Australian Government
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Monsoonal North — National Hydrological Projections Assessment report

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Cover image: View of Lake Argyle nearby Kununurra, Western Australia - this reservoir lake is full of freshwater crocodiles and is a popular place for fishing and various family water sports, PetroGraphy, 30 March, 2017,

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1 Introduction to the National Hydrological Projections

Australia's climate is changing: temperatures are increasing and precipitation patterns are shifting, as described in the *State of the climate 2020* (CSIRO & Bureau of Meteorology 2020). On average, Australia has warmed by 1.44 ± 0.24 °C since national records began in 1910. Streamflow has changed across the country, broadly increasing in the north and decreasing in the south. The *State of the climate 2020* reports that, in Australia's south-west, cool-season (May–October) precipitation has declined by around 16% since 1970. The decrease is even more pronounced for the winter months (May–July) for the same period. In the south-east of Australia, precipitation started to decline around 1990, and the average cool-season precipitation from 2000 to 2019 was 12% less than last century (CSIRO & Bureau of Meteorology 2020). Along with this observed decline in precipitation, streamflow has declined substantially in both the south-west and south-east; changes in streamflow are typically disproportionally larger than changes in precipitation (Chiew 2006; Wasko et al. 2021; Zhang et al. 2016). In contrast, precipitation has increased across many northern parts of the country, and streamflow follows this trend (Zhang et al. 2016).

With rising greenhouse gas (GHG) levels in the atmosphere, temperature changes are projected to continue and intensify in the future, causing further warming and changes in all components of the climate and hydrological system (CSIRO & Bureau of Meteorology 2015). Given the limited water available for many Australian communities, businesses, governments and environments, these changes represent ongoing challenges to the management of Australia's water resources. The future security of our food and energy supplies, and our ecosystems, depends on water availability, as the demand for water is also growing.

To ensure that future water needs are met, decision-makers need forward-looking datasets and methods to evaluate a range of conceivable futures while accounting for uncertainty. The National Hydrological Projections product suite supports the process of strategic decision-making processes for future water resource management, adaptation and water policy developments. It consists of nationally consistent hydrological projections datasets, information and guidance material on future changes in Australia's projected hydrological variables.

The National Hydrological (NHP) Projections service complements projections work that has been undertaken by many federal and state governments, universities, and other organisations across Australia. A broad overview of available projections for Australia is given in Table 1.1. It is important to understand the varying nature of these projections including NHP in selected global climate models and their generation, greenhouse gas emission pathways, downscaling methods, spatial resolution, output variables and anticipated purpose ahead of their use. Further details about the Australian projections landscape, guidance material and readily available projections datasets can be found here: https://www.climatechangeinaustralia.gov.au/en/overview/about-site/landscape/

Table 1.1. Projections landscape for Australia

Name	State	Link
Climate Change in Australia	National	https://www.climatechangeinaustralia.gov.au/en/
Electricity Sector Climate Information	National	https://www.energy.gov.au/government-priorities/energy-security/electricity-sector-climate-information-esci-project
NSW and Australian Regional Climate Modelling project	New South Wales/Australian Capital Territory	https://climatedata-beta.environment.nsw.gov.au/
Climate Change NT	Northern Territory	https://climatechange.nt.gov.au/
Long Paddock	Queensland	https://www.longpaddock.qld.gov.au/qld-future-climate/
SA Climate Ready	South Australia	https://environment.sa.gov.au
Climate Futures for Tasmania	Tasmania	https://climatefutures.org.au/projects/climate-futures-tasmania/
Victorian Climate Projections 2019 Victorian Water and Climate Initiative	Victoria	https://www.climatechangeinaustralia.gov.au/en/projects/victorian-climate-projections-19 https://www.water.vic.gov.au/climate-change/reserach/vicwaci
Western Australian climate projections	Western Australia	https://www.wa.gov.au/government/publications/western-australian-climate-projections-summary

1.1 Developing the National Hydrological Projections

Broadly, the National Hydrological Projections were produced by choosing representative emission pathways (RCPs) and using a number of global climate model (GCM) inputs to run with a hydrological landscape water balance model (Figure 1.1).

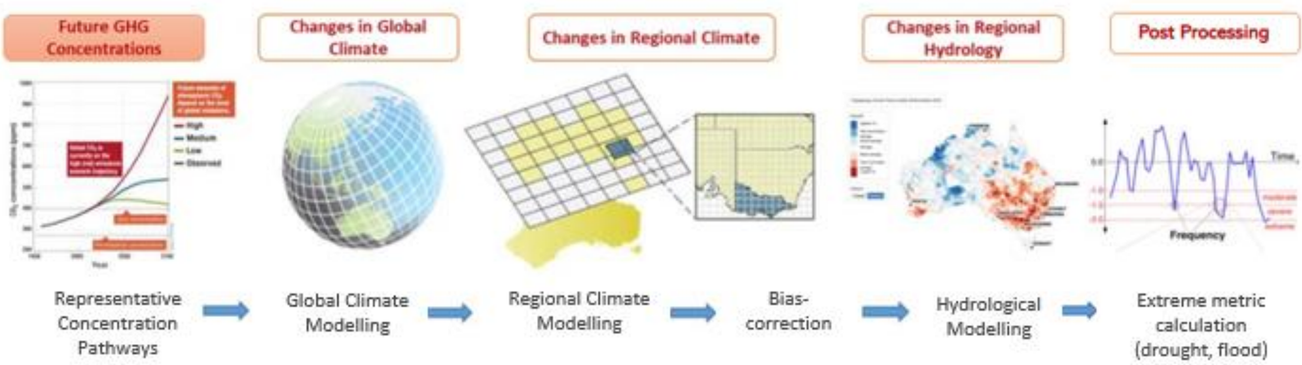


Figure 1.1. National Hydrological Projections workflow principles showing the processing steps: i) selecting representative concentration pathways, ii) running the 4 selected global climate models and also a regional climate model, iii) correcting the discrepancies between climate input and observation (bias correction) to produce the climate data, iv) running the climate data through a hydrological model to project hydrological changes and v) calculating projected hydrological extremes

State-of-the-art techniques were used to resolve the climate data to a finer geographic scale and correct for biases (to adjust for discrepancies between observations and the climate models). The resultant climate data was processed through a hydrological model to produce projections of future hydrological changes and extreme conditions.

