (right panel for each region), across the South West, Central West, Pilbara and Kimberley regions. The change is relative to the reference period (1976–2005).

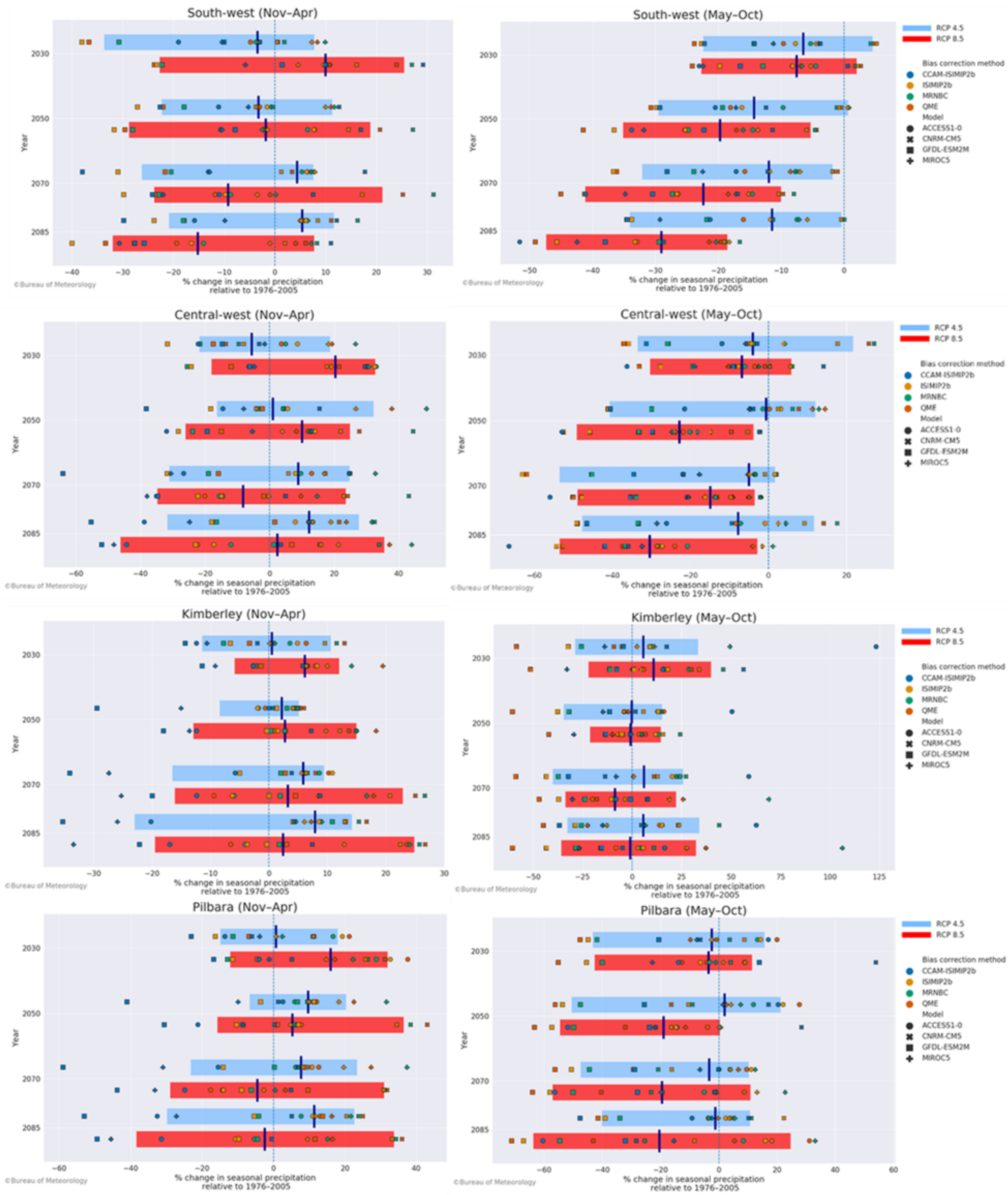


Figure 4: Relative (%) change in cool season (May–October) and warm season (November–April) precipitation projected by each ensemble member for 2030, 2050, 2070 and 2085 in the South West, Central West, Kimberley and Pilbara regions. The red bar shows the 10th to 90th percentiles for RCP 8.5. The blue bar shows the 10th to 90th percentiles for RCP 4.5. The dark blue line shows the ensemble median. The change is relative to the reference period (1976–2005).

5. Regional comparisons of monthly precipitation projected by DoW (2015) and NHP

DoW (2015) provided scaling anomalies for wet, median and dry scenarios in each region of Western Australia (based on 90th, 50th and 10th percentiles of change in regional mean annual precipitation). This chapter compares the change in precipitation projected by DoW (2015) scaling anomalies with dry (10th), median (50th) and wet (90th) percentiles of the NHP ensemble. The monthly climatology projected by DoW (2015) and NHP in the South West, Pilbara, Kimberley, and Central West regions are relative to the historical 1976 to 2005 reference period. The comparison for each region is shown in Figure 5. The plots include:

- historical period (blue line) – 10th (dotted line), median (solid line) and 90th (dashed line) percentile of modelled NHP data from 1976 to 2005
- the 10th, median and 90th percentiles scaled using DoW (2015) anomalies (yellow line) applied to the historical period
- the 10th, median and 90th percentiles of the NHP ensemble (grey line).

Climatology of the DoW (2015) and NHP projections is consistent in all regions. However, there are some differences in the magnitude of the average monthly projections in each region (Figure 5). In the South West both projection ensembles project similar monthly dry precipitation (10th percentile), with a comparable projected change from the historical reference period (Figure 5). The median of the NHP ensemble projects a larger reduction in precipitation for most months between March and October, with the magnitude of the projected change being consistent between projection ensembles from November to February and July to August. The largest difference in projected precipitation is evident for the wet scenario (90th percentile), with a notably reduced monthly precipitation between May and October and an increase in November to January for the NHP ensemble (Figure 5).

In the Central West it is evident that the difference in the monthly precipitation projections will change using the anomaly or 10th, median and 90th approach. In this region the NHP projects a smaller monthly precipitation for the dry scenario (10th percentile) compared with the historical period 10th percentile and DoW (2015) dry scenario in most months (Figure 5). The largest difference in projected magnitude of monthly precipitation is evident between May and August for both the median and 90th percentile or wet scenario (Figure 5). Minimal differences in monthly precipitation projections are evident across most months in the Kimberley and Pilbara. There are some small differences in the wetter months (December–March) (Figure 5).

Current practice to apply the projections in a planning context in Western Australia has moved away from using wet, median and dry scenarios towards assessing the full range of plausible future projections, using a subset of these for detailed analysis and taking a storyline approach. Storylines are explored in Chapter 6. However, comparison of the wet, median and dry scenarios is useful to show that the monthly pattern of projections is similar, although some differences in the size of the projected change are found between the DoW (2015) and NHP approaches. This reflects the larger ensemble of plausible futures that the NHP 16-member ensemble provides.

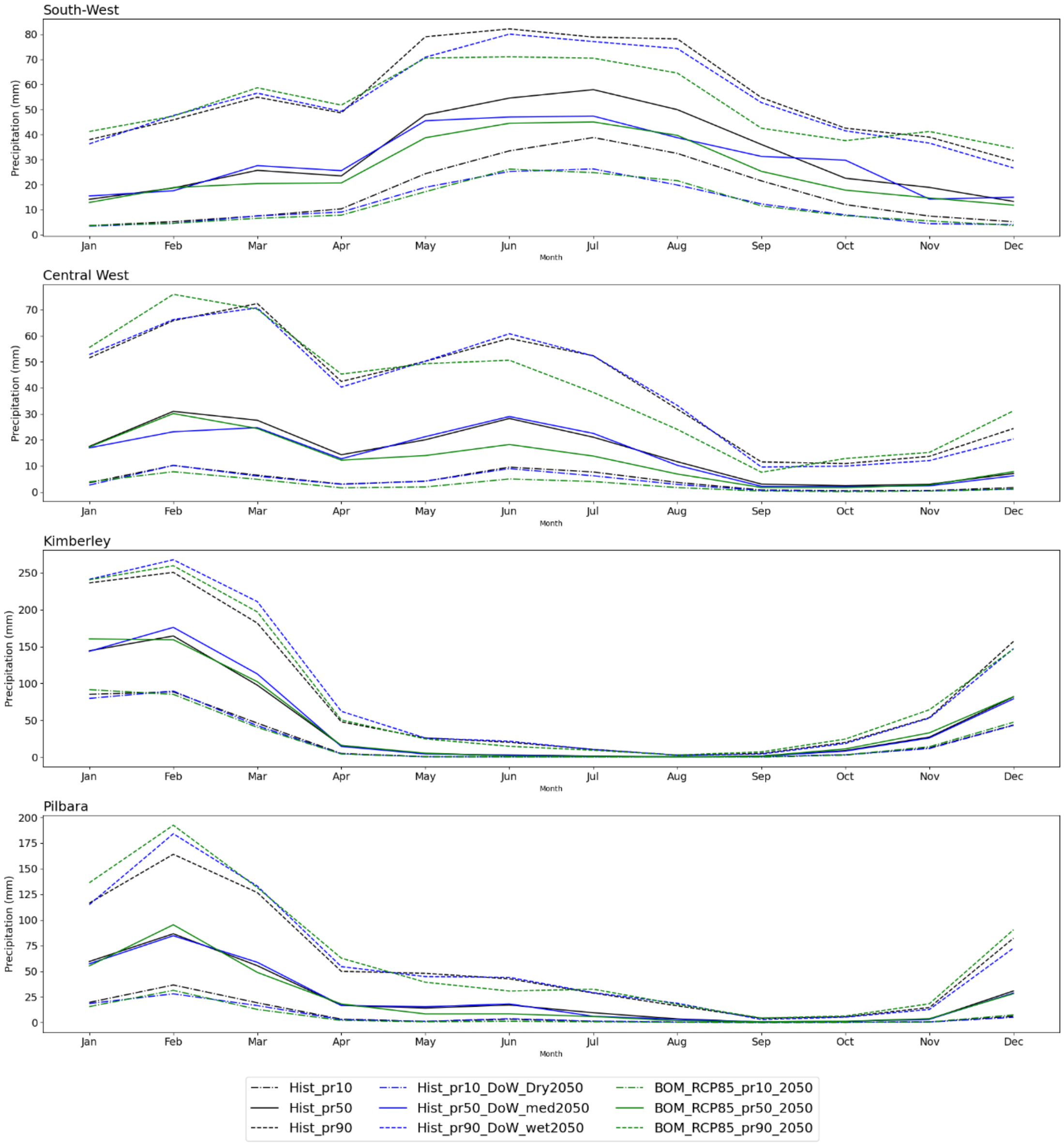


Figure 5: Comparison of month-by-month total average precipitation historical, NHP and DoW (2015) 2050 projections in the South West (SW), Central West (CW), Pilbara (P) and Kimberley (K) regions. Each plot includes 10th, median and 90th historical time-series (Hist_pr10, Hist_pr50, Hist_pr90); DoW (2015) dry, median and wet anomalies applied to historical time-series (Hist_pr10_DWER_Dry2050 Hist_pr50_DoW_med2050, Hist_pr90_DWER_Wet2050) and the 10th, median and 90th percentiles of the NHP ensemble (BOM_RCP85_pr_10th_2050, BOM_RCP85_pr50_2050 and BOM_RCP85_p90_2050).

6. Methodology for comparison of NHP and DoW (2015) seasonal projections and hydrological impacts

A comparison of projections produced by different methods needs to consider several factors. In brief, these could include: any differences between the choices of future emissions pathways, GCMs, downscaling and bias correction methods, as well as modelling uncertainty and the historical reference period and future time slices chosen. Comparison of outputs could include: the range and pathway of projected change signals for different variables across each projection set's model ensemble, their ability to capture the seasonal cycle, observed trends and changes in circulation.

The comparison of projected precipitation in Section 7 focuses on 2050 time-slice, which includes the 30-year period between 2036–2065. This period was chosen because the use of projections in water planning will be most useful at this timescale, rather than a longer-term time slice such as 2070 or 2085. It also minimises the differences in projections introduced by different greenhouse gas concentration pathways, as typically the pathways are largely similar at 2050 and diverge after this point.

Precipitation was chosen for the comparison because: i) it is available in both projection ensembles, and ii) it drives other climate and hydrological variables important for water resource management. Projected potential evapotranspiration (PET), runoff and soil moisture were used to derive aridity and drought indicators to identify hydrological impacts across each region (Chapter 8). This has been completed for NHP only, as these variables were not produced as part of DoW (2015).

6.1. Using a storyline approach to select ensemble members for comparison

A storyline is a narrative that uses climate projections to define the link between climate drivers and their impact on landscape or hydrological processes under plausible climate futures (Shephard et al. 2019; Narsey et al. 2023)). Examples of where the storyline approach has been applied in Western Australia include changes in cool season runoff impacting warm season soil moisture (Turner et al. 2022; Srikanthan et al. 2022) and western Pilbara water availability (Narsey et al. 2023).

Four NHP ensemble members were chosen based on the storyline approach in the South West, Central West, Pilbara and Kimberley. The ensemble members were chosen to reflect a spread of wet and dry plausible futures that the NHP project for each region. For example, a dry or wet future, increased or decreased precipitation variability, or little change in precipitation (chosen ensemble members detailed in Section 7). Those ensemble members were then used to compare monthly and annual precipitation projections with the DoW (2015) monthly and annual projections at point locations within each region: Perth Airport, Scadden, Morowa, Gascoyne Junction, Marble Bar and Fitzroy Crossing.

6.2. Site-based relative change in seasonal precipitation (total and variability)

The relative change (%) for precipitation projected for 2050 was derived for each NHP ensemble member and DoW (2015) scenario for the warm (November–April) and cool (May–October) seasons at Perth Airport, Scadden, Morowa, Gascoyne Junction, Marble Bar and Fitzroy Crossing.

Projected warm and cool season precipitation variability (coefficient of variation) for the 2050 period by each NHP ensemble member and DoW (2015) were derived at Perth Airport, Scadden, Morowa, Gascoyne Junction, Marble Bar and Fitzroy Crossing.

The DoW (2015) historical reference period is 1961 to 1990 and differs from the NHP historical period of 1976 to 2005 by 15 years. There is some difference in the external forcing over this period (e.g. increased atmospheric carbon dioxide), thus if there is a growing response to climate change over time, the strength of that response should be greater under DoW (2015) than NHP.

Note, however, that not all external forcing is increasing over time – for example aerosol forcing and the size of the ozone hole are likely to decrease, and will likely stabilise in the near future. These factors are most relevant in spring/summer, and it is unclear how these trends will influence the relative change in precipitation explored here, but it is assumed the difference over 15 years will be small. The weather or climate variability simulated by a particular model at a particular time can also modify the intensity of the response, as each climate model simulates its own internal variability.

7. Projected precipitation in the warm and cool seasons

7.1. South West region

A reduction in cool season precipitation is projected for 2050 and continues the drying trend observed in this region (Figure 4) (Turner et al. 2022). The NHP provide 32 plausible futures (16 members per RCP) within a region. For this assessment, four ensemble members were chosen for each region that illustrate a different change in precipitation variability and related soil moisture within the cool season (Figure 6). The ensemble members provide a spread of projected changes in precipitation (ensemble members are circled in Figure 6 left/upper) and include:

1. A large increase (> 30%) in precipitation variability and a large decrease (>30%) in soil moisture: MIROC5–CCAM-ISIMIP2b
2. A decrease (<5%) in cool season precipitation variability and a moderate decrease in soil moisture (<15%): ACCESS1-0–MRNBC
3. A moderate increase (<15%) in precipitation variability and moderate decrease (<15%) in cool season soil moisture: CNRM-CM5–ISIMIP2b
4. A small increase (<10%) in cool season precipitation variability and a large decrease in soil moisture (<30%): GFDL-ESM2M–QME

The spread of precipitation and soil moisture change projected by ensemble members differ between the warm season (November–April) and cool season (May–October) (Figure 6 right/bottom). An extended investigation of projected precipitation and associated impacts within a region could also include additional members that represent pertinent warm season features within that region.

The time-series of the chosen storyline ensemble members are shown relative to the median, 10th and 90th percentile of the whole ensemble (RCP 4.5 and RCP 8.5) in Figure 7. CNRM-CM5–ISMIP2b projects a precipitation magnitude higher than the ensemble median. This is in contrast with GFDL-ESM2M–QME that projects a drier scenario.

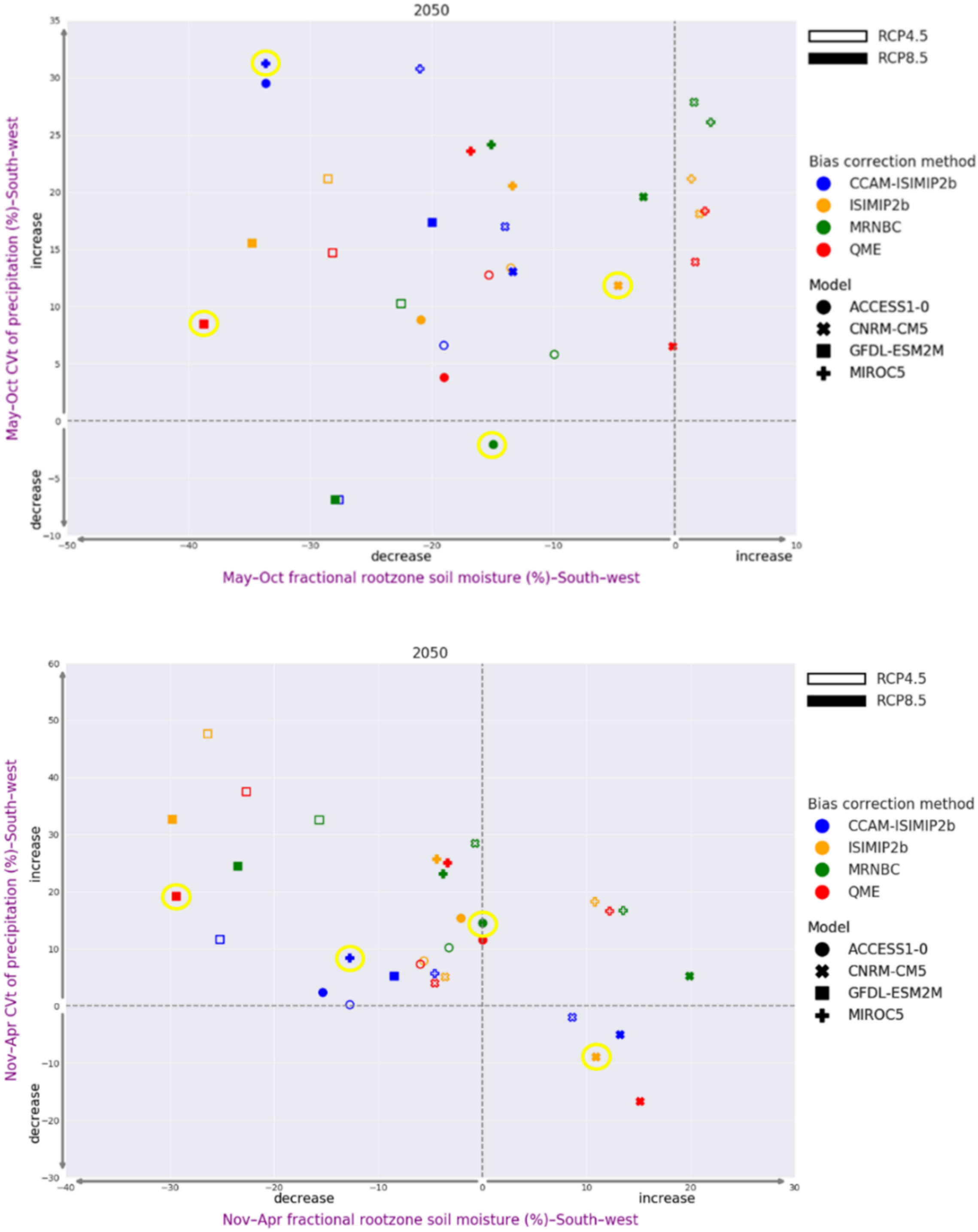


Figure 6: Projected change (%) in precipitation variability versus change (%) in soil moisture in the South West region during a) the cool season (May–October) (top) and b) warm season (November–April) (bottom). The ensemble members (circled) chosen for storylines to investigate differences in projected precipitation change at 2050 in the South West include: MIROC–CCAM-ISIMIP2b, ACCESS1-0–MRNBC, CNRM-CM5–ISIMIP2b and GFDL-ESM2M–QME (RCP 8.5).