Australian and international climate modelling groups simulate the world's weather and climate with global climate models under historical and future forcing from greenhouse gases as well as from atmospheric and solar forcing ('forcing' is the term used to describe the impacts of factors that affect Earth's climate). The models used for the National Hydrological Projections stem from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012) undertaken by the World Climate Research Programme's Working Group on Coupled Modelling (WGCM) (PCMDI 2021).

First, 2 future scenarios were selected to represent potential future pathways of greenhouse gas concentrations, aerosols and other atmospheric chemical constituents: medium (RCP4.5) and high (RCP8.5) emissions of greenhouse gases (RCP stands for 'representative concentration pathway') (Figure 1.2). The medium RCP4.5 scenario sees emissions peak by mid-century at around 50% higher than the 2000 level then rapidly decline over 30 years before stabilising at half of the 2000 level. The high RCP8.5 greenhouse gas emission scenario simulates rapid emission increases through early and middle parts of the century to reach 950 ppm CO_2 by 2100. Both RCP4.5 and RCP8.5 were the only RCPs available for a dynamically downscaled regional climate model over Australia.

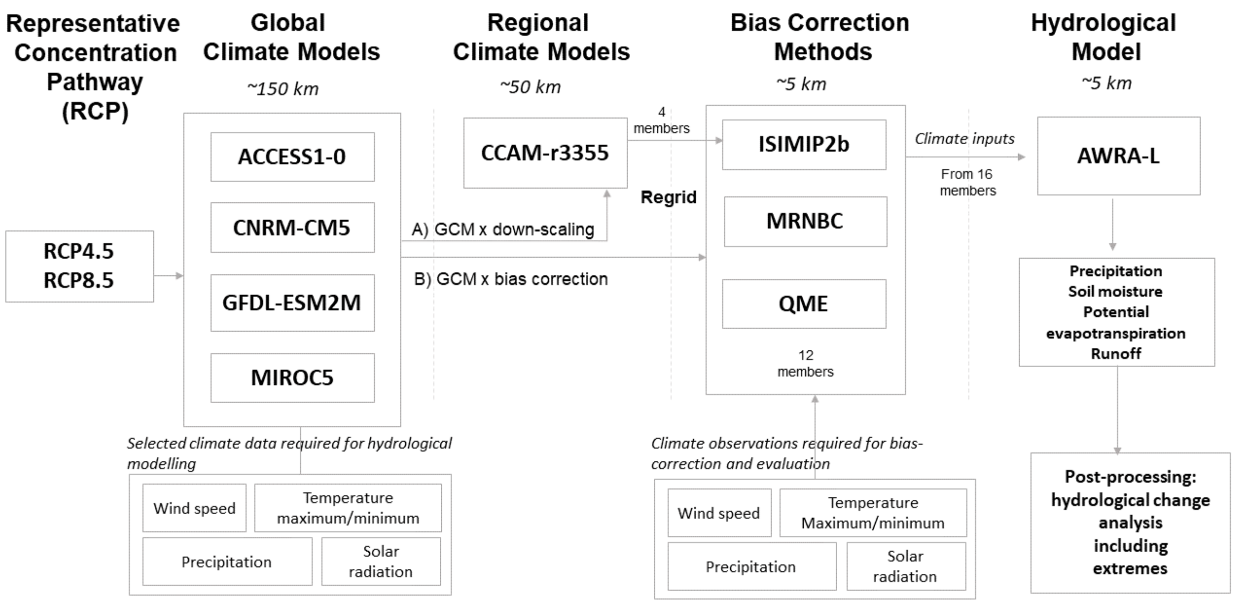


Figure 1.2. National Hydrological Projections showing details of the processing steps: i) 2 representative concentration pathways (RCP4.5 as medium and RCP8.5 as high) are selected, ii) 4 CMIP5 global climate models (GCMs) are selected, iii) path A – each GCM is downscaled by a regional climate model (RCM) to a 50km (0.5°) scale and then re-gridded to a 5 km (0.05°) scale. The RCM uses one bias-correction method (ISIMIP2b) that corrects the necessary climate inputs (precipitation, temperature, wind and solar radiation) against observations, iv) path B – each GCM is re-gridded to a 5 km (0.5°) scale and corrected directly using one of 3 bias-correction methods, and v) climate data from the 16-member ensemble is used to run the hydrological Australian Water Balance Model (AWRA-L) to produce hydroclimate change information for precipitation, soil moisture, runoff and evapotranspiration. These hydroclimatic variables are processed to understand future changes on the Australian water cycle components, including extremes

As shown in Figure 1.2, 4 CMIP5 GCMs were chosen, each with a spatial resolution of about 150 kilometres (km) (Srikanthan et al. 2022). These climate models were chosen as a subset of the models used in the Climate Change in Australia assessment (see Chapter 5 in CSIRO & Bureau of Meteorology 2015). The 4 global climate models were selected to represent a range (wet, medium and dry) of plausible future climates across Australia and for their ability to provide all the necessary climate inputs for the Australian Water Resources Assessment Landscape hydrological model (AWRA-L, version 6.1) (Frost & Wright 2018). In addition, a regional climate model (RCM) was used to bring each of the 4 selected GCMs to a finer resolution output of about 50 square kilometres (km^2) over Australia. These regional models better account for regional climatic influences, such as local topography.