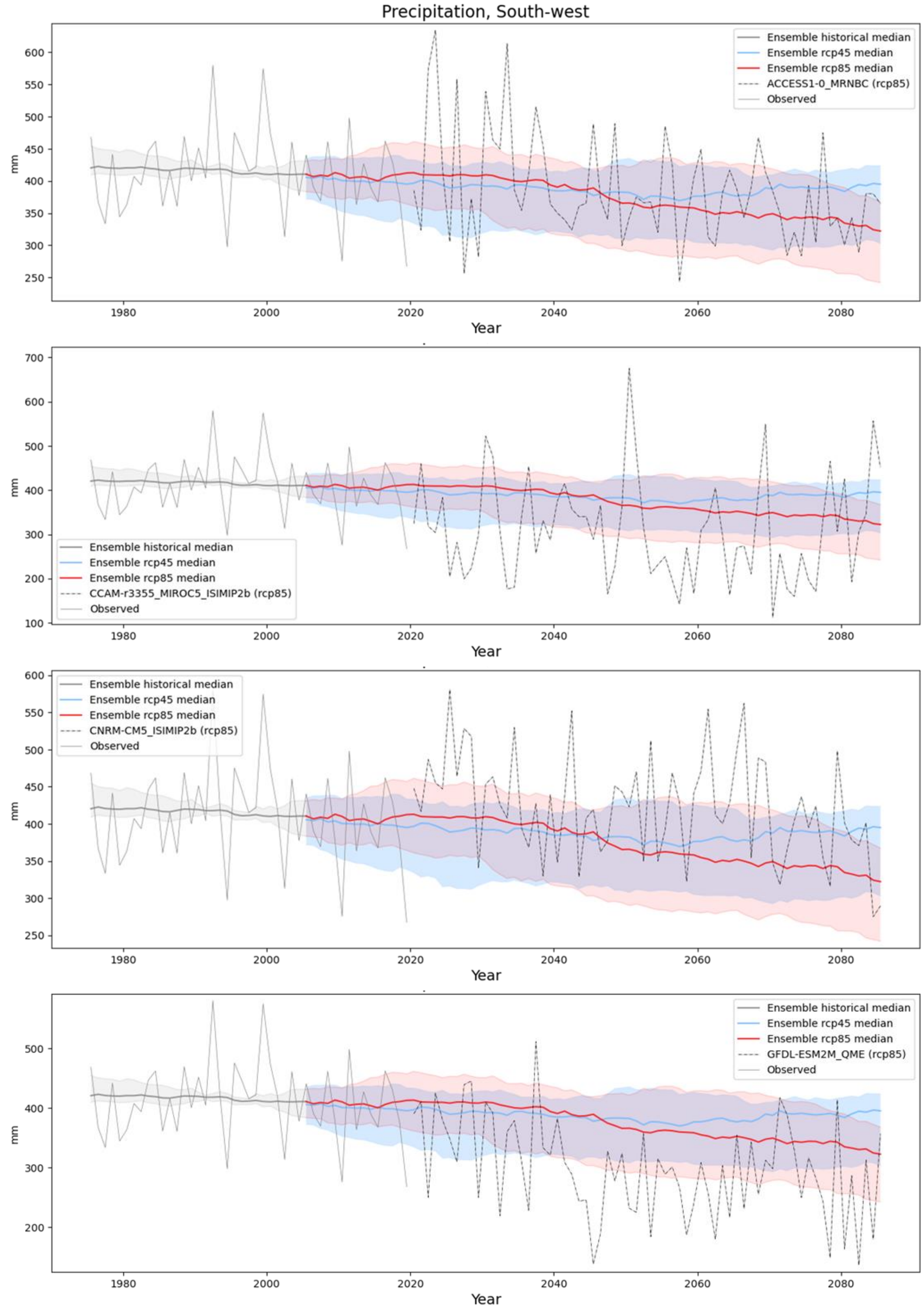


Figure 7: Annual modelled precipitation projected to 2099 by the NHP 16-member ensemble for RCP 4.5 (blue) and RCP 8.5 (red) in the South West region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. The grey line represents the observed historical median precipitation based on AWAP data. The dashed line represents the time-series of the selected ensemble members (from top to bottom): ACCESS1-0–MRNBC, MIROC–CCAM-ISIMIP2b, CNRM-CM5–ISIMIP2b and GFDL-ESM2M–QME.

The seasonality of projected precipitation at 2050 is comparable with DoW (2015) projections, with greater variability in magnitude evident at the Scadden and Morowa sites (Figure 8). However, the monthly magnitude in the cool season (May–October) is sometimes lower than the DoW (2015) 2050 projections, particularly for GFDL-ES2M–QME and MIROC–CCAM-ISIMP2b at Scadden, Perth Airport and Morowa. CNRM-CM5–ISMIP2b and ACCESS1-0–MRNBC projected higher 2050 precipitation in May, and August to October at the South West sites.

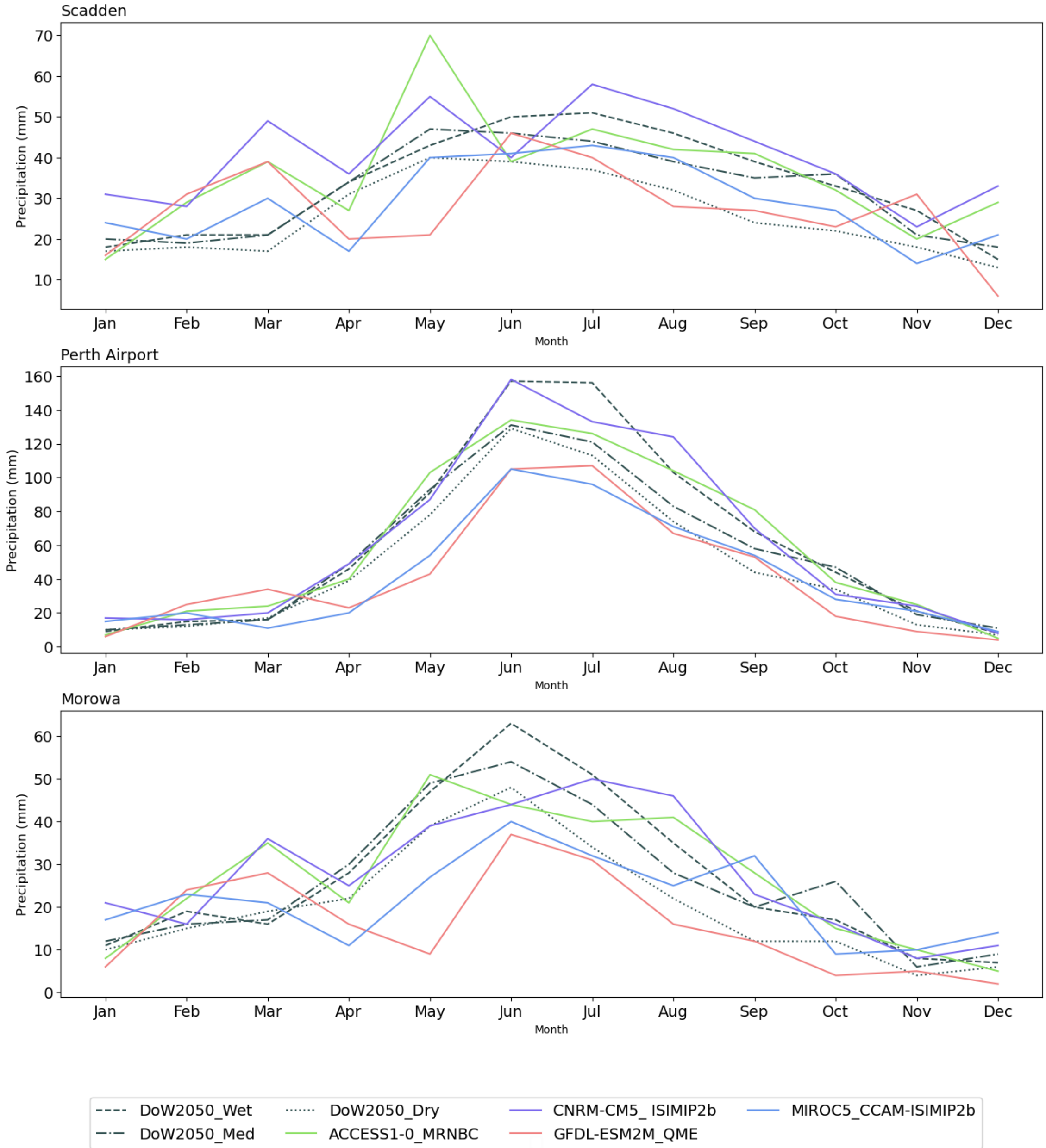


Figure 8. Monthly total precipitation 2050 projections for DoW (2015) wet, dry and median scenarios, and NHP ensemble members MIROC5–CCAM-ISIMP2b, CNRM-CM5–ISIMIP2b, Access1-0–MRNBC and GFDL-ESM2M–QME at Scadden, Perth Airport and Morowa in the South West region.

A comparison of annual time-series should not compare precipitation projected for individual years but should consider the time slice as a whole. The annual precipitation time-series projected at Scadden, Perth Airport and Morowa shows the difference in annual variability projected between 2036 to 2065 (Figure 9). Compared with DoW (2015), NHP expands the plausible range of projected annual variability. NHP projects more frequent and drier years than DoW (2015).

The annual peaks (wet years) projected by DoW (2015) at Perth Airport, while comparable in magnitude, are projected more often by the NHP ensemble members. Large annual precipitation peaks projected by MIROC5–CCAM-ISIMIP2b in 2050 are evident at all South West sites (Figure 9). The magnitude of projected annual precipitation by CNRM-CM5–ISIMIP2b and ACCESS1-0–MRNBC is greater than DoW (2015) projections at Scadden and Morowa. MIROC5–CCAM-ISIMIP2b and GFDL–QME ensemble members project a drier future than DoW (2015) projections at all three sites. The GFDL-ESM2M and CCAM–ISIMIP2b ensemble members have been found to project a drier future in the South West (Turner et al. 2022) and most other NRM regions (see https://awo.bom.gov.au/about/overview/ assessment-reports).

All NHP ensemble members and DoW (2015) scenarios projected a decrease in cool season precipitation at 2050 for Perth Airport and Morowa, and all but one NHP projection projected decreases for Scadden (Figure 10). There are differences between sites as to the degree of the projected precipitation changes and how they compare with the DoW (2015) scenarios. At Morowa, the average annual cool season precipitation reduction of -50% projected by the DoW dry scenario is comparable with the NHP GFDL-ESM2M (QME, ISIMIP2b) and ACCESS1-0 (CCAM-ISIMIP2b) cool season projections (Figure 10). The DoW (2015) dry scenario projected a -41% decrease in cool season precipitation at Scadden: this is greater than the reductions projected by all NHP ensemble members, but similar to:

- GFDL-ESM2M–QME (-35% decrease)
- GFDL-ESM2M–ISIMIP2b (-34% decrease)
- ACCESS1-0–CCAM-ISIMIP2b (-26% decrease).

Decreased cool season precipitation (-28%, DoW_med) projected at Perth Airport is greater for the NHP ensemble members:

- GFDL-ESM2M: QME (-40%), ISIMIP2b (-39%)
- MIROC5–CCAM-ISIMIP2b (-39%)
- ACCESS1-0–CCAM-ISIMIP2b (-35%).

The NHP assessment of the Southern and South-Western Flatlands NRM region found a spread in projected precipitation changes during the warm season resulting from variability in the summer signal (November–April) (Turner et al. 2022). This trend is consistent for the Perth Airport, Morowa and Scadden sites (Figure 11). DoW (2015) projected a decrease in precipitation during the warm season for the wet, median and dry scenarios. In contrast, almost half the NHP ensemble members including CNRM:

QME (28%), MRNBC (16%), ISIMIP (7%), CCAM-ISIMIP2b (12%); ACCESS1-0: QME (6%), MRNBC (1%); and GFDL-ESM2M–CCAM–ISIMIP (5%) projected an increase in warm season precipitation (Figure 10). The four ensemble members chosen for the seasonal and annual comparison (figures 8 and 9) represent the spread in projections of plausible futures between the drier models (GFDL-ESM2M and MIROC5) and wetter models (CNRM-CM5 and ACCESS1-0) (Figure 10). These results indicate that when practitioners choose a subset of projections through storylines to investigate plausible futures within a region, they must investigate how the climate metrics driving the water resource system differ (e.g. annual totals, seasonal patterns, variability, aridity index).

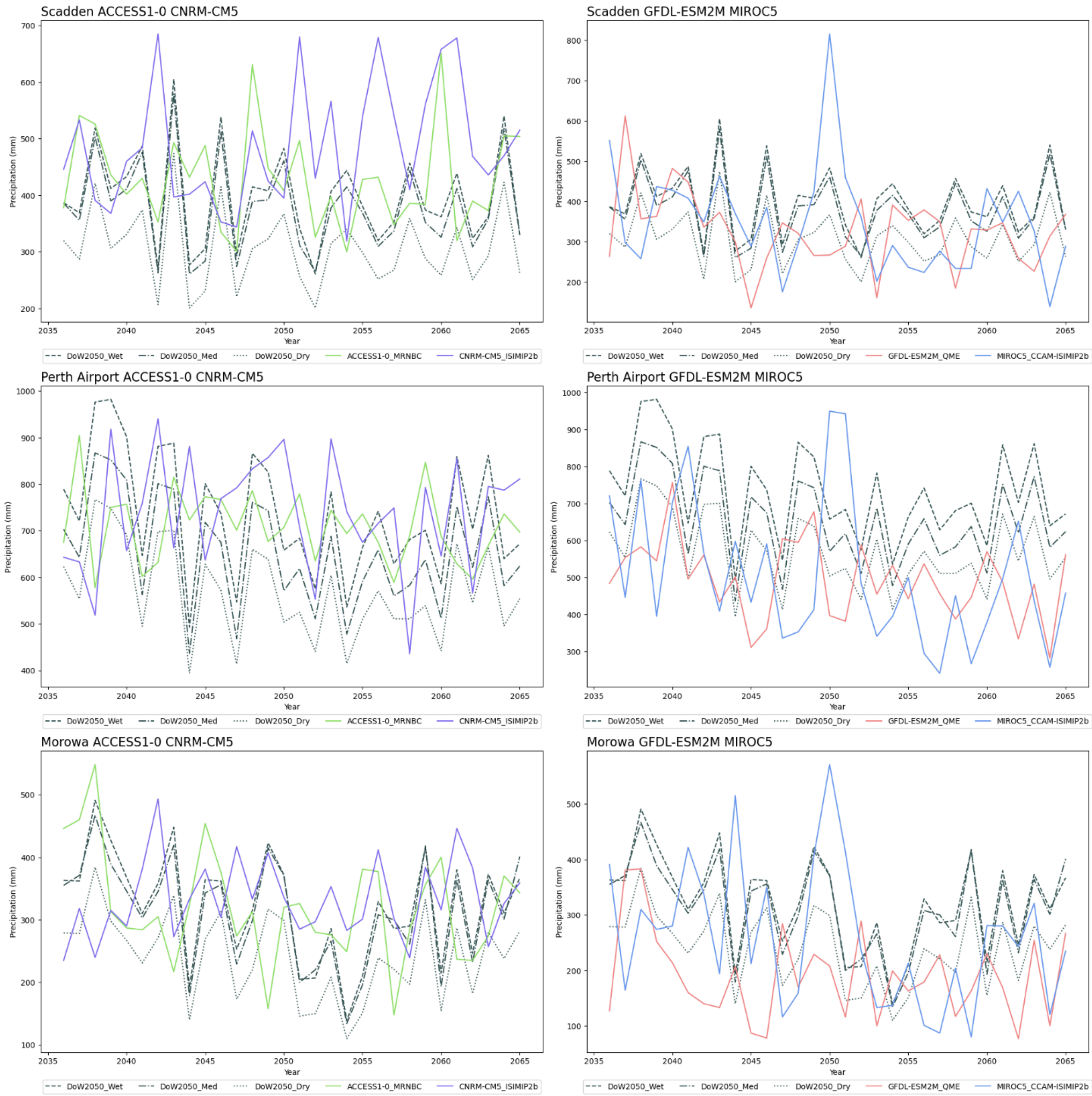


Figure 9: Annual time-series for the DoW (2015) wet, dry and median scenarios, and NHP ensemble members MIROC5–CCAM-ISIMIP2b, CNRM-CM5–ISIMIP2b, ACCESS1-0–MRNBC and GFDL-ESM2M–QME at Scadden, Perth Airport and Morowa in the South West region.

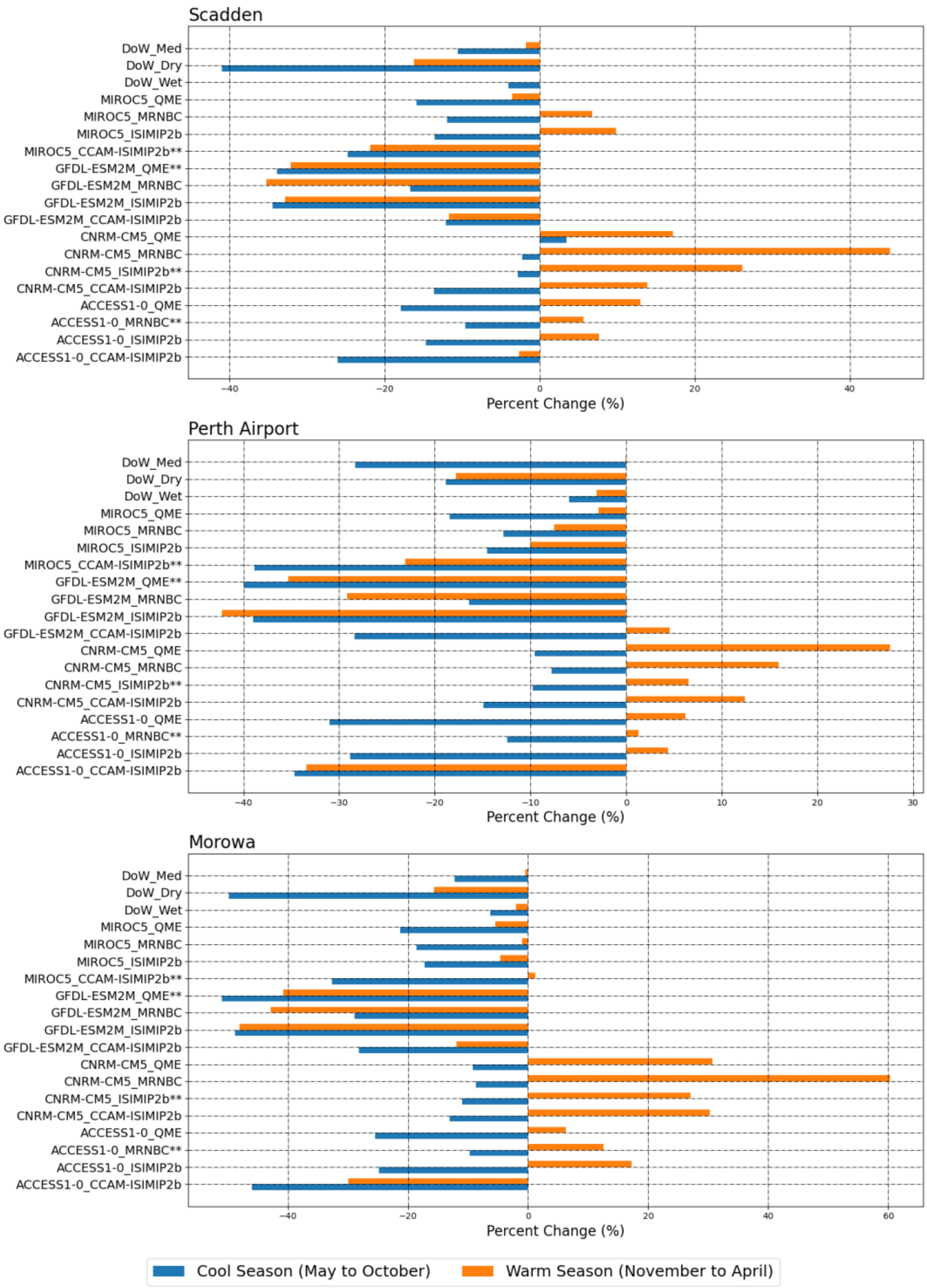


Figure 10: Relative change (%) in average annual precipitation for the warm season (November–April, orange) and cool season (May–October, blue) at Scadden, Perth Airport and Morowa in the South West region. Change is relative to 1976–2005. Change in DoW scenario is relative to 1961–1990. The asterisks (**) mark the ensemble members used to compare the monthly and annual time-series (Figures 8, 9).

The annual coefficient of variability of warm and cool season precipitation projected by the DoW (2015) dry, median and wet scenarios is within the range of variability projected by the NHP suite (Figures 11, 12 and 13). The NHP projects a wider range of variability. There is a minimal difference in precipitation variability between the historical reference period and the 2050 projections for the DoW (2015) dry, median and wet scenarios at Perth Airport, Scadden and Morowa (Figures 11, 12 and 13). This is expected as the DoW (2015) constant monthly scaling approach results in variability which is the same as, or similar to the baseline period.

The four NHP ensemble members chosen as examples of storylines in the South West region and the DoW (2015) dry, median and wet scenarios are highlighted with a blue and green box respectively in Figures 11, 12 and 13. The projected change in cool and warm season precipitation variability differs between ensemble members and sites. For example, MIROC–CCAM-ISMIP2b projects minimal changes (less than 10%) in cool season precipitation variability at Perth and Scadden and in warm season variability at Morowa. It also projects large changes in warm season precipitation variability at Perth (59%) and in the cool season variability at Morowa (34%). Meantime CNRM-CM5–ISIMIP2b projects moderate changes in warm season precipitation variability at Perth (30% increase) and Scadden (24% increase), as well as a small change (less than 10%) in cool season variability at Perth, and in both warm and cool season variability at Morowa and Scadden.

Differences in warm and cool season precipitation variability projected by ensemble members is also shown by ACCESS1-0–MRNBC and GFDL–QME. ACCESS1-0–MRNBC projects changes between a 26% decrease in the cool season at Perth and a 25% increase in the warm season at Scadden (Figures 11, 12 and 13). GFDL-ESM2M–QME projects a change between a 19% decrease in precipitation variability (cool season at Perth and a 25% increase (warm season at Perth) at Scadden, Morowa and Perth (Figure 11, 12, 13). While the projected seasonal coefficient of variability differs between NHP ensemble members, note that the higher precipitation variability in the warm season of the reference and the 2050 period is maintained by all ensemble members at each site within the South West region (Figures 11, 12 and 13).

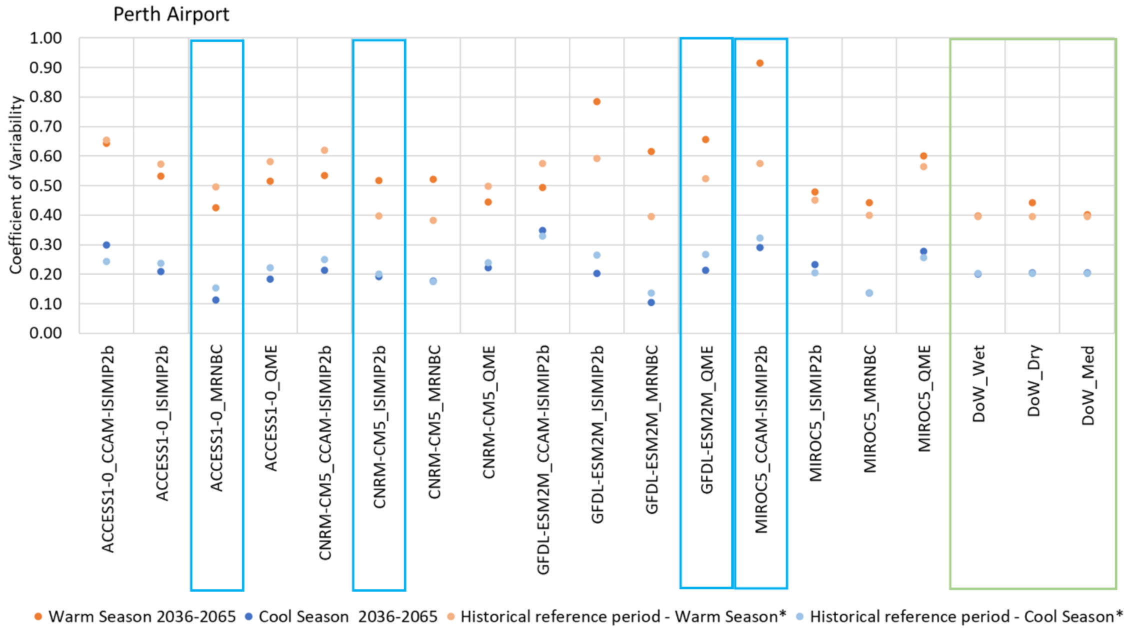


Figure 11: Annual precipitation coefficient of variability for the warm season (November–April) and cool season (May–October) at Perth Airport in the South West region. The NHP historical reference period is 1976–2005. The DoW (2015) historical reference period is 1961–1990. The four blue boxes show the ensemble members selected by storylines used to compare the monthly and annual time-series (Figures 9 and 10). The green box shows the Wet, Median and Dry scenarios of DoW (2015).

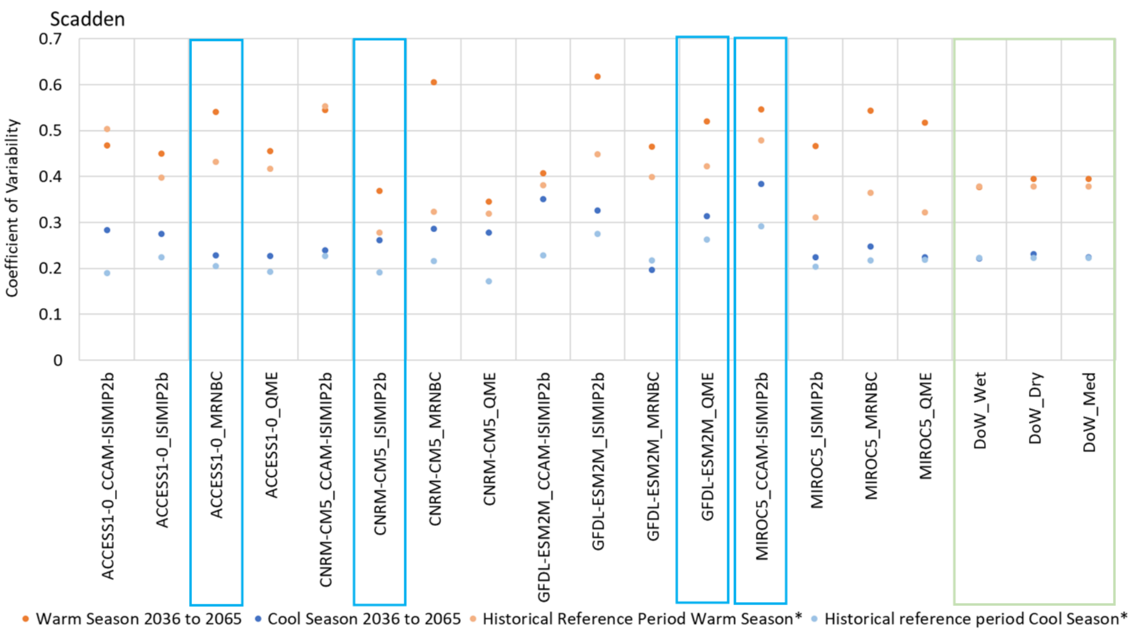


Figure 12: Annual precipitation coefficient of variability for the warm season (November–April) and cool season (May–October) at Scadden in the South West region. The NHP historical reference period is 1976–2005. The DoW (2015) historical reference period is 1961–1990. The four blue boxes show the ensemble members used to compare the monthly and annual time-series (Figures 8 and 9). The green box shows the Wet, Median and Dry scenarios of DoW (2015).

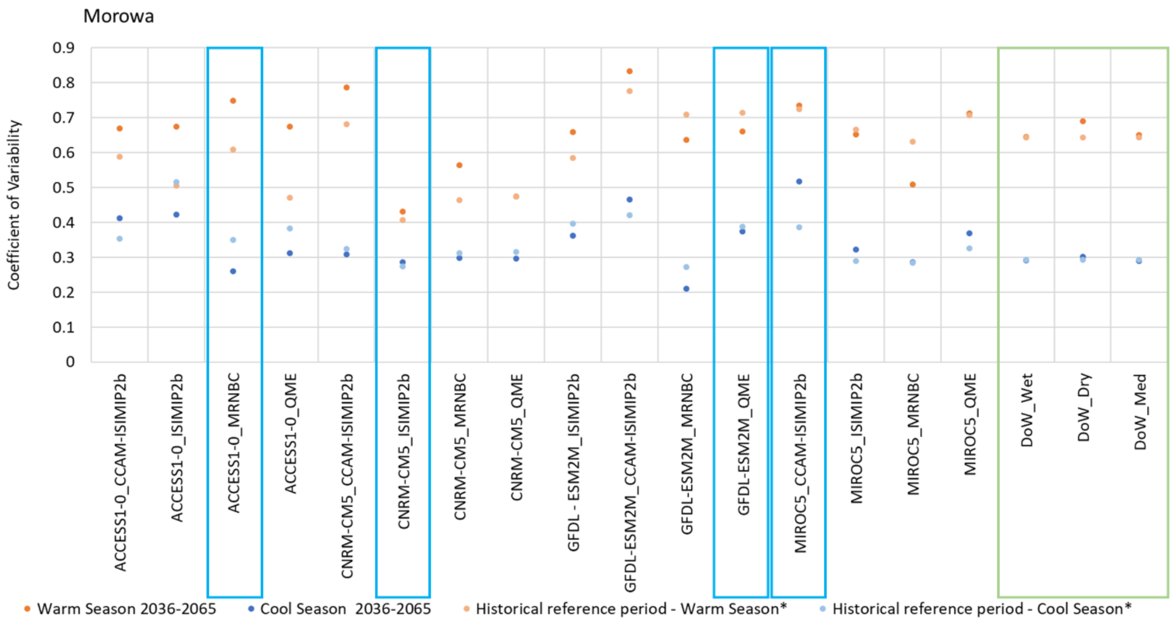


Figure 13: Relative change (%) in annual precipitation coefficient of variability for the warm season (November–April) and cool season (May–October) at Morowa in the South West region. The NHP historical reference period is 1976–2005. The DoW (2015) historical reference period is 1961–1990. The four blue boxes show the ensemble members used to compare the monthly and annual time-series (Figures 9 and 10). The green box shows the Wet, Median and Dry scenarios of DoW (2015).

7.1.1. Summary of comparison

Key findings of the comparison between the DoW (2015) and NHP ensembles in the South West region are summarised in Table 3.

Table 3: Comparison of 2050 precipitation projections in the South West region.

Season	Trends
Selected NHP storylines	MIROC5–CCAM-ISIMIP2b: increased cool season precipitation variability and decreased soil moisture CNRM-CM5–ISIMIP2b: increased cool season precipitation variability and slightly decreased cool season soil moisture – a wetter projection relative to other RCP 8.5 projections ACCESS1-0–MRNBC: decreased cool season precipitation variability and soil moisture – a median projection GFDL-ESM2M–QME: little change in cool season precipitation variability and decreased soil moisture – a drier projection

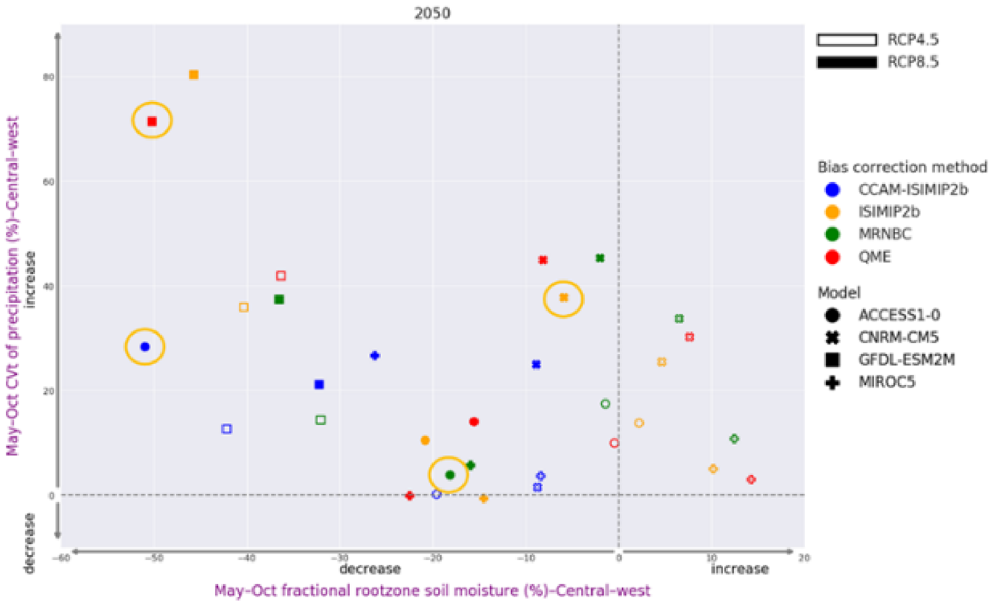
Season	Trends
Monthly precipitation	The monthly pattern of seasonality is similar between projections, however there are differences in the magnitude of average monthly precipitation (Figure 8). Lower average monthly precipitation is projected by GFDL-ESM2M–QME and MIROC–CCAM-ISIMIP2b from April to August at Scadden, Perth Airport and Morowa. Higher average monthly precipitation is projected by the NHP between December and March, particularly at Scadden and Morowa (CNRM-CM5–ISIMIP2b and MRNBC–ACCESS1-0). Averaged monthly precipitation mean maxima are similar for the NHP and DoW (2015) projections at Perth Airport between August and March.
Cool (May–October)	The drying trend of cool season precipitation in the South West region was evident at three sites and projected by the NHP and DoW (2015) (Figure 10). At Perth, the DoW (2015) cool season projections (-28.3 to -5.93% decrease) are within the NHP cool season projections (-39.9 to -9.7%). There are also comparable projections at Morowa with large cool season precipitation reductions projected by the NHP (-51% to -9.7%) and DoW (2015) (-49% to -6.2%). At Scadden, the largest decrease (-40%) was projected by DoW (2015) but is comparable to a 33% reduction projected by one NHP ensemble member. The full NHP ensemble shows an increase in cool season precipitation (3.5%) at Morowa. The full range of projected change should be considered when assessing long-term impacts.
Warm (November–April)	The rainfall totals and soil moisture are low in the warm season, so percentage change can be relatively large. The spread of summer precipitation projections is influenced by the ability of GCMs to simulate the tropical and coastal processes that produce summer precipitation in the South West region (Turner et al. 2022). This is shown by the large spread of projected change in warm season precipitation at Perth (-35% to 45%), Morowa (-48% to 60%) and Scadden (-35% to 45%). The NHP storyline subset represents this spread, including large reductions and increases (Figure 9). By comparison, the DoW (2015) projections show a considerably smaller spread of projected reduction across all three sites (-17% to -0.1%). The NHP ensemble provides insights into the range of plausible futures of warm season precipitation in the South West.
Inter-annual variability	Annual time-series of the NHP and DoW (2015) projections show that the pattern-scaling approach does not change the precipitation variability from the baseline period to the dry, median and wet scenarios (Figure 9). The NHP projects more frequent and drier years than DoW (2015). Changes in inter-annual seasonal variability is evident between cool and warm seasons and between NHP ensemble members (Figures 11, 12 and 13). Large increases in variability are evident in the warm season, double the variability change projected in the cool season. The DoW (2015) scenarios are within the NHP range, with the cool season variability change at the lower end of the range (Figure 11).