Before using climate inputs from climate models, biases in the global and regional climate model forcing were corrected against observations in a process called bias correction. Three bias-correction methods were applied to the climate data from the models, resulting in the following 16-member ensemble (Figure 1.2):

- 12 members – comprising each of the 4 global climate models corrected with 3 different bias-correction methods
- 4 members – comprising each of 4 global climate models, downscaled and adjusted to a finer resolution as a regional climate model and corrected with one bias-correction method.

Each ensemble member reflects the chosen characteristics of its bias-correction method; the range of ensemble members lets decision-makers select the approach best suited to their needs.

To examine future impacts of climate change and to inform decisions on adaptation, outputs from the climate modelling process were re-gridded to a 5 km scale and used in our hydrological model to provide projections at that scale across Australia. 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 over Australia of soil moisture, runoff and potential evapotranspiration (the amount of evaporation and transpiration that would occur at a particular location when water available for this process is non-limited).

To assess hydrological changes, temporal results are aggregated in 30-year periods centred around 2030, 2050, 2070 and 2085 on annual and seasonal timescales. These results are shown as maps demonstrating the spatial variability of the region's change or as graphs showing aggregated results across the regions.

Each step of the National Hydrological Projections modelling chain is carefully evaluated to understand the uncertainties associated with the modelling process. 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
- the hydrological modelling itself.

More details on how we address these uncertainties are discussed in Chapter 3. Further information on these models and the choices made in their selection as well as the evaluation process are detailed in our scientific publications and reports.

1.2 National Hydrological Projections hydrological assessment reports

Projection results feature many sources of uncertainty, including uncertainty over future trajectories of atmospheric greenhouse gas concentrations, how a warmer climate will lead to changes to hydroclimatic features and feedback loops, and the ability of climate models to represent those features. Acknowledging these uncertainties, the National Hydrological Projections ensemble provides a unique opportunity to examine impacts of plausible future changes on Australia's hydroclimate and its water resources.

To understand future impacts on Australia's water resources, region-specific assessment reports have been prepared on plausible future hydrological changes, including changes in precipitation, runoff, potential evapotranspiration and soil moisture as well as changes in extremes including droughts and floods. These assessment reports are based on 8 regions, formed from clusters of natural resource management (NRM) regions of Australia, that can be affected differently by climate change. These regions broadly represent groups of similar climatic and biophysical settings in Australia and corresponding natural resources. The National Hydrological Projections build on these regions and the scientific work that was previously carried out by the Climate Change in Australia (CCiA) initiative (CCiA n.d. a). CCiA provided the most nationally comprehensive, robust and consistent scientific information on future climate changes for Australia. Projected climate change has been described in detail in the individual CCiA reports for the NRM clusters (CCiA n.d. b), with additional regional detail being provided through ongoing initiatives from Australian state and federal governments. This work builds a complementary picture in the context of the regional hydrological cycle, regional water assets and its future impacts.

These hydrological assessment reports are a demonstration case of the applicability of the National Hydrological Projections data and plausible future water resource impact analysis across Australia. They are intended to provide a high-level regional picture and raise awareness of plausible hydrological changes for a water-sensitive audience, including Australia's water, energy and environmental managers; emergency and recovery services; transport operators; farmers; and people generally interested in future changes to water resources. The reports present information in the form of 'storylines' of plausible future occurrences of hydrological extreme events (e.g. floods) and long-term hydroclimatic changes. This information can be used to guide investment decisions and develop mitigation and adaptation strategies.

This report focuses on the Monsoonal North region and is structured as follows:

- Chapter 1 introduces the National Hydrological Projections.
- Chapter 2 describes the assessment region, including its physiographic and hydroclimatic characteristics, recent conditions and long-term hydroclimatic trends.
- Chapter 3 evaluates our ability to simulate future hydrological changes, including the multiple levels of uncertainty, whether the climate models chosen can represent the region's climate and how well the hydrological AWRA-L model performs in the region. It also presents the results from the evaluation of the bias-correction methods. This information provides important context for the following chapter.
- Chapter 4 assesses the region's future hydroclimate conditions, which are presented as available National Hydrological Projections storylines. Changes are shown for precipitation, evapotranspiration, soil moisture and runoff assessed against the reference period (1976–2005). The chapter also provides insights into plausible future extremes of wet and dry periods.
- Chapter 5 demonstrates the applicability of storylines by exploring future water-sensitive impacts of selected case studies.

All foundational National Hydrological Projections datasets underpinning the assessment report analyses are also available as application-ready datasets via the National Computational Infrastructure (NCI) Data Catalogue (https://dx.doi.org/10.25914/6130680dc5a51).

For further detailed regional analysis, guidance on the use of National Hydrological Projections data or further general information, please contact us via water@bom.gov.au.

2 Regional description and hydroclimate of the Monsoonal North region

The Monsoonal North region covers northern Australia except for Cape York (Figure 2.1). It has 2 subregions that meet on the Northern Territory – Queensland border. The western subregion covers the Kimberley region of Western Australia and the northern part of the Northern Territory. Bordering along the north is the Timor Sea, and the Gulf of Carpentaria lies along the coastal eastern edges. The eastern subregion contains the Northern Gulf and Southern Gulf NRM regions and the Burdekin NRM region south of Townsville (Moise et al. 2015).

The northern part of the Monsoonal North region has savanna woodlands and pockets of tropical rainforest. As a result of the monsoonal climate and infertile soils, a single vegetation type – savanna – dominates the landscape from Kimberley to Cape York. The region has spectacular ranges and escarpments of the Kimberley and the Ord-Victoria uplands in the south-west. They contrast to the coastal plains of Kakadu.

The main agricultural industries in the region are grazing (beef), sugarcane, horticulture (vegetables, mangoes, melons and other tropical fruits), nurseries, forestry and some broadacre cropping. There are 2 large irrigation storages: Lake Argyle (Australia's second-largest surface water storage after the Tasmania's Lake Gordon/Lake Pedder storage system) in the eastern Kimberley and Burdekin Falls Dam (the largest in Queensland). A number of smaller storages supply town water around Townsville and Darwin (Figure 2.1).

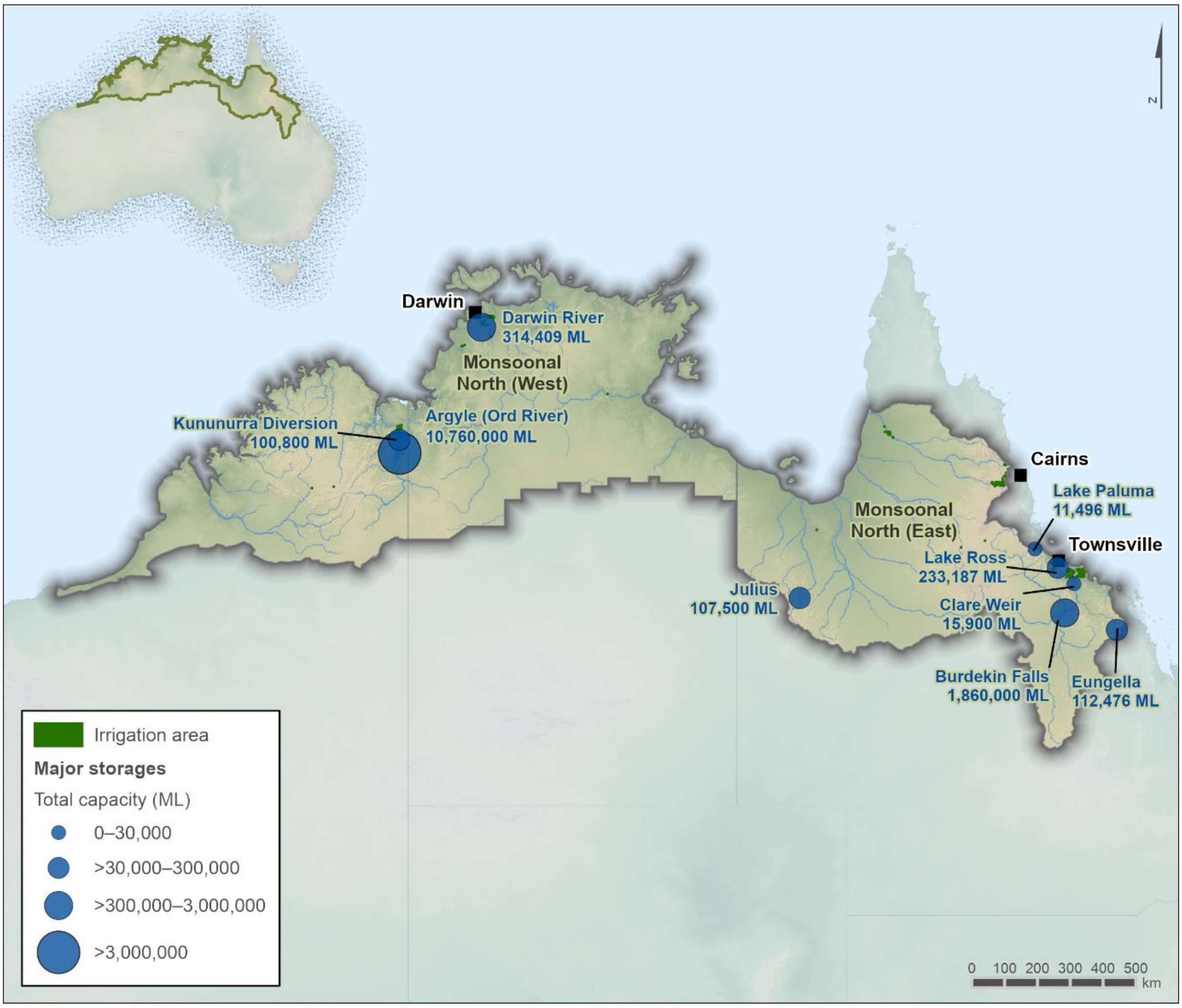


Figure 2.1 Monsoonal North region showing the western and eastern subregions

2.1 Climate

Precipitation in northern Australia is summer dominant, largely varying between wet and dry seasons (Figure 2.3). During the wet season, the monsoon trough – the line of low pressure along the intertropical convergence zone – brings periods of cloud, heavy precipitation, tropical depressions and tropical cyclones to the Monsoonal North region (Suppiah 1992). Almost all the region's precipitation (up to 95%) falls during this summer monsoon season (December–March).

The average annual precipitation was 890 millimetres (mm) for western Monsoonal North and 665 mm for the eastern subregion during the 30-year reference period from 1976 to 2005. Most of the precipitation and runoff comes from the north and the eastern outskirts of the region (Figure 2.2). There is a gradient from north to south with mean annual precipitation, runoff and soil moisture decreasing while potential evapotranspiration increases (Figure 2.2).

Very low monthly precipitation totals of less than 10 mm are common during the dry season (Figure 2.3). Most precipitation falls near the coast, and totals decrease significantly from the north (1,750 mm annual mean) to the south (400 mm annual mean) (Moise et al. 2015). There is a transitional period between wet and dry seasons in northern Australia – the 'build-up' – with high temperature and increasing humidity as well as occasional precipitation events, typically occurring from October to November. There is also a 'build-down' period in April and May when rain clouds have dispersed, and clear skies prevail.