7.2. Central West region

The decrease in projected cool season (May–October) precipitation at 2050 under the RCP 8.5 emission scenario in the Central West (Figure 4) is characterised by a storyline with a projected increase in precipitation variability and a projected decrease in soil moisture (Figure 14 top). The warm season (November–April) projections are for increased precipitation variability and a spread of increased and decreased changes in soil moisture (Figure 14 bottom). The four ensemble members (circled in Figure 14) chosen for comparison with DoW (2015) and the NHP ensemble at Gascoyne Junction include:

1. GFDL-ESM2M–QME: projects a large increase (70%) in cool season precipitation variability and a large (50%) decrease in cool season soil moisture.
2. ACCESS1-0–CCAM-ISIMIP2b: projects a moderate increase (~30%) in cool season precipitation variability and a large decrease (50%) in cool season soil moisture.
3. ACCESS1-0–MRNBC: projects a small increase (~5%) in cool precipitation variability and a moderate decrease (18%) soil moisture. This contrasts with moderate projected increases in warm season precipitation variability (~18%) and soil moisture (~10%).
4. CNRM-CM5–ISIMIP2b: projects a 7% decrease in cool season soil moisture and an 18% increase in warm season soil moisture. The spread of projected precipitation variability includes a small decrease (3%) and a moderate increase (18%) between the warm season and cool season respectively (Figure 14).

The annual magnitude and variability of CNRM-CM5–ISIMIP2b, ACCESS1-0–CCAM-ISIMIP2b and GFDL-ESM2M–QME time-series relative to the whole NHP ensemble are shown in Figure 15. CNRM-CM5–ISMIP2b projects a precipitation magnitude higher than the ensemble median and ACCESS1-0–CCAM-ISIMIP2b projects a drier scenario.



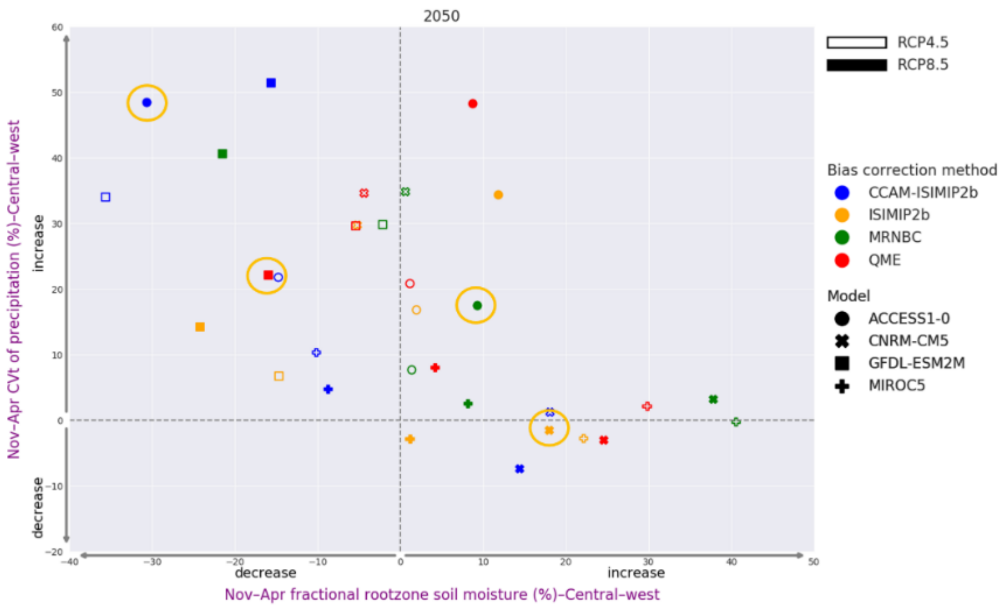


Figure 14: Projected change (%) in precipitation variability versus change (%) in soil moisture in the Central West region during a) the cool season (May–October) (top) and b) warm season (November–April) (bottom). The ensemble members chosen for storylines (circled) to investigate differences in projected change in precipitation at 2050 in the Central West include: GFDL-ESM2M–QME, ACCESS1-0–CCAM-ISIMIP2b, ACCESS1-0–MRNBC and CNRM-CM5–ISIMIP2b (RCP 8.5).

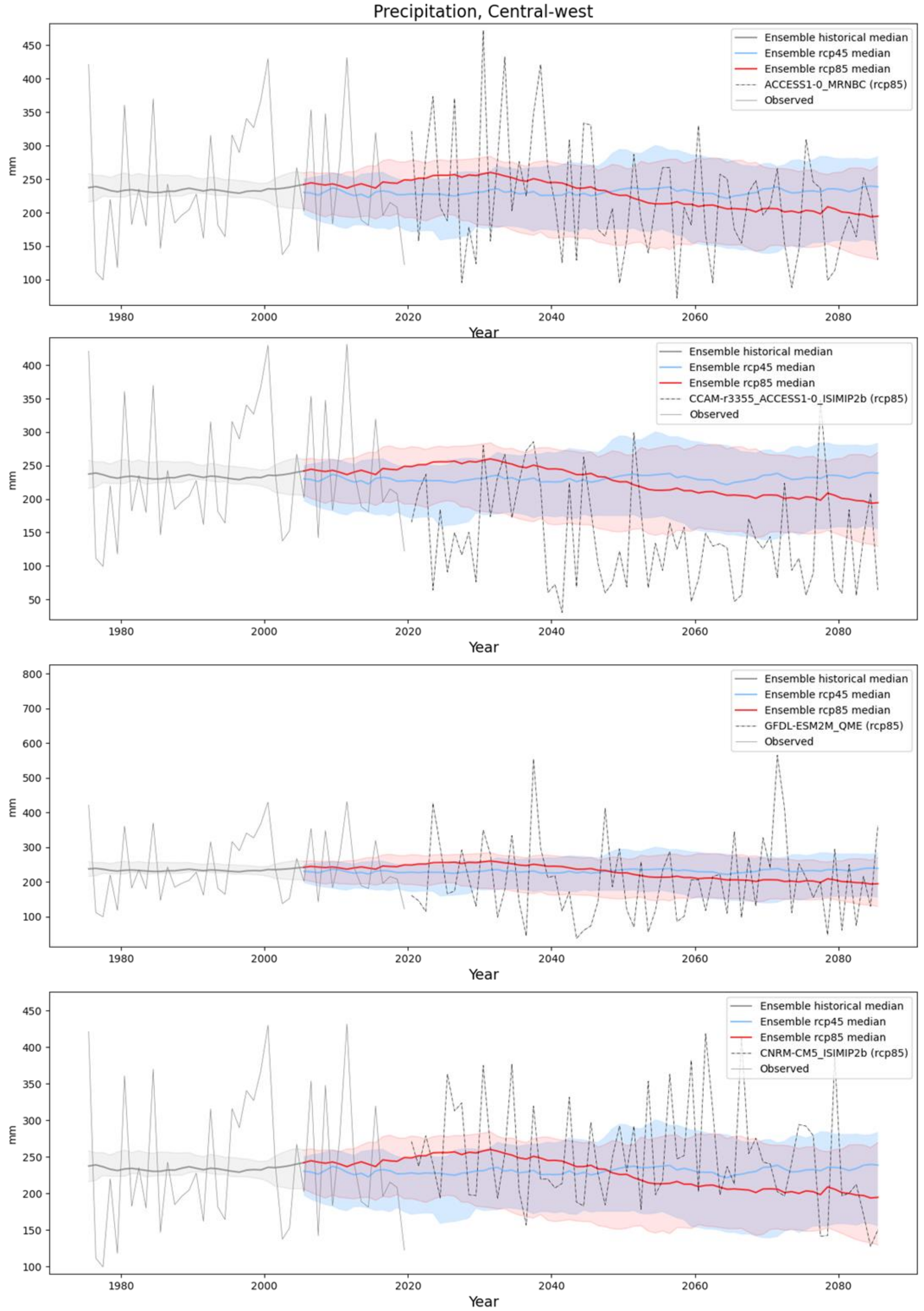


Figure 15: Annual modelled precipitation projected to 2099 by the 16-member ensemble for RCP 4.5 (blue) and 16-member ensemble for RCP 8.5 (red) in Central West region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. The grey line represents the observed historical median precipitation based on AWAP data. The dashed lines represent the time-series of the selected ensemble members (from top to bottom): ACCESS1-0–MRNBC, ACCESS1-0–CCAM-ISIMIP2b, GFDL-ESM2M–QME, CNRM-CM5–ISIMIP2b.

Projected precipitation decreases in the cool season months (May–October) is greater for the NHP ensemble members than the DoW (2015) projections (Figure 10). By contrast, three of the four selected ensemble members, except for ACCESS1-0–CCAM-ISIMIP2b, project greater monthly precipitation than the DoW (2015) scenarios during December to March (Figure 10, Figure 16).

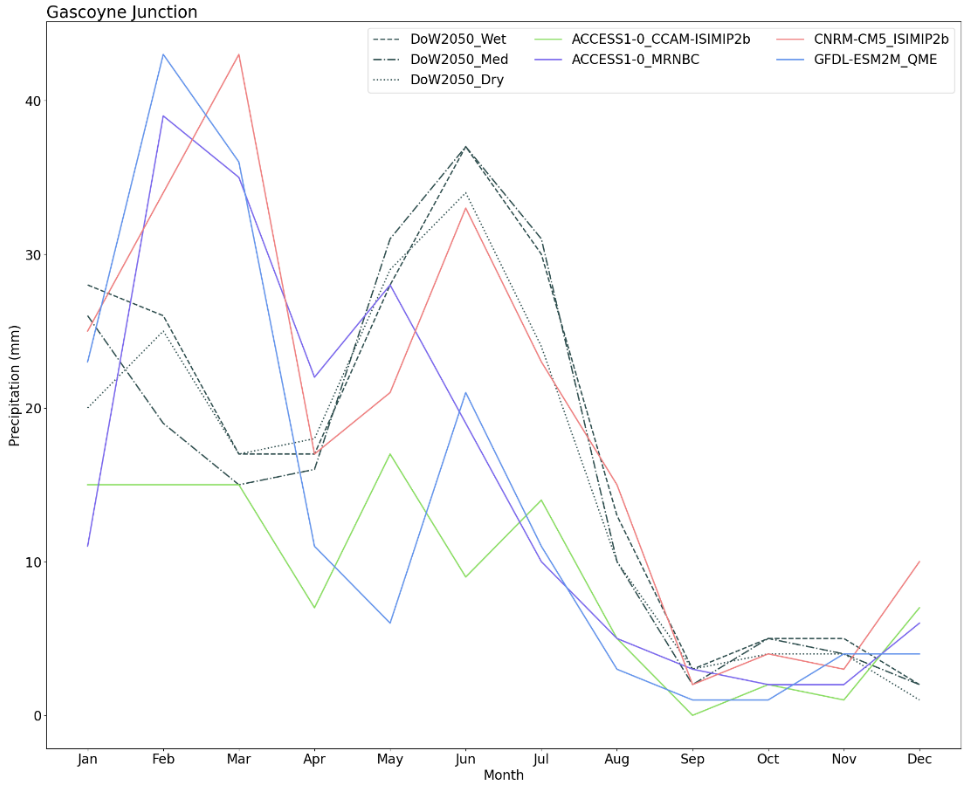


Figure 16: Monthly projections for DoW (2015) wet, dry and median scenarios (black lines) and NHP ensemble members (ACCESS1-0–CCAM-ISIMIP2b, CNRM-CM5–ISIMIP2b, ACCESS1-0–MRNBC and GFDL-ESM2M–QME) at Gascoyne Junction in the Central West region.

Annually, GFDL-ESM2M–QME and ACCESS1-0–CCAM-ISIMIP2b project lower annual precipitation during the 2036 to 2065 period than the DoW (2015) dry, median and wet scenarios (Figure 17). The annual time-series shows variability in the magnitude of precipitation projected by CNRM-CM5–ISIMIP2b and ACCESS1-0–MRNBC, with greater annual precipitation projected for the last half of the 2050 period (Figure 17). Several annual precipitation peaks are similar between DoW (2015) and the NHP, although some additional wet years are projected by NHP ensemble members, namely 2047 (GDFL–QME), 2057 (Access1-0–CCAM-ISIMIP2b, ACCESS1-0– MRNBC) and 2063 (ACCESS1-0–MRNBC, CNRM-CM5–ISIMIP2b). Note that comparison of individual years between different projections is not recommended. However, projections can provide information on the changes in the occurrence and variability of extreme events that may occur within a time period.

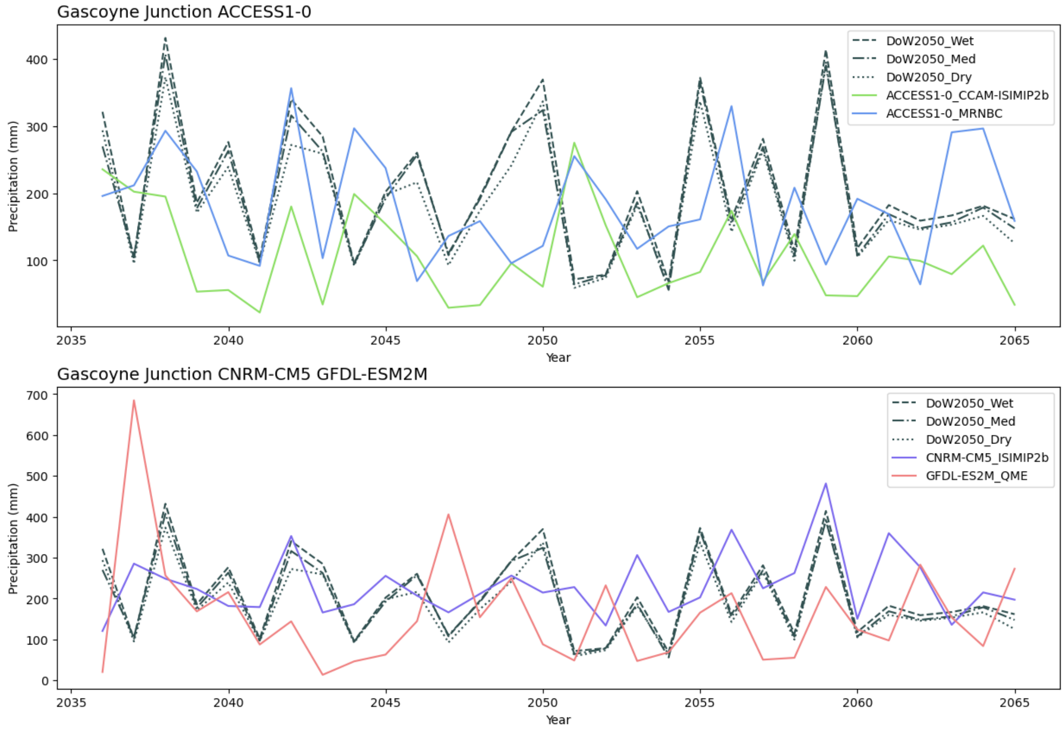


Figure 17: Annual time-series for the DoW (2015) wet, dry and median scenarios, and NHP ensemble members ACCESS1-0–CCAM-ISIMIP2b, CNRM-CM5–ISIMIP2b, ACCESS1-0–MRNBC and GFDL-ESM2M–QME.

Projected seasonal magnitude and variability at Gascoyne Junction differs considerably between the DoW (2015) scenarios and NHP ensemble members (Figure 10, 18). Projected changes in seasonal precipitation for the four NHP ensemble members chosen for comparison show a reduction in cool season precipitation between -3% (CNRM-CM5–ISMIP2b) and -54% (ACCESS1-0–CCAM-ISIMIP2b) (Figure 18). The projected change in warm season precipitation ranges from -48% (Access1-0–CCAM-ISIMIP2b) to 27% (CNRM-CM5–ISIMIP2b). This does not represent the whole range of the NHP ensemble, with the greatest change (79% increase) projected by CNRM-CM5–MRNBC (Figure 10). The magnitude of projected changes in cool and warm season precipitation in the DoW (2015) scenarios is considerably smaller than most NHP ensemble members, namely between 1 and 14% (Figure 18).

Disparity in projected changes of precipitation variability is evident in both the warm and cool seasons for all four ensemble members (Figure 19). The NHP ensemble does give a range of projected changes in variability, with the four ensemble members representing most of that range (Figure 19). Little change in variability is projected by the DoW (2015) dry, median and wet scenarios for the cool or warm seasons (Figure 19). This is expected as the DoW (2015) constant monthly scaling approach results in the same/similar variability as the baseline period. The range of variability in the warm season for the NHP ensemble reflects the uncertainty in the GCMs to accurately represent the tropical processes that influence summer precipitation in this region.

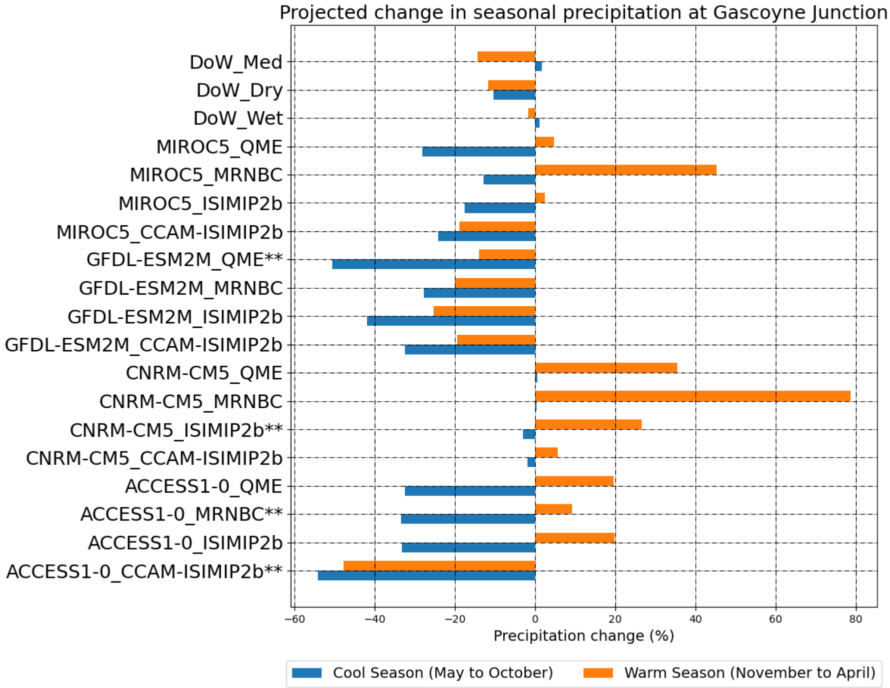


Figure 18: Relative change (%) in average annual precipitation for the warm season (November–April, orange) and cool season (May–October, blue) at Gascoyne Junction in the Central West. Change is relative to 1976–2005. Change in the DoW (2015) scenarios is relative to 1961–1990. The asterisks (**) mark the ensemble members used to compare the monthly and annual time-series in Figures 16 and 17.

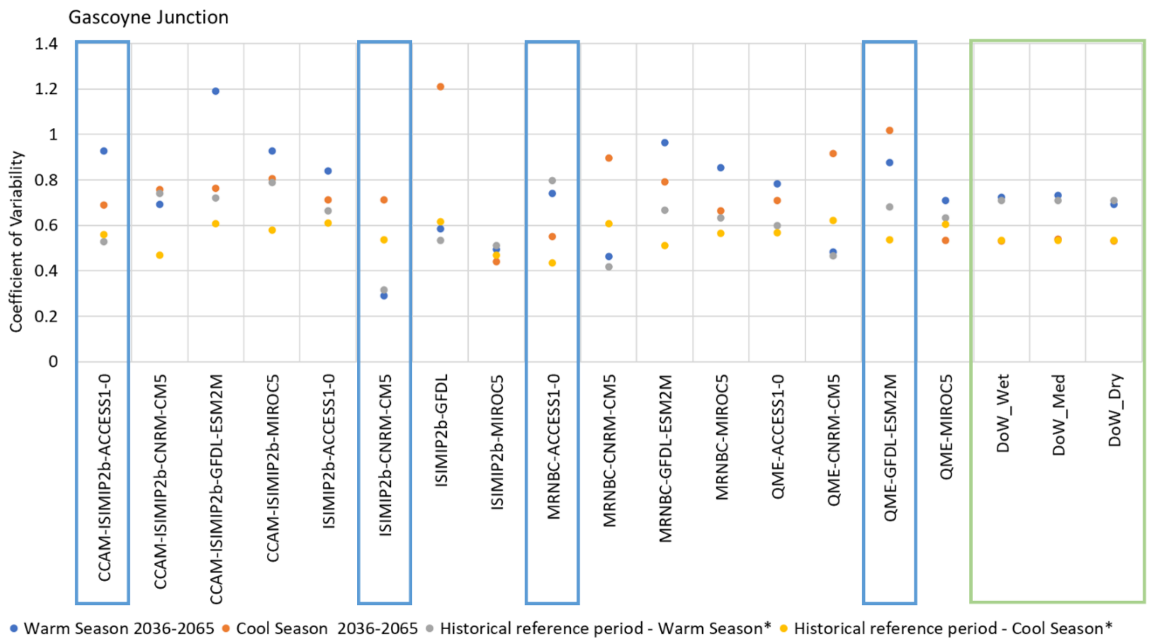


Figure 19: Relative change (%) in annual precipitation coefficient of variability for the warm season (November–April) and cool season (May–October) at Gascoyne Junction. The NHP historical reference period is 1976–2005. The DoW (2015) historical reference period is 1961–1990. The four blue boxes show the ensemble members selected by storylines used to compare monthly and annual time-series (Figures 16 and 17).

7.2.1. Summary of comparison in the Central West region

Key findings of the comparison between the DoW (2015) and NHP ensembles in the Central West region are summarised in Table 4.

Table 4: Comparison of 2050 precipitation projections at Gascoyne Junction in the Central West region.

Season	Trends
Selected NHP storylines	GFDL-ESM2M–QME: projects a large increase (70%) in cool season precipitation variability and a large (50%) decrease in cool season soil moisture. ACCESS1-0–CCAM-ISIMIP2b: projects a moderate increase (~30%) in cool season precipitation variability and a large decrease (50%) in cool season soil moisture. ACCESS1-0–MRNBC: projects a small increase (~5%) in cool precipitation variability and a moderate decrease (18%) in soil moisture. This contrasts with a moderate projected increase in warm season precipitation variability (~18%) and soil moisture (~10%). CNRM-CM5–ISIMIP2b: projects a 7% decrease in cool season soil moisture and 18% increase in warm season soil moisture. The spread of projected precipitation variability includes a small decrease (3%) and a moderate increase (18%) between the warm season and cool season respectively (Figure 14).
Monthly precipitation	Seasonality is comparable between the NHP and DoW (2015) projections at Gascoyne Junction (Figure 16): • Lower precipitation is projected between May and October for the NHP, compared with DoW (2015), except for CNRM-CM5–ISIMIP2b, which is higher for August. • NHP projects higher monthly precipitation compared with DoW (2015) between December and March, except for ACCESS1-0–CCAM-ISIMIP2b, which is lower for all months except December.
Cool (May–October)	Larger precipitation reductions were projected by the NHP (up to 54%) compared with the DoW (2015) scenarios (-10.36% to 1.63%) (Figure 18).
Warm (November–April)	The NHP projections for the warm season are considerably wetter than the DoW (2015) scenarios. The NHP projections show a large spread of decreases and increases in warm season precipitation (Figure 18). The DoW (2015) warm season projections (-14% to -1.79% reductions) are within the NHP warm season projections (-48% to 79%) (Figure 18).
Inter-annual variability	The NHP ensemble subset projects some larger annual precipitation peaks and troughs compared with the DoW (2015) scenarios (Figure 17). Most NHP ensemble members project change in the variability of cool and warm season precipitation (Figure 19), although the direction and degree of change is not consistent. At Gascoyne Junction, the DoW (2015) cool season projections are at the lower end of the NHP range (Figure 19). Minimal change in variability is projected by the DoW (2015) scenarios as the pattern-scaling approach does not change the precipitation variability from the baseline period to the dry, median and wet scenarios (Figure 19).

7.3. Pilbara region

In the warm, wet season (November–April) in the Pilbara region, both precipitation increases (west/coastal) and decreases (east/inland) are projected for 2050 (Figure 3). The spread of NHP ensemble members in this region includes the largest annual precipitation increase of RCP 8.5 emissions projected by CNRM-CM5 ensemble members, with QME, MRNBC and ISIMIP2b bias corrections standing out with large projected increases of 35% to 43% (Figure 4). All other ensemble members project between a 30% decrease and a 10% increase (Figure 4). GFDL-ESM2M–CCAM-ISIMIP2b and ACCESS1-0–CCAM-ISIMIP2b both project the largest annual precipitation reductions. In the dry season (May–October), the projected drying trend is evident across the whole region (Figure 3). Most ensemble members project annual precipitation to be reduced between 0 and 64% (Figure 4). CNRM-CM5–CCAM-ISMIP2b is the one exception: it projects an increase of 28%. Although the 2050 time-slice has most projections decreasing, it is important to note that more projected increases are seen in other time slices. This illustrates why practitioners should consider what planning horizon they need for a management decision and how the projections may change between time slices.

Four ensemble members under the RCP 8.5 emission scenario were chosen for storylines (circled in Figure 20) to investigate the differences in projected change in precipitation at 2050 in the Pilbara region, which found:

1. ACCESS1-0–QME: a large increase in precipitation variability with minimal change in soil moisture
2. MIROC5–ISIMIP2b: a small increase in precipitation variability with minimal change in soil moisture
3. GFDL-ESM2M–CCAM-ISIMIP2b: a moderate increase in precipitation variability and moderate decrease in soil moisture
4. CNRM-CM5–MRNBC: a moderate decrease in precipitation variability and a moderate increase in soil moisture.

Cool season precipitation variability and soil moisture projected by these ensemble members does differ between seasons (Figure 20, bottom). The annual time-series for CNRM-CM5–MRNBC, MIROC5–ISIMIP2b and GFDL-ESM2M–CCAM-ISIMIP2b relative to the whole NHP ensemble are shown in Figure 21. The chosen ensemble members represent the median, low and high ends of projected precipitation in relation to the median of the NHP ensemble.

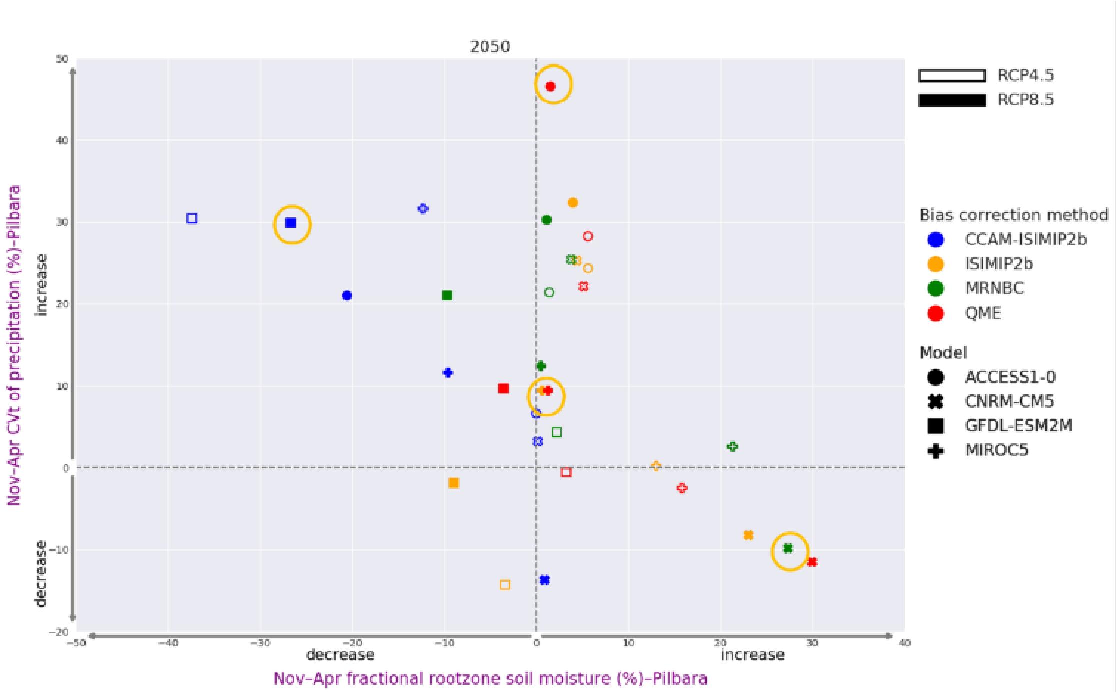


Figure 20: Projected change (%) in precipitation variability versus change (%) in rootzone soil moisture in the Pilbara region during the cool season (May–October) (bottom) and warm season (November–April) (top). The ensemble members chosen for storylines (circled) to investigate differences in projected change in precipitation at 2050 in the Pilbara region include: ACCESS1-0–QME, MIROC5–ISIMIP2b, GFDL-ESM2M–CCAM-ISIMIP2b and CNRM-CM5–MRNBC (RCP 8.5).

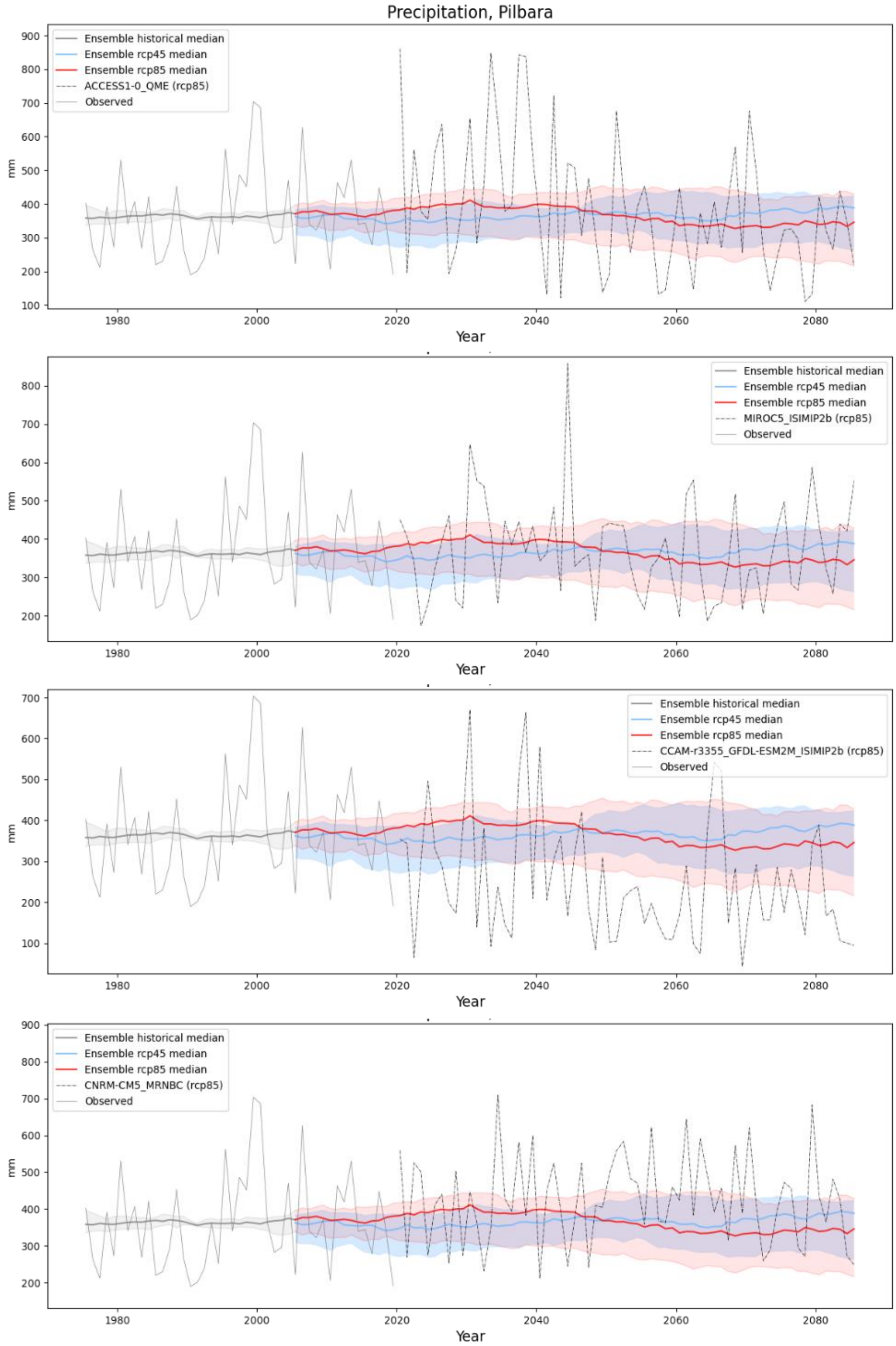


Figure 21: Annual modelled precipitation projected to 2099 by the 16-member ensemble for RCP 4.5 (blue) and RCP 8.5 (red) in the Pilbara region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. The grey line represents the observed historical median precipitation based on AWAP data. The dashed lines represent the time-series of the selected ensemble members (from top to bottom): ACCESS1-0–QME, MIROC5–ISIMIP2b, GFDL-ESM2M–CCAM-ISIMIP2b and CNRM-CM5–MRNBC.

Seasonality of the average monthly precipitation projected by the NHP ensemble members for Marble Bar in the dry season (May–October) are similar to the DoW (2015) scenarios, particularly in the lowest precipitation months of September and October. Variation in the NHP average monthly peaks is evident from May to August (Figure 22). The range of monthly projected precipitation is greater in the wet season (November–April), particularly in February and April. ACCESS1-0–QME and MIROC5–ISIMIP2b project the higher monthly precipitation, whereas GDFL-ESM2M consistently projects lower precipitation (Figure 22). The spread of summer wet season precipitation projections is influenced by the ability of GCMs to simulate the tropical processes that produce summer precipitation in this region.

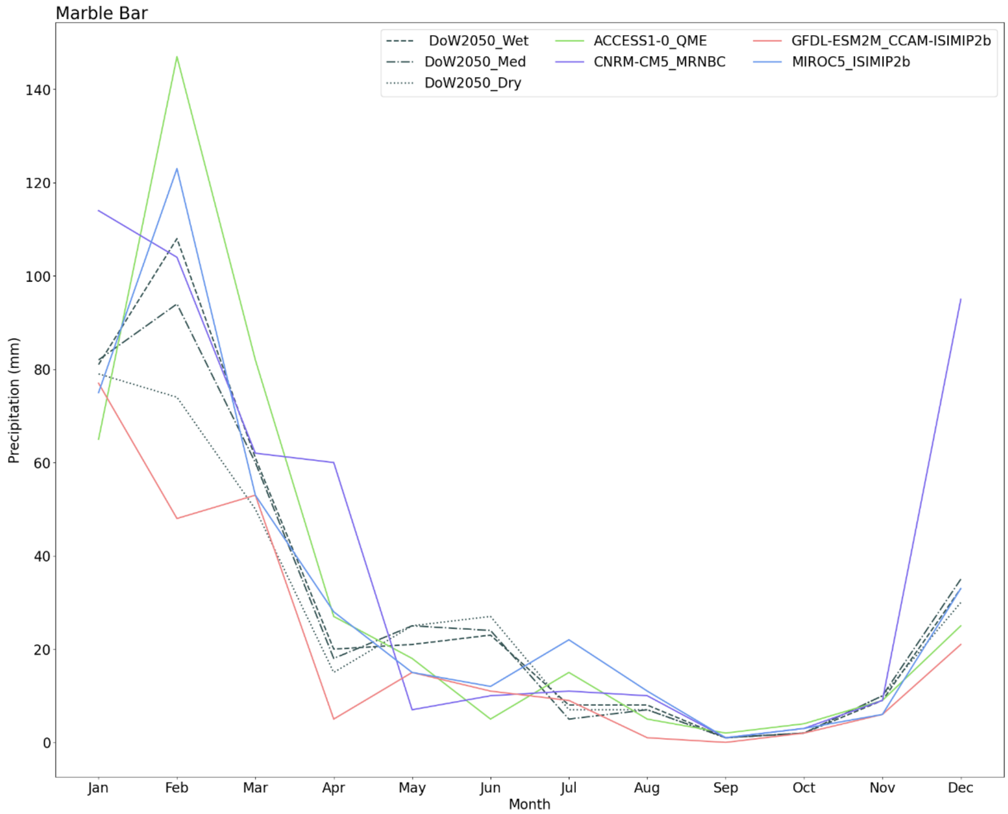


Figure 22: Average monthly projections for the DoW (2015) wet, dry and median scenarios, and NHP ensemble members: GFDL-ESM2M–CCAM-ISIMIP2b, CNRM-CM5–MRNBC, ACCESS1-0–QME and MIROC5–ISMIP2b.