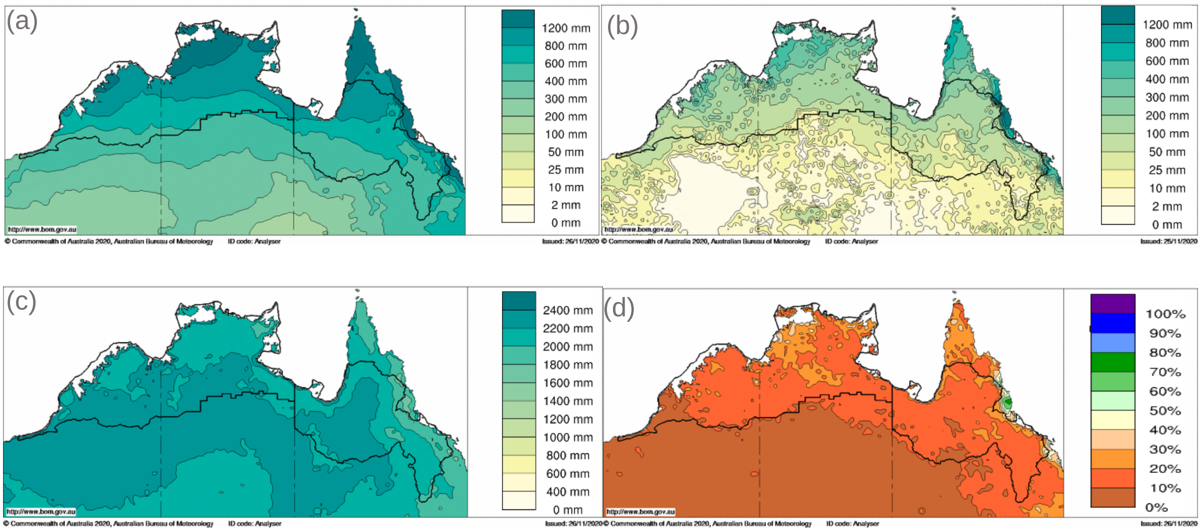


Figure 2.2. Monsoonal North annual average hydroclimate (1976–2005) showing (a) observed precipitation and AWRA-L modelled values for (b) runoff, (c) potential evapotranspiration and (d) soil moisture

Precipitation also varies strongly from year to year. Multi-year precipitation variability in north-west Australia is largely independent of remote forcing from low-frequency variations of the El Niño–Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) in the tropical Pacific. It appears to be promoted locally by a combination of precipitation-wind-evaporation and soil moisture–precipitation feedbacks, where soil moisture can serve as a source of multi-year memory and thus can be linked to multi-year wet or dry periods (Sharmila & Hendon 2020). The eastern subregion of the Monsoonal North region is influenced by the ENSO. The El Niño phase of ENSO is often associated with below-average winter and/or spring precipitation, a late onset and shortened duration of the summer monsoon, and a slower start to the cyclone season (McBride & Nicholls 1983). The Madden–Julian Oscillation (MJO) also influences precipitation across the western subregion between October and April by modulating the timing of the onset of the monsoon and influencing the transitions from active to inactive monsoon phases (Wheeler et al. 2009). The duration and severity of the dry season is also influenced by the Indian Ocean Dipole (IOD), which is most active during winter and spring (Ashok et al. 2003; Cai et al. 2009).

Precipitation in the eastern Monsoonal North subregion is associated with moist onshore south-east trade winds, monsoonal lows or tropical cyclones.

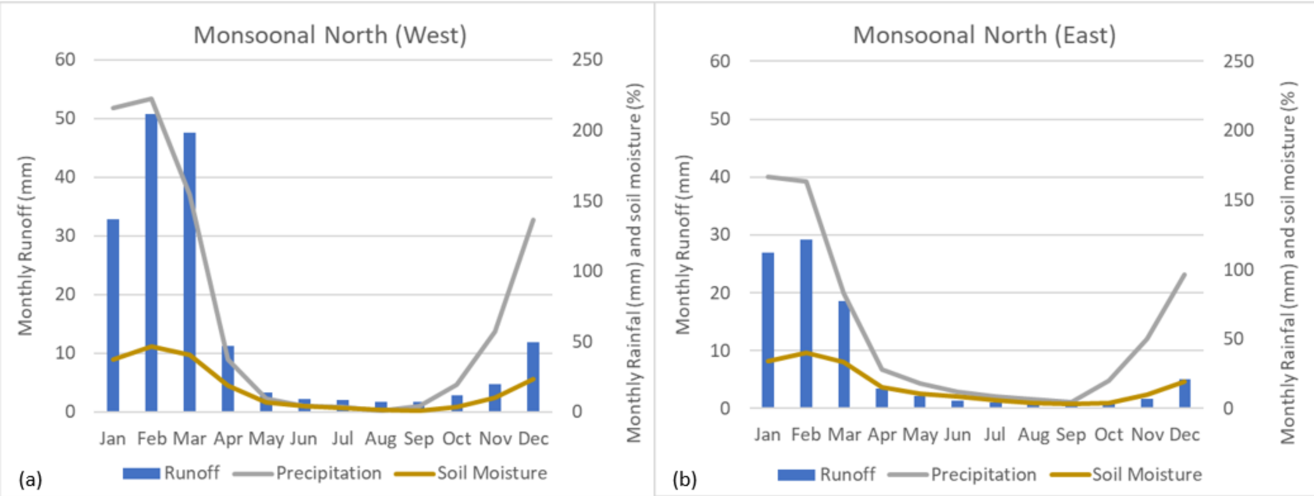


Figure 2.3. Monthly average observed precipitation and AWRA-L modelled runoff and soil moisture for (a) western and (b) eastern Monsoonal North subregions for the reference period (1976–2005)

The Monsoonal North region receives most of its precipitation during the summer monsoonal wet season (December to April), and a large part of the runoff also occurs in this period (Figure 2.3). Runoff is highly seasonal, with most of the region experiencing 95% or more of its annual runoff during the wet season. Runoff follows the same pattern as precipitation: the most northerly regions have the highest mean annual runoff and the southerly regions the lowest (Figure 2.2).