Comparing annual precipitation for the 2050 time slice (2036 to 2065) has two distinct halves. In the period between 2036 and 2046, the NHP ensemble members project mostly wetter futures compared with the DoW (2015) scenarios (Figure 23). GFDL-ESM2M–CCAM-ISIMIP2b projects lower annual precipitation between 2045 and 2065. Most DoW (2015) annual peaks are surpassed by the NHP ensemble members in most years, particularly CNRM-CM5–MRNBC (Figure 23). Note that comparison of individual years between different projections is not recommended. However, projections can provide information on the changes in the occurrence and variability of extreme events that may occur within a time period.

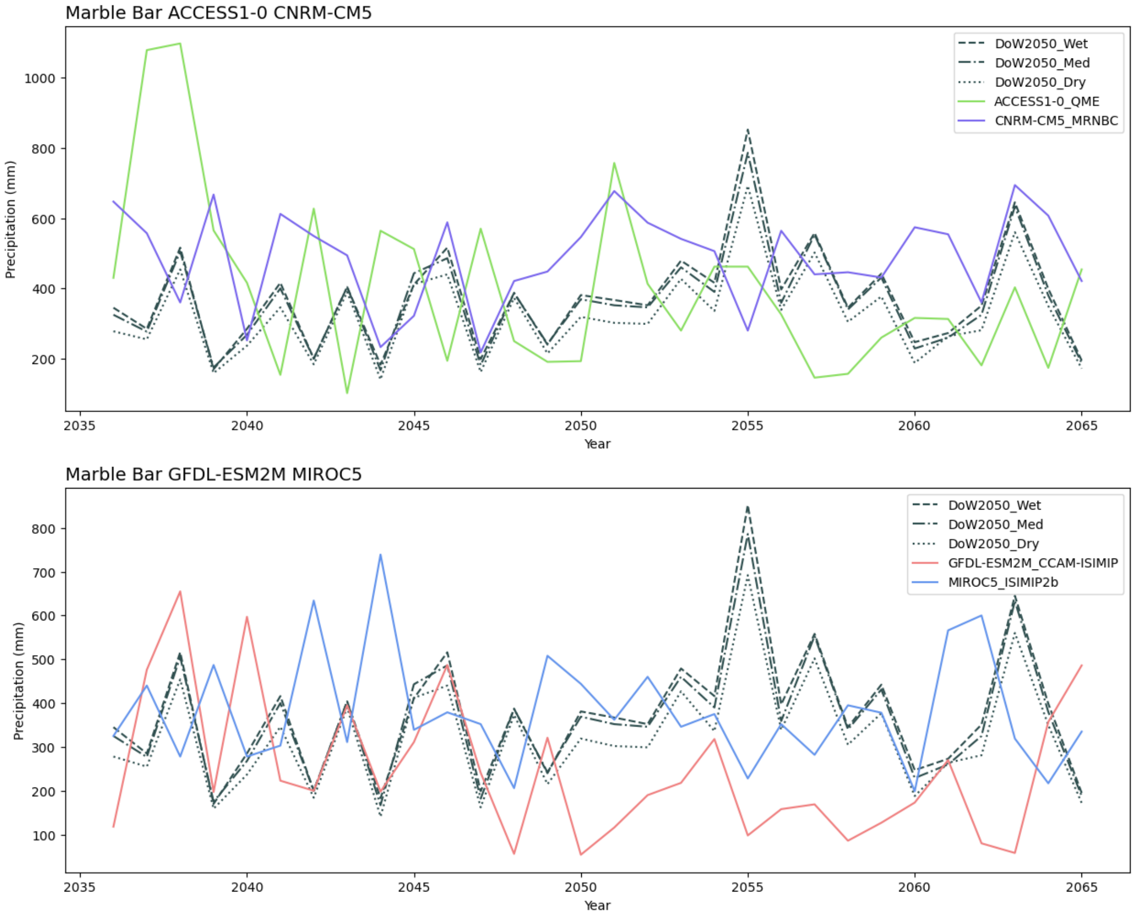


Figure 23: Annual precipitation at Marble Bar projections for the 2050 time slice (2036 to 2065), for the DoW (2015) wet, dry and median scenarios, and NHP ensemble members: GFDL-ESM2M–CCAM-ISIMIP2b, CNRM-CM5–MRNBC, ACCESS1-0–QME and MIROC5–ISMIP2b.

The four ensemble members that were chosen using storylines for the time-series comparison do not include the largest increases or decreases in projected seasonal precipitation (Figure 24). Comparing the projected change in seasonal precipitation at Marble Bar, the DoW (2015) projections – which range from a 14% decrease (warm season) to a 7% increase (cool season) – are within the range of the NHP and comparable to some of the NHP ensemble members. However, they are also considerably smaller than the full NHP projected range. In particular, cool season GFDL ensemble members project a decrease in precipitation that ranges between 36% and 69%; and most warm season CNRM ensemble members range between a 14% decrease and a 53% increase (Figure 24).

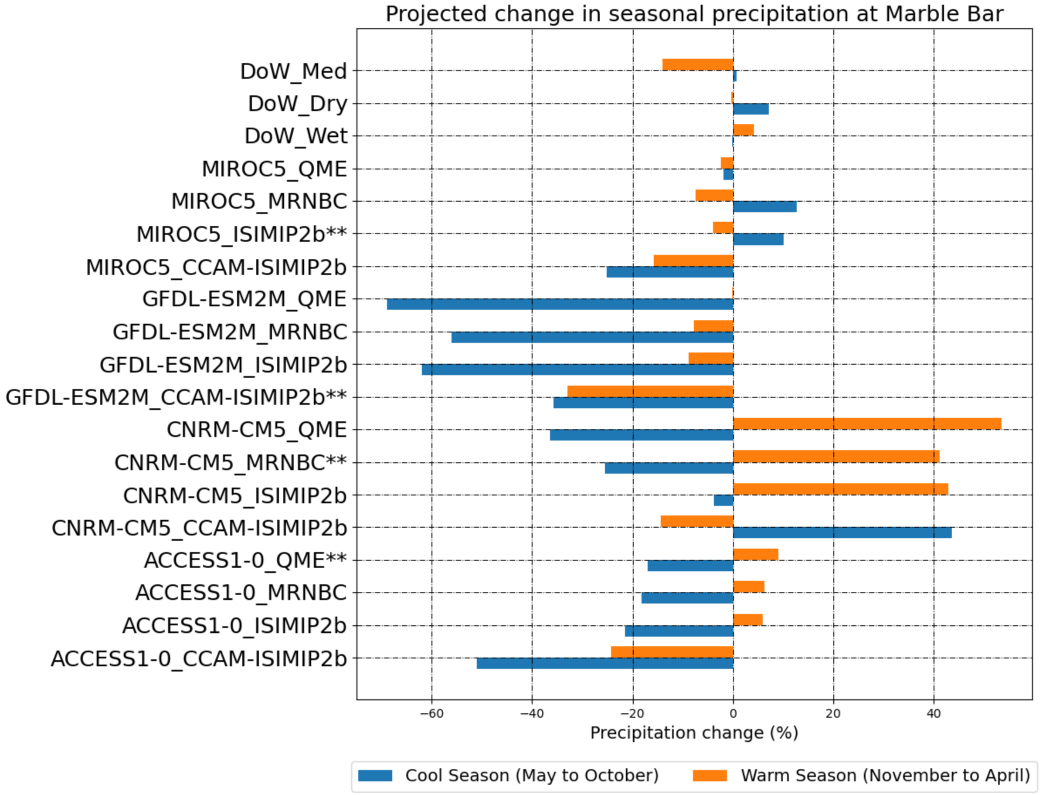


Figure 24: Relative change (%) in average annual precipitation for the warm season (November–April, orange) and cool season (May–October, blue) at Marble Bar in the Pilbara region. Change is relative to 1976–2005. Change in the DoW (2015) scenarios is relative to 1961–1990. The asterisks (**) mark the ensemble members used to compare monthly and annual time-series in Figures 22 and 23.

When considering the selection of ensemble members, practitioners should consider the key climate metrics that drive the water system as annual trends are not necessarily the driving factor in the Pilbara region. Another climate metric to consider is that the projected change in seasonal variability can differ between ensemble members. The large spread in projected change in annual and seasonal precipitation magnitude in the Pilbara region is also reflected in the projected change in precipitation variability at Marble Bar (Figure 25). For example, annual variability of cool season (May–October) precipitation is projected to decrease by ACCESS1-0 (ISIMIP2b, MRNBC, QME), CNRM-CM5 (ISIMIP2b, MRNBC, QME) and MIROC5 (ISIMIP2b, MRNBC) ensemble members. The remaining NHP ensemble members, including the CCAM regional climate model projections, project a cool season precipitation variability increase (Figure 25). The variability projected by the DoW (2015) scenarios is within the range of the chosen NHP ensemble members. The NHP ensemble projects a wider range of changes in precipitation variability for the suite of plausible futures in the Pilbara region (Figure 25).

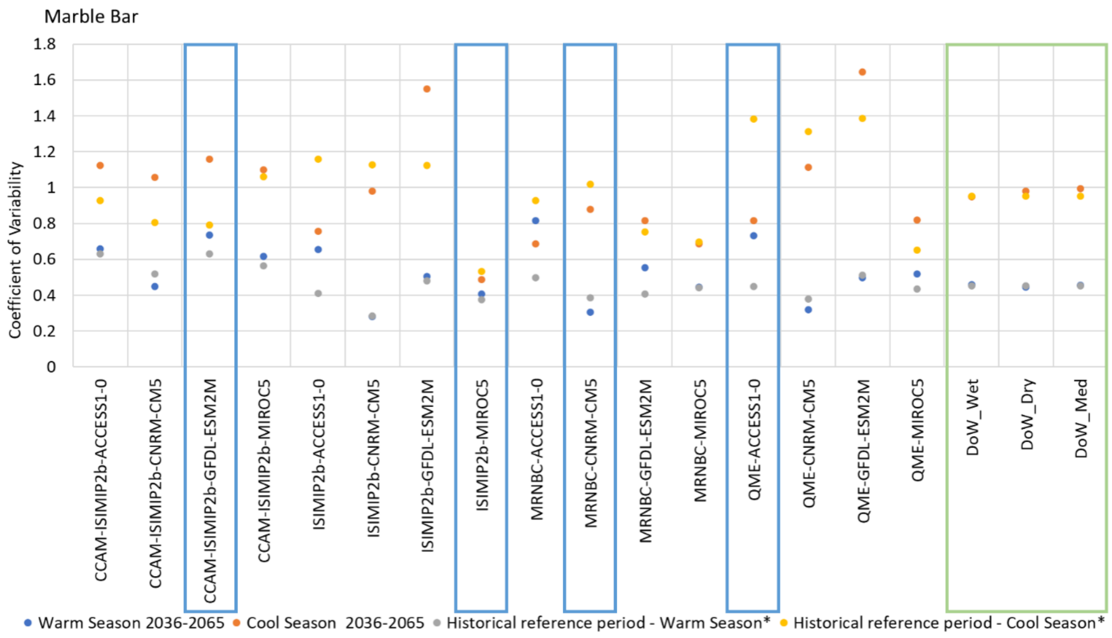


Figure 25: Annual precipitation coefficient of variability for the warm season (November–April) and cool season (May–October) at Marble Bar. The NHP historical reference period is 1976–2005. The DoW (2015) historical reference period is 1961–1990. The four blue boxes show the ensemble members used to compare the monthly and annual time-series (Figures 21 and 22).

7.3.1. Summary of comparison in the Pilbara region

Key findings of the comparison between the DoW (2015) and NHP ensembles in the Pilbara region are summarised in Table 5. Projected changes in precipitation are not consistent across the region, in space or in time.

Table 5: Comparison of 2050 precipitation projections at Marble Bar in the Pilbara region.

Season	Trends
Selected NHP storylines	GFDL-ESM2M–CCAM-ISIMIP2b: A moderate increase in precipitation variability and moderate decrease in soil moisture. MIROC5–ISIMIP2b: A small increase in precipitation variability with minimal change in soil moisture. CNRM-CM5–MRNBC: A moderate decrease in precipitation variability and a moderate increase in soil moisture. QME–ACCESS1-0: A large increase in precipitation variability with minimal change in soil moisture.
Monthly precipitation	Seasonality of monthly projections is similar for the NHP and DoW (2015) scenarios (Figure 22). The NHP has increased variability in average monthly peaks between May and August. The largest range in NHP projected average monthly precipitation is evident for February and April. These months are in the wet season and are influenced by the tropical processes that can increase uncertainty in summer precipitation projections

Season	Trends
Cool (May–October)	Projected precipitation change includes large decreases and increases shown by NHP ensemble members. Typically, the NHP projects a decrease in dry season precipitation (Figure 24). DoW (2015) has a considerably smaller change in cool season precipitation.
Warm (November–April)	Projected precipitation change included moderate decreases and large increases shown by NHP ensemble members. DoW (2015) projections are considerably smaller by comparison but within the range of NHP projections (Figure 24). On average, the NHP tends to project a wetter future for wet season precipitation (Figure 4), however drier conditions are also plausible. There is uncertainty in the ability of GCMs to simulate the tropical processes that produce summer precipitation in the Pilbara region (Oke et al. 2022).
Inter-annual variability	The annual time-series shows larger precipitation peaks and troughs projected by the NHP ensemble members compared with the DoW (2015) scenarios (Figure 25). Variability in cool and warm season precipitation is projected to change by all NHP ensemble members, yet the direction and degree of change in not consistent between ensemble members (Figure 25). The DoW (2015) projections are within the NHP range. Minimal change in variability is projected by the DoW (2015) scenarios as the pattern-scaling approach does not change the precipitation variability from the baseline period to the dry, median and wet scenarios (Figure 25).

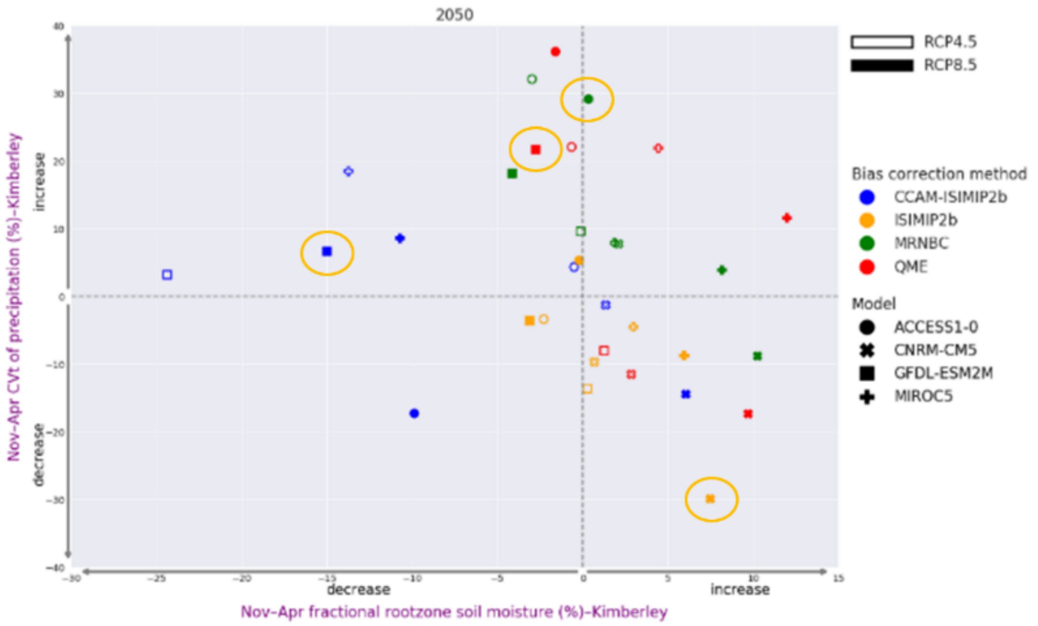
7.4. Kimberley region

The NHP ensemble projects increased warm, wet season (November–April) precipitation at the 2050 time slice under RCP 8.5 emission scenarios (Figure 3) for the Kimberley region. The cool season (May–October) has projected precipitation increases (north) and decreases at the 2050 time slice under RCP 8.5 emission scenarios (Figure 3). In the wet season the NHP ensemble has projected decreases (-18%: GFDL–CCAM-ISIMIP) to increases (18%: MIROC–QME) in annual precipitation (Figure 4). Projected annual precipitation decreases in the cool season were greater (-40%) with a wider spread, to a 25% increase projected by CNRM-CM5–MRNBC (Figure 4). GCMs do represent the influence of ESNO events in the monsoonal region of Australia (Srikanthan et al. 2022). However, uncertainty in the modelling representing changes to wet season precipitation is reflected in both large reductions and increases projected by the ensemble members. All projected precipitation changes in this region should be considered plausible futures (Srikanthan et al. 2022).

A storyline of the spread of projected change in precipitation variability versus rootzone soil moisture in the cool and warm seasons of the Kimberley region is shown in Figure 26. To capture the variability in projections, four ensemble members were chosen which reflect wet season projections:

1. GFDL-ESM2M–CCAM-ISIMIP: Small precipitation variability increases (<10%) and moderate decreases (-15%) in soil moisture.
2. GFDL-ESM2M–QME: Large increases (22%) in precipitation variability and small decreases (-5%) in soil moisture
3. ACCESS1-0–MRNBC: Large increases (30%) in precipitation variability and minimal change in soil moisture.
4. CNRM-CM5–ISIMIP2b: Large decreases (-30%) in precipitation variability and small increases (7.5%) in soil moisture.

The annual time-series of GFDL-ESM2M–CCAM-ISIMIP, CNRM-CM5–ISIMIP2b and GFDL-ESM2M–QME relative to the whole ensemble for the Kimberley are shown in Figure 27. The chosen ensemble members represent a median, low and high end of projected precipitation in relation to the median of the NHP ensemble.



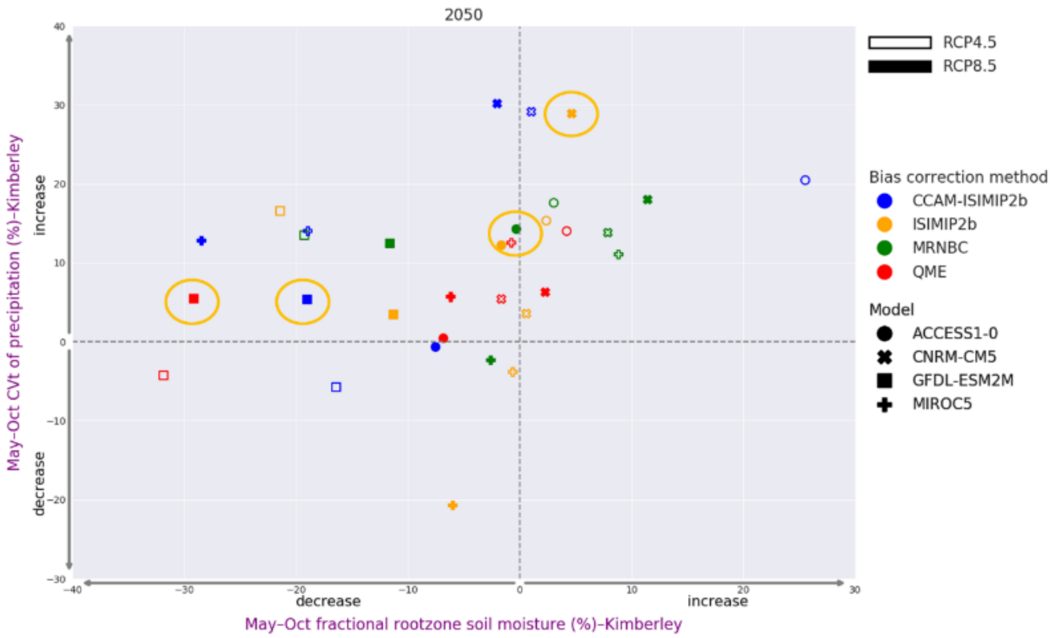


Figure 26: Projected change (%) in precipitation variability versus change (%) in rootzone soil moisture in the Kimberley region during the cool season (May–October) (bottom) and warm season (November–April) (top). The ensemble members chosen for storylines (circled) to investigate differences in projected change in precipitation at 2050 in the Kimberley region include: ACCESS1-0–MRNBC, CNRM-CM5–ISIMIP2b, GFDL-ESM2M–CCAM-ISIMIP2b and GFDL-ESM2M–QME.

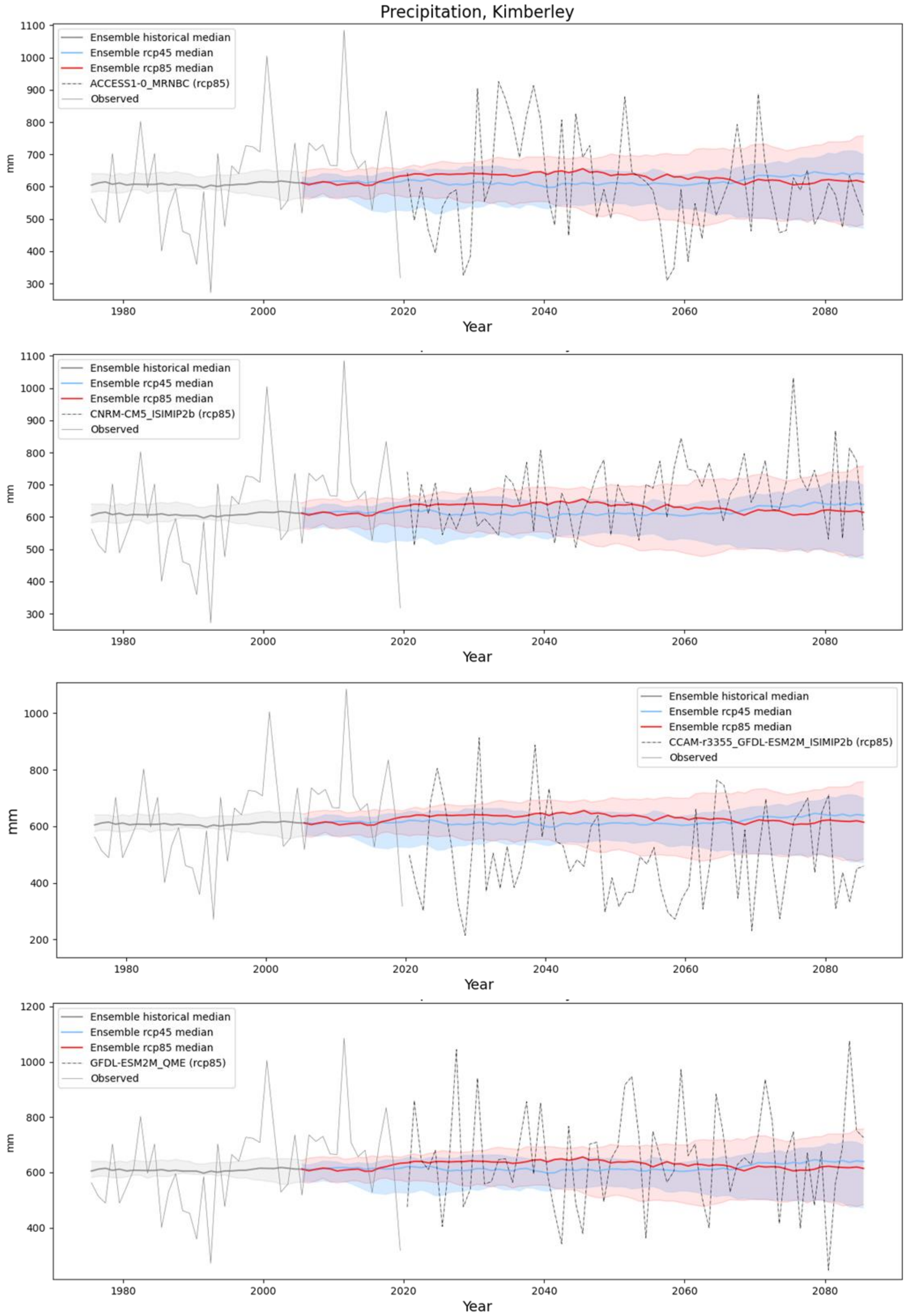


Figure 27: Annual modelled precipitation projected to 2099 by the 16-member ensemble for RCP 4.5 (blue) and RCP 8.5 (red) in the Kimberley region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. The grey line represents the observed historical median precipitation based on AWAP data. The dashed lines represent the selected ensemble members: ACCESS1-0–MRNBC, CNRM-CM5–ISIMIP2b, GFDL-ESM2M–CCAM-ISIMIP2b, GFDL-ESM2M–QME.

Comparing average monthly precipitation projected by DoW (2015) and the NHP at Fitzroy Crossing shows there is strong agreement between the DoW (2015) and NHP scenarios between May and October (Figure 28). CNRM-CM5–ISIMIP2b, GFDL-ESM2M–QME and ACCESS1-0–MRNBC project greater average monthly precipitation between November and March (Figure 28). The GFDL-ESM2M–CCAM-ISIMIP2b projects lower precipitation compared with the DoW (2015) scenarios. The spread of NHP summer wet season precipitation projections is influenced by the ability of GCMs to simulate the key climate drivers associated with monsoonal summer precipitation in this region.

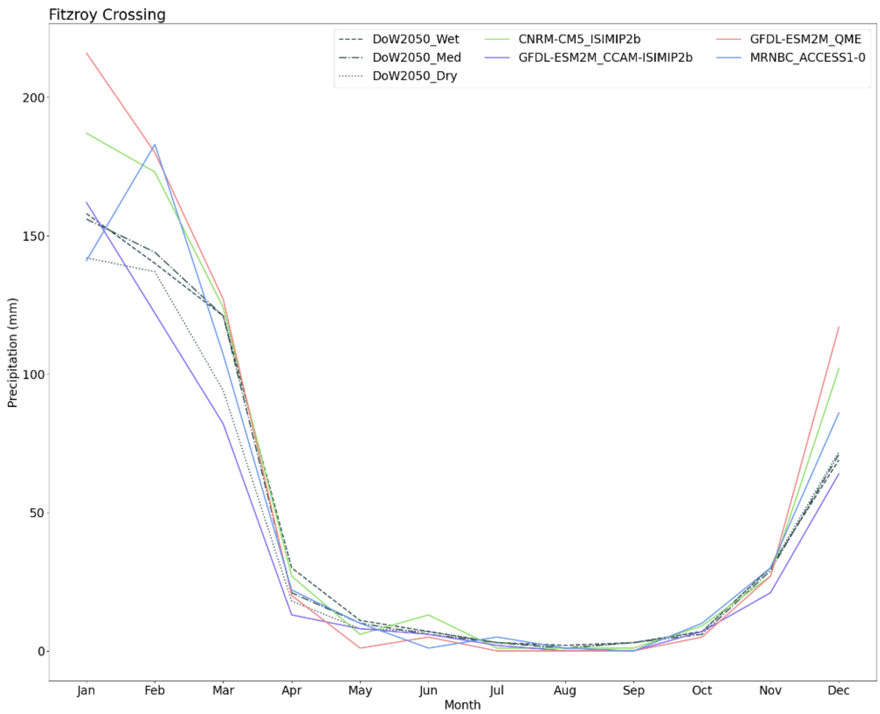


Figure 28: Monthly projections for DoW (2015) wet, dry and median scenarios, and NHP ensemble members: ACCESS1-0–CCAM-ISIMIP2b, CNRM-CM5–ISIMIP2b, ACCESS1-0–MRNBC and GFDL-ESM2M–QME at Fitzroy Crossing.

The annual time-series of the 2050 time slice (2036–2065) of the DoW (2015) and four NHP ensemble members at Fitzroy Crossing are shown in Figure 29. Greater variability is evident in the NHP ensemble members. When comparing variability, practitioners should not consider individual years or the timing of events, but rather the magnitude and frequency of wet years and dry years throughout a time-slice period. The NHP ensemble members project higher wet years throughout the series, particularly GFDL-ESM2M–QME, ACCESS1-0–MRNBC and CNRM-CM5–ISIMIP2b. Precipitation projected by GFDL-ESM2M–CCAM-ISIMIP2b reduces between 2047 and 2065 and is lower than the DoW (2015) scenarios.

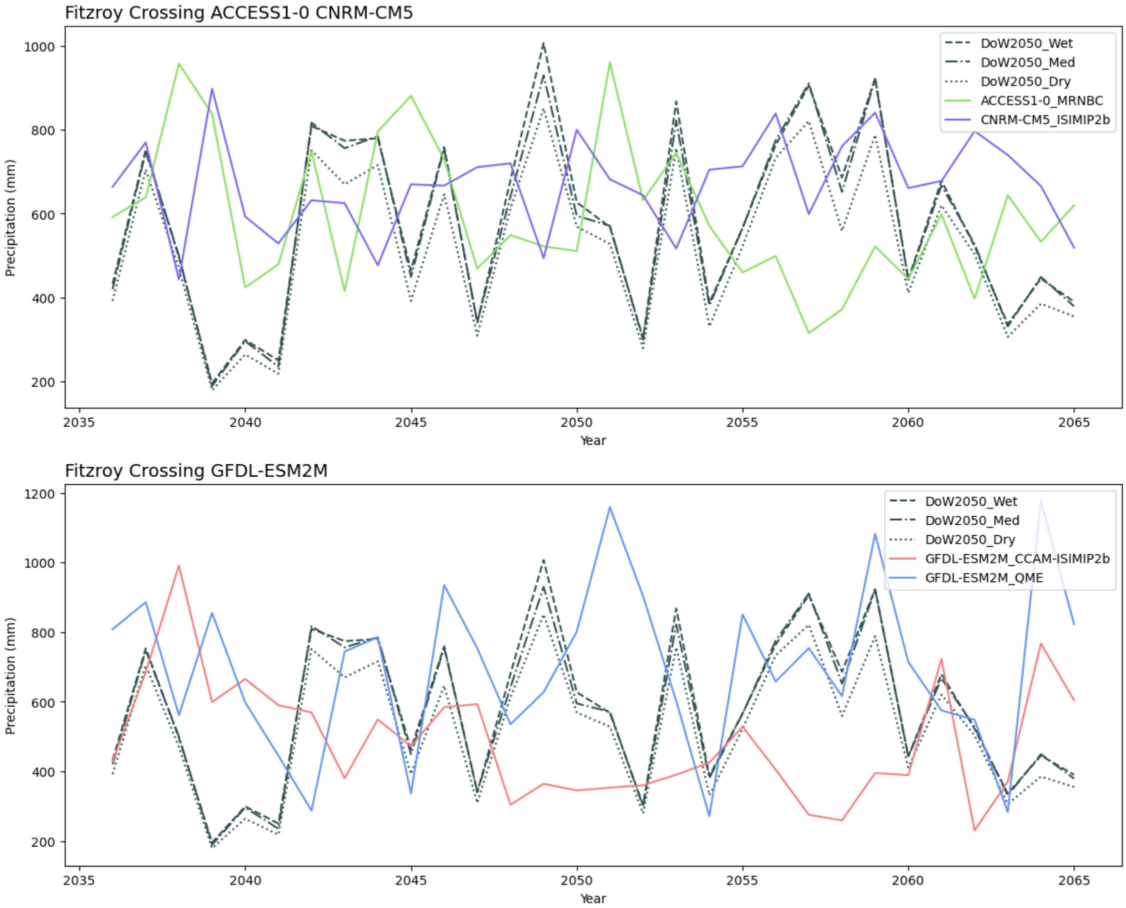


Figure 29.:Annual time-series for the DoW (2015) wet, dry and median scenarios, and NHP ensemble members.

NHP show a large decrease in cool season (May–October) precipitation by GFDL-ESM2–QME (-52%), with most other NHP ensemble members projecting between an 8% increase and 22% decrease in average annual cool season precipitation (Figure 30). Three NHP ensemble members project increases including CNRM-CM5 (3%: ISIMIP; 8%: CCAM-ISIMIP2b), and ACCESS1-0–ISIMIP2b (2%). The four NHP ensemble members chosen for comparison project some of the largest decreases in cool season precipitation (e.g. GFDL-ESM2M–QME and CCAM-ISIMIP2. In the wet, warm season (November–April), average annual precipitation changes projected by the NHP ensemble member range from -17% to 21%, with most NHP projections showing an increase in wet season precipitation. The DoW (2015) scenarios project changes in warm and cool season precipitation that fall within the NHP ensemble members (Figure 30).

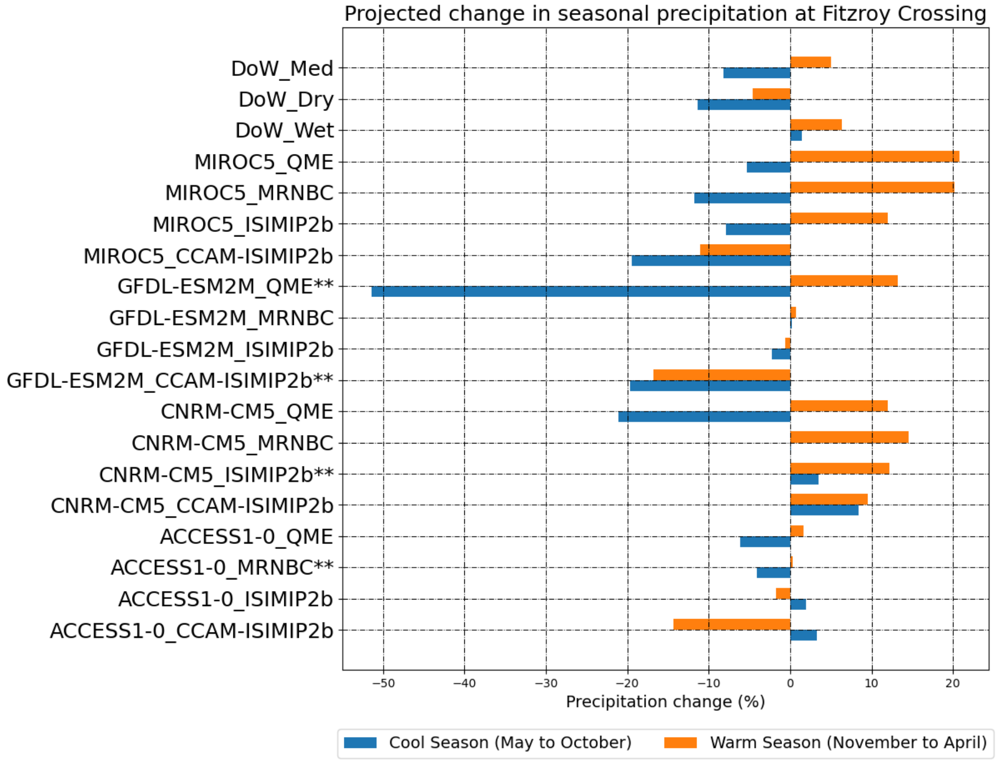


Figure 30: Relative change (%) in average annual precipitation for the warm season (November–April, orange) and cool season (May–October, blue) at Fitzroy Crossing in the Kimberley region. Change is relative to 1976–2005. Change in the DoW (2015) scenarios is relative to 1961–1990. The asterisks (**) mark the ensemble members used to compare the monthly and annual time-series in Figures 28 and 29.

All NHP ensemble members and the DoW (2015) scenario show higher precipitation variability in the cool season during the historical reference period (Figure 31). Increases in cool season precipitation variability is projected for three of the four NHP ensemble members chosen for comparison, GFDL–CCAM-ISIMIP2b being the exception (Figure 31). As expected, there was negligible change in the cool and warm season precipitation variability projected by the DoW (2015) scenarios, as the pattern-scaling approach does not change the precipitation variability from the baseline period to the dry, median, and wet scenarios.