Since the 1970s, precipitation, runoff and soil moisture have shown an increasing trend across the Monsoonal North region. During the dry season, lack of precipitation combines with high evapotranspiration resulting in the region's soil becoming very dry (Figure 2.4). Over much of the Monsoonal North region, potential evapotranspiration exceeds 2,000 mm/year; it can approach 10 mm/day during the wet season. Potential evaporation from November to April ranges from 1,200 mm in the north to more than 1,800 mm in the south. Evapotranspiration rates are smaller in the south from May to October (less than 1,200 mm). While a large proportion of Australia's annual runoff is generated within the Monsoonal North region, these evapotranspiration rates remain high for most of the year (CSIRO 2009), which limits runoff into rivers and storages. The high evapotranspiration rates mean that most of the area has a net precipitation deficit for 10 months of the year (i.e. potential evapotranspiration is greater than the amount of precipitation received), so the area is largely a water-limited landscape.

The latter part of the 20th century saw variable conditions with individual years of very high precipitation associated with the impact of tropical cyclones, sequences of years with below-average precipitation (in the late 1980s and early 1990s), and above-average precipitation since the mid-1990s. The largest increases in recent decades have been observed across north-western areas of the region. Since 1980, annual precipitation has increased by 82 mm/decade in the western subregion and 84 mm/decade in the eastern subregion. These increases in precipitation are associated with increased early monsoonal precipitation intensity and a possible extension of wet season.

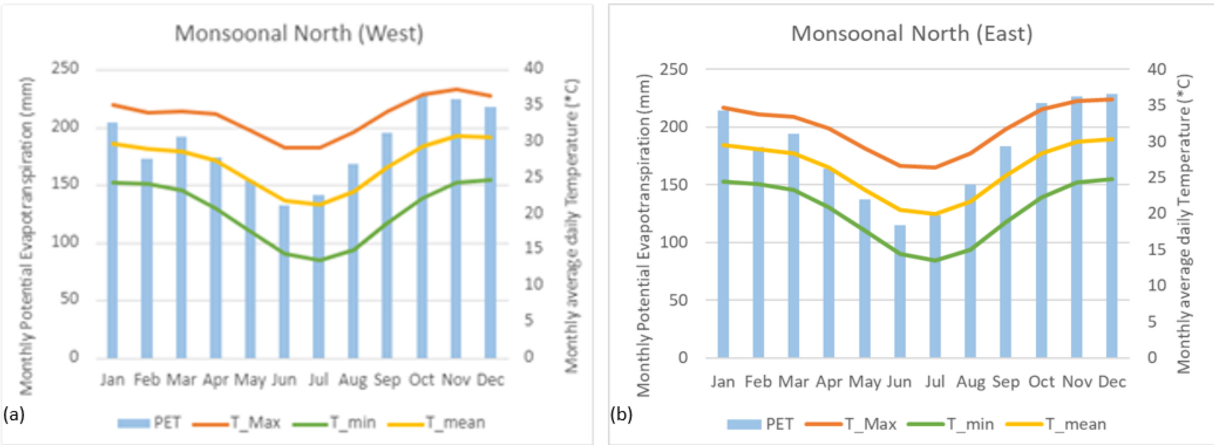


Figure 2.4. Monthly average observed maximum, minimum and mean temperature and AWRA-L modelled potential evapotranspiration for the (a) western and (b) eastern Monsoonal North subregions for the reference period (1976–2005)

2.2 Recent hydroclimatic trends and condition

In recent decades, the Monsoonal North region has seen above-average precipitation and runoff (Figure 2.5). The year 2019 was an exception; precipitation that year was about 25% below average and the wet season was the third driest on record since 1961. In 2018–19, north-west Australia had a delayed start to the monsoon; the onset date in Darwin of 23 January was the equal third latest start since reliable records commenced in 1957. It was the driest wet season in the Northern Territory since 1992–93, and total precipitation was 34% below the long-term average.

In 2018–19, runoff was similarly lower than the long-term average for the Monsoonal North region and it was the driest wet season since 1992–93. Low precipitation during the dry season months of June and July 2018 contributed to evapotranspiration largely exceeding precipitation during July 2018. Modelled annual potential evapotranspiration for the western subregion in 2019 was 2,264 mm, 83 mm higher than long-term mean (1911–2020) of 2,181 mm. Modelled annual potential evapotranspiration for the eastern subregion for 2019 was 2,136 mm, 5 mm below the long-term mean (2,141 mm). However, spatial variation across the region can be very large. Annual runoff for the western Monsoonal North subregion for 2019 was 66 mm, less than half the long-term mean for that subregion (145 mm). Annual runoff in the eastern subregion was 192 mm, twice that subregion's long-term mean (96 mm).

Despite these recent increases in precipitation across most of tropical Australia, coastal regions of the tropical east coast have experienced decreases in annual precipitation. Consistent with the overall increase in annual precipitation, runoff in the region has been observed to increase since 1950 (Zhang & Moise 2016). Similarly, increasing soil moisture trends have been observed since 1970. Apart from 2019, the past 13 years have seen above-average soil moisture over much of the Monsoonal North region. Observed trends in potential evapotranspiration since the 1980s are also rising throughout the region, with some local exceptions along the northern coastline.

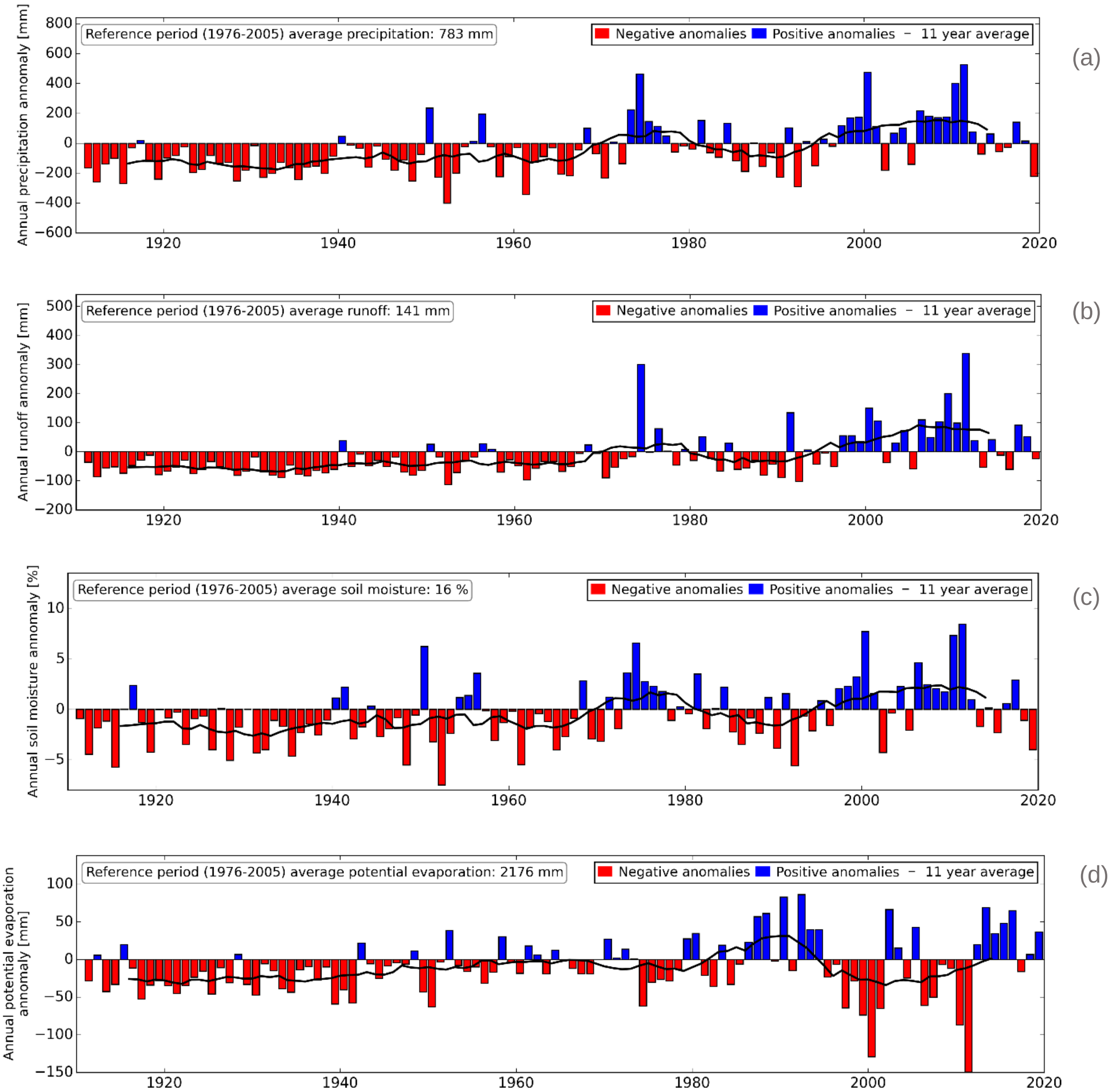


Figure 2.5. Monsoonal North annual anomalies relative to the reference period (1976–2005) mean in (a) observed precipitation and AWRA-L modelled values for (b) runoff, (c) soil moisture and (d) potential evapotranspiration

2.3 Water availability and management

Total annual precipitation and runoff vary considerably from year to year, and the Monsoonal North region has high physical water availability relative to use over the year. Streamflow is highly seasonal – high streamflow and frequent flooding occur during the wet season (November–April). The perennial rivers of the region support endemic wildlife, irrigation development, and domestic and stock use, and also have high cultural value.

To sustain agricultural production and town water supply, water is typically stored for use during the dry season (May–October). Water use is also largely reliant on groundwater and its replenishment during the wet period. As water availability is generally much greater than water needs, water use allocations and actual diversions vary little between years.

With Lake Kununurra, Lake Argyle is part of the Ord River Irrigation Scheme. Currently some 150 km^2 of farmland is under irrigation in the East Kimberley region.

For the city of Darwin, most of the water (up to 90%) comes from the Darwin River Dam, located around 50 km south of Darwin. The remaining 10% of the water supply comes from groundwater through the McMinns and Howard East borefields, about 30 km south-east of Darwin near Howard Springs. The water supply is strongly influenced by climate, especially the timing and variability of precipitation. Receiving almost no precipitation for up to 8 months every year affects the amount of water flowing into Darwin River Dam and the amount of water use, especially outdoors (e.g. in gardens). Dry season flow in the contributing rivers is mostly dominated by input of groundwater from the 2 underlying aquifers in the Daly region: Tindall Limestone and Oolloo Dolostone.

Irrigation water in the Northern Territory is primarily sourced from groundwater found in the Daly Basin and the Darwin Rural area. Aquifer behaviour differs significantly between those 2 groundwater resources. In the Daly Basin, the Tindall Limestone aquifer and the Oolloo Dolostone aquifer have potential to store recharge between years, and groundwater levels (and storage) have been increasing over the past 30 years. Conversely, the Darwin Rural area has ‘fill and spill’ aquifers, which become fully saturated before the end of an average wet season and then spill, increasing surface water runoff. Fill and spill aquifers have decreased capacity to store water between wet seasons if there are 2 or more consecutive below-average wet seasons.