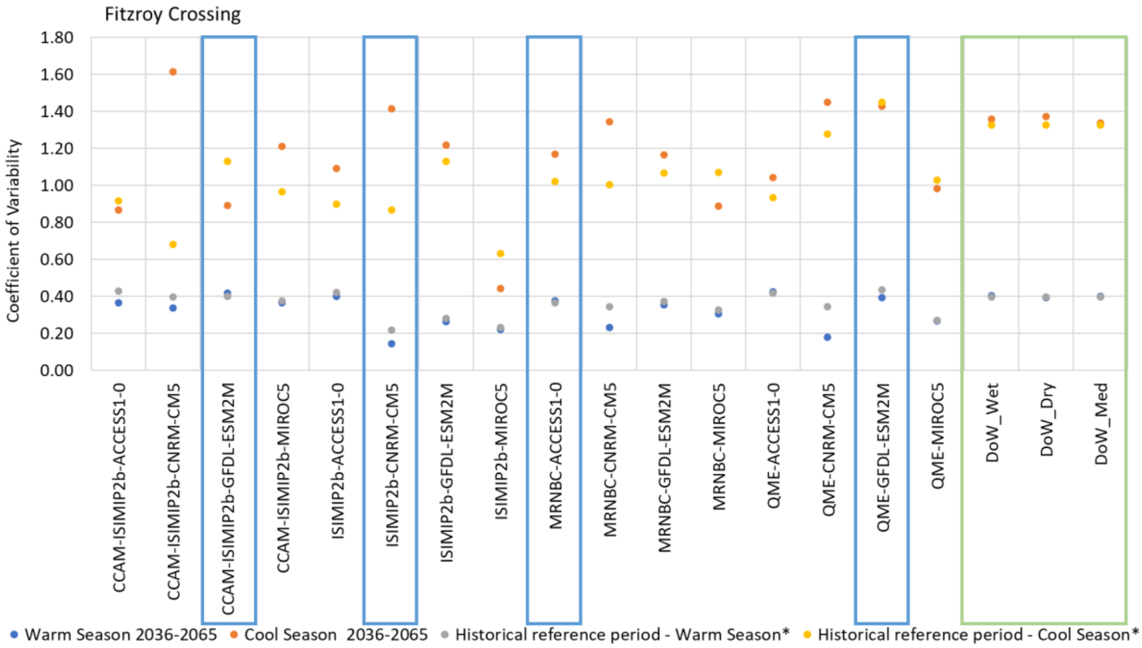


Figure 31: Annual precipitation coefficient of variability for the warm season (November–April) and cool season (May–October) at Fitzroy Crossing. The NHP historical reference period is 1976–2005. DoW (2015) historical reference period is 1961–1990. The four blue boxes show the ensemble members used to compare the monthly and annual time-series (Figures 26 and 27).

7.4.1. Summary of comparison in the Kimberley region

Key findings of the comparison between the DoW (2015) and NHP ensembles in the Kimberley region are summarised in Table 6.

Table 6: Comparison of 2050 precipitation projections at Fitzroy Crossing in the Kimberley region

Season	Trends
Selected NHP storylines	GFDL-ESM2M–CCAM-ISIMIP: Small precipitation variability increases (<10%) and moderate decreases (-15%) in soil moisture. GFDL-ESM2M–QME: Large increases (22%) in precipitation variability and small decreases (-5%) in soil moisture. Acess1-0–MRNBC: Large increases (30%) in precipitation variability and minimal changes in soil moisture. CNRM-CM5–ISIMIP2b: Large decreases (-30%) in precipitation variability and small increases (7.5%) in soil moisture.
Monthly precipitation	Seasonality of monthly projections is comparable between the NHP and DoW (2015) scenarios, particularly between May and October (Figure 28). Monthly precipitation projected by NHP ensemble members is higher than DoW (2015) scenarios between November and March (CNRM-CM5–ISIMIP2b, GFDL-ESM2M–QME and ACCESS1-0–MRNBC).

Season	Trends
Cool (May–October) Warm (November–April)	The DoW (2015) scenarios project changes in warm and cool season precipitation variability that fall within the precipitation change projected by NHP ensemble members (Figure 30). The four NHP ensemble members chosen for comparison project some of the largest decreases in cool season precipitation, such as GFDL-ESM2M (QME and CCAM-ISIMIP2b). The spread of change in projected precipitation including both increases and decreases is comparable between DoW (2015) and NHP ensemble members. However, practitioners should consider the spread of projected change within the NHP ensemble when choosing ensemble members for further investigation.
Inter-annual variability	NHP projects greater interannual variability and larger wet years and dry years in precipitation compared with the DoW (2015) scenarios (Figure 29). Projected precipitation variability differs between ensemble members. Cool season (May–October dry season) variability is projected to increase by the NHP ensemble members (Figure 31), Minimal projected changes in variability change are evident in the warm season and DoW (2015) scenarios (both cool and warm season) as the pattern-scaling approach does not change the precipitation variability from the baseline period to the dry, median and wet scenarios.

8. Hydrological impacts: aridity and dry conditions projected for 2050

8.1. Projected changes in aridity index

The change in aridity projected for 2050 was investigated using the four storyline ensemble members at Perth Airport, Scadden, Morowa, Gascoyne Junction, Marble Bar and Fitzroy Crossing. This analysis was not carried out for the DoW (2015) projections. It is included to illustrate how the aridity projected by the four storylines chosen for comparison can vary within a region, and over time.

Aridity index quantifies water deficiencies within a region: the smaller the aridity index the more arid a region. It is calculated by:

$$Aridity\ Index = \left(\frac{Total\ \ annual\ precipitation}{Total\ \ annual\ PET}\right)$$

Aridity anomaly = projected annual aridity index – averaged annual historical aridity index

- A negative anomaly = projected aridity index < historical aridity index. Aridity of a site is projected to increase.
- A positive anomaly = projected aridity index > historical aridity index. Aridity of a site is projected to decrease.

Aridity is projected to increase in most years within the 2050 (2036–2065) time slice at Perth Airport, Scadden, Morawa and Gascoyne Junction. For some years CNRM-CM5–ISIMIP2b, MIROC5–CCAM-ISIMIP2b and ACCESS1-0–MRNBC ensemble members project a decrease in aridity (positive anomaly – Figure 32). This reflects the wetter warm season projected by these ensemble members (Figure 10, Figure 18). The consistent negative anomalies projected by GFDL-ESM2M–QME, MIROC5–CCAM-ISIMIP2b for sites in the South West region reflect the drying conditions projected for both the warm and cool seasons, particularly for the MIROC5 and GFDL-ESM2M within this region (Figure 10).

In the Pilbara and Kimberley regions, the spread of changes in aridity at Marble Bar and Fitzroy Crossing reflects the plausible spread of futures projected by ensemble members. It is driven by less model agreement of projected precipitation, in contrast to high confidence in the potential evapotranspiration and temperature in the northern regions (Srikanthan et al. 2022). One example is the distinct difference in projected aridity changes between years by GFDL-ESM2M–QME and GFDL-ESM2M–CCAM-ISIMIP2b at Fitzroy Crossing. The influence of increased warm (wet) season precipitation is shown by a positive anomaly projected by CNRM-CM5 and ACCESS1-0 ensemble members at both Marble Bar and Fitzroy Crossing (Figure 29). In these regions the variability in projected aridity is driven by less certainty in the projected precipitation.

The drying trend projected in the South West is reflected in the large portion of negative aridity anomalies at Scadden, Perth Airport and Morowa (Figure 32) across the period. The year-to-year variability of aridity anomalies at Marble Bar and Fitzroy Crossing reflects the large spread of increased and decreased precipitation projections in these regions. CNRM-CM5, which projects more wet years, consistently projects a decrease in aridity (more positive anomalies). In contrast, GFDL-ESM2M, which projects more dry years, consistently projects increasing aridity (more negative anomalies). As stated previously, comparing individual years between ensemble members is not recommended, however a region's aridity can be considered across the time slice as a whole.

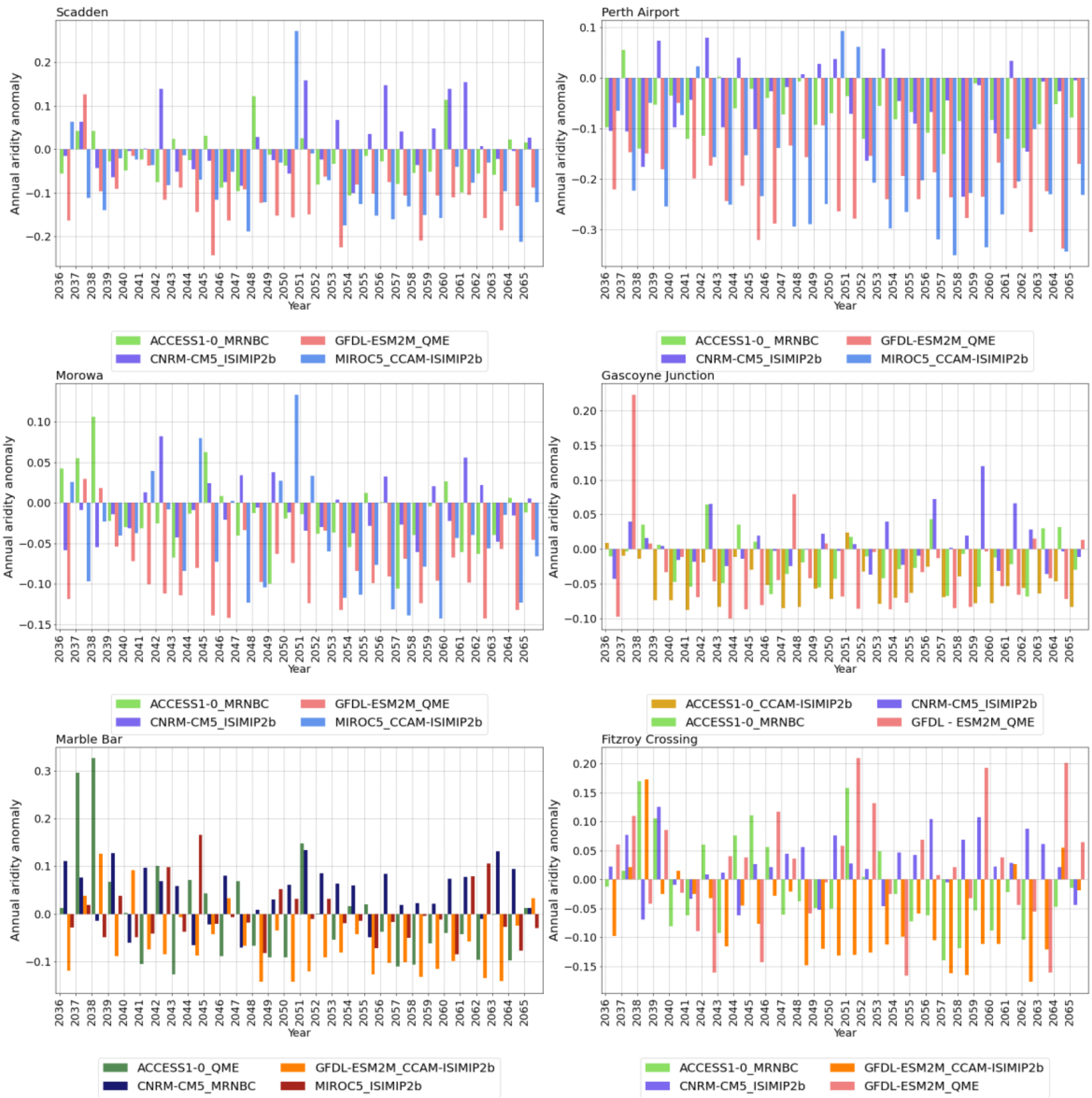


Figure 32: Annual aridity anomaly projected for 2050 at Scadden, Perth Airport, Morowa, Gascoyne Junction, Marble Bar and Fitzroy Crossing. Anomaly equals projected annual aridity (total precipitation/total potential evapotranspiration) minus historical average annual aridity.

8.2. Dry conditions

Projected extreme dry events were investigated through meteorological (precipitation), hydrological (runoff) and agricultural (soil moisture) indicators. A meteorological extreme dry state refers to an area being subject to below-average precipitation that results in dry landscape conditions. A hydrological extreme dry state refers to when water resources are insufficient; for example, in rivers and water storages. An agricultural extreme dry state is determined through the impacts of soil moisture deficits on crops and vegetation and its subsequent effect on livestock (Srikanthan et al. 2022).

Frequency (% average time in drought), duration (average number of months) and intensity (% relative change) was calculated for each projection for the Kimberley, Pilbara, Central West and South West regions. An extreme dry condition is defined by applying a threshold quantile of 15% (derived from a two-year rolling average) to future projections. Any month below the 15% threshold is classified as being in drought. The 15th percentile corresponds approximately to a threshold of −1 for the widely used Standardised Precipitation Index (SPI) (McKee et al. 1993; Matic et al. 2022). We use this threshold to ensure we have a sufficient number of dry conditions to infer trends in drought metrics reliably. Previous work has shown that while simulated drought characteristics can be somewhat sensitive to the choice of threshold, inter-model differences represent a much greater source of uncertainty (Ukkola et al. 2018); (Matic et al. 2022). Duration is defined as the number of consecutive months for which the hydrological variable is below the drought threshold. As we use 3-month running means to determine droughts, the minimum drought duration is 3 months. Intensity is the relative difference between the climatological mean and the running-mean monthly value (expressed as %), averaged across all the months during a drought event. Frequency was calculated as the percentage of months for which the hydrological variable was below the drought threshold during a given time period.

Dry conditions have been assessed at Perth Airport, Scadden, Morowa, Gascoyne Junction, Marble Bar and Fitzroy Crossing (Figure 33). The duration, frequency and intensity of extreme dry conditions are all projected to increase across the NHP ensemble. The projected drought frequency (percentage of time in drought) is variable between NHP ensemble members within each region. Frequency of dry conditions has the largest range in the South West region, which also has the greatest duration (number of months) and greatest increase in intensity (Figure 32).

Aridity index and meteorological, hydrological and agricultural indicators show the impact of projected precipitation changes on runoff and soil moisture in each region. Utilising these indicators is a useful tool to explore the variation of impacts at a site or within a region. This will aid the selection of ensemble members to further investigate hydrological and catchment processes.

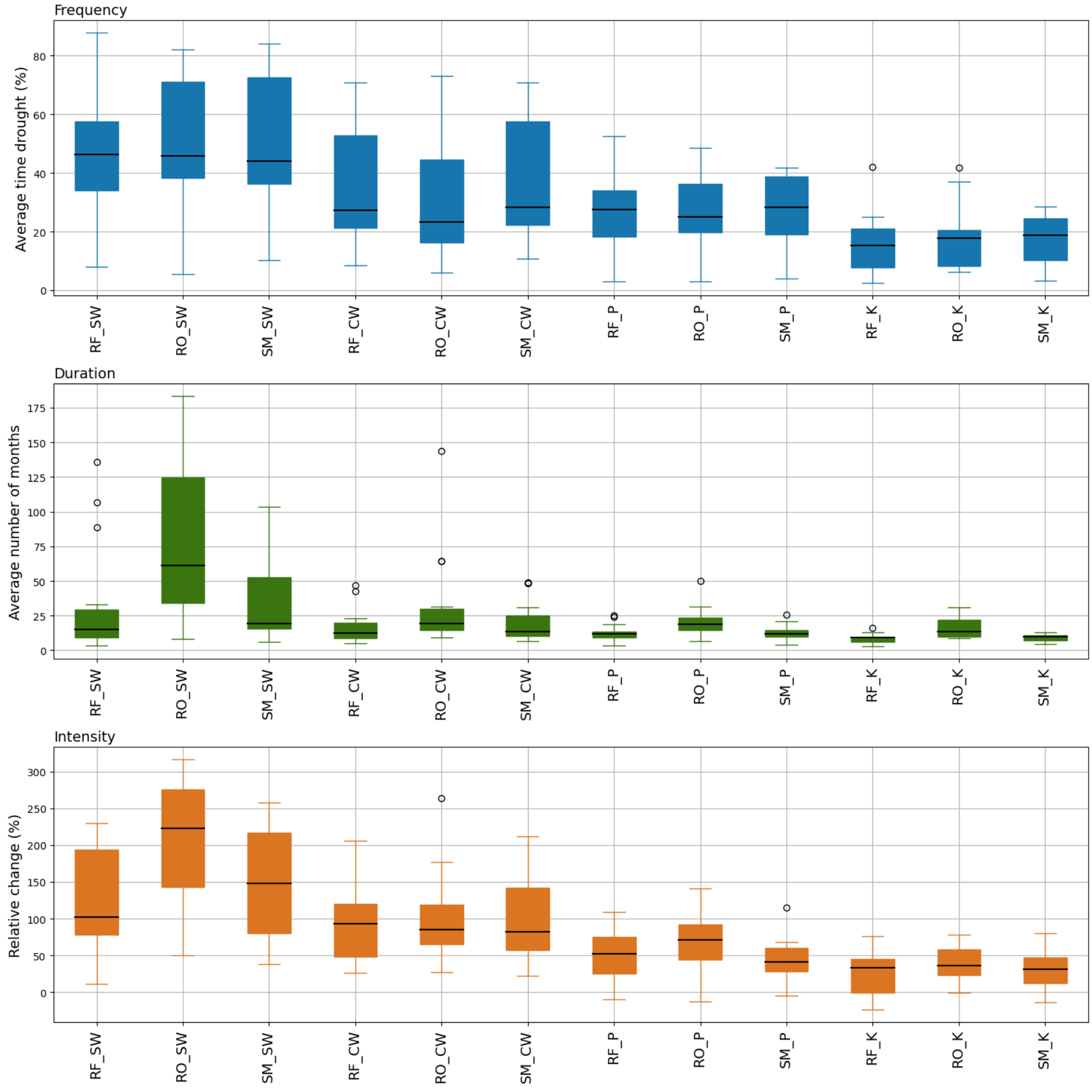


Figure 33: Frequency (% average time in drought), duration (average number of months) and intensity (% relative change in intensity) of meteorological (RF: precipitation), hydrological (RO: runoff) and agricultural (SM: soil moisture) droughts for 2050 (2036 – 2065), in the Kimberley (K), Central West (CW), Pilbara (P) and South West (SW) regions. An extreme condition is defined by 15% quartile of the historical period.

9. Application of NHP in water resource planning and assessment

A storyline approach (Shepherd et al. 2018) was used to select NHP ensemble members to represent a range of hydroclimatic changes in recent years, such as the reduction in cool season precipitation in south-western Western Australia or increases in precipitation variability in the state's north. The comparison of the NHP ensemble subset and DoW (2015) scenarios in each region provides an overview of projected hydroclimatic characteristics for practitioners to consider when they apply the NHP.

DWER has released an updated *'Guide to future climate projections for water management in Western Australia'* (DWER 2024). The guide provides a practical framework for water resource planners and decision-makers to use climate change projections in climate impact and risk assessments. The guide recommends practitioners refer to this consistency assessment, as well as to similar assessments for the location of interest, before re-doing any climate assessments underpinned by DoW (2015) projections. Practitioners should consider whether previous water resource decisions may change based on the NHP and whether they need to be updated or not.

Another recommendation is for current practice to move away from using wet, median and dry scenarios, as outlined in DoW (2015), towards a 'storyline approach' that allows a risk-based assessment to investigate the full range of plausible future projections with a subset of projections for detailed analysis. The results of this assessment show that when practitioners are choosing projections to represent plausible futures within a region, they should investigate the differences that may be evident in the climate characteristics that drive the water resource system. For example, annual totals, cool and warm season precipitation patterns, annual precipitation variability and changes in the aridity index within and between regions.

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