The primary sources of water for irrigation in the Burdekin area are Burdekin Falls Dam and Lake Eungella. A small portion (20%) of the average annual water supply is provided from groundwater. The Burdekin Haughton Water Supply Scheme sources water from the Burdekin Falls Dam. It supplies water for irrigation in the lower Burdekin River region and supplements the water requirements for urban and local businesses, including quarries and sugar mills in Townsville and Thuringowa. Clare Weir is also part of the Burdekin Haughton Scheme. Lake Ross is the largest urban storage supplying water to the city of Townsville, which is also supplied by Lake Paluma.

The long-term sustenance of aquatic flora and fauna requires maintaining the environmental flows of many of the region’s rivers. The quality and quantity of the water and the timing of environmental flows are important. The Daly River in the Northern Territory is a unique perennial river system sustained by vast aquifers that support an abundance of aquatic wildlife, including 90 species of fish and 8 species of freshwater turtle. The Flinders, Gilbert and Mitchell rivers flow into the southern Gulf of Carpentaria, sustaining many important freshwater assets, such as significant commercial and recreational fisheries, threatened species and wetlands of national significance. The Kakadu World Heritage Area includes wetland values, significant portions of the catchments of 4 major rivers (Wildman River and West, South and East Alligator rivers) and Aboriginal cultural values, which are closely associated with water.

Since Lake Argyle was created in 1972, new ecosystems have formed in the dammed Ord River Valley. Lake Argyle, Lake Kununurra and the lower Ord River’s floodplain have been added to the Ramsar Convention’s list of internationally important wetlands. The Ord River is habitat for more than 75 bird species (DPIRD 2020).

For the Burdekin NRM region, rules governing storage releases and limiting abstractions are designed to achieve the environmental objectives, that is, retaining various temporal flow characteristics at different nodes along the rivers. The volume of water released will depend upon the environmental flow objectives and flow conditions. Various performance indicators are used for assessing environmental flow objectives. As the Burdekin catchment drains into the Great Barrier Reef World Heritage Area, water quality management is important and is managed through the *Reef 2050 long-term sustainability plan* (Commonwealth of Australia 2015).

3 Ability to simulate hydroclimatic conditions of the Monsoonal North region

Assessing how well climate and hydrological models simulate key elements of the hydroclimate for Australia and the Monsoonal North region is an essential part of understanding the potential future impacts of climate change. Assessments of model performance against observations and the latest scientific understanding of hydroclimatic processes provide a basis for confidence, in the sense of enabling trust in sets of projections. Models are not expected to reproduce observations exactly but rather are assessed in terms of their ability to capture important aspects of variability and their representation of important processes. Bias correction is an important step in the process of hydrological impact modelling. It brings information simulated by global climate models about the impacts on our climate system of rising greenhouse gases together with our best representation of hydrological processes at local scales (in this case, the assessment region). Bias-corrected climate data and the simulated hydrological output data are compared against observations to assess the performance of the models and processes. For a detailed description of the modelling process and a technical assessment of performance, please see the National Hydrological Projections technical report (Srikanthan et al. 2022).

Climate and hydrological models are always an imperfect representation of the reality (and plausible future) and are therefore associated with various sources of uncertainties. These uncertainties are intrinsic to hydroclimatic modelling and arise from the selection of climate models and the differences in model responses in a warming climate. These differences include the representation of climate drivers and their expression through, for example, El Niño and La Niña events and can also include the uncertainty of future human behaviours affecting greenhouse gas emissions. Further sources of uncertainties stem from the influence of bias corrections as well as from the hydrological modelling and the representation of hydrological processes itself. Thus, we can never forecast the exact time series of Australian temperature, precipitation and other climate drivers, and the National Hydrological Projections will differ from observations over short to medium periods. These uncertainties influence our ability to simulate the hydroclimate in Australia. This section briefly introduces the models and methods used in these National Hydrological Projections and assesses our ability to simulate the hydroclimate of the Monsoonal North in the context of uncertainties. More details on the methods used can be found in the technical report (Srikanthan et al. 2022).

A number of choices were made in developing the datasets used in these National Hydrological Projections. Four global climate models (GCMs) were selected: ACCESS1-0, CNRM-CM5, GFDL-ESM2M and MIROC5. These models were selected from the suite of 42 models in the international Coupled Model Intercomparison Project Phase 5 (CMIP5). These 4 were chosen because they fulfilled important requirements, including the following:

- GCM data was available for input into the hydrological models.
- The GCM had been used to force one or more dynamical downscaling models.
- The GCM represents the large-scale drivers of climate and weather variability well.
- The GCM simulates Australia's precipitation, temperature, wind and radiation relatively well.
- The 4 models together represent the range of future precipitation and temperature changes relative to the spread of the 42 models of the CMIP5 ensemble.

The range of climate responses from each GCM, in any particular year, derives from the particular state of the weather and large-scale variability occurring within that model in that year. Each GCM models its own weather, and the climate varies over the longer term of the simulation in response to changing atmospheric levels of greenhouse gases, aerosols and ozone in the upper atmosphere (and the Antarctic ozone hole).

In addition, one atmosphere-only climate model was used to 'downscale' the GCMs from their 150 km resolution to 50 km. CCAM, CSIRO's Conformal Cubic Atmospheric Model, is a global model in which the grid point spacing is stretched to have fine resolution over Australia. Additional dynamically downscaled data was available to the National Hydrological Projections under the Victorian Climate and Water Initiative (VicWACI) and other initiatives of the Victorian Government. Another regional model known as WRF (Weather Research and Forecasting model) dynamically downscaled the GCMs to about 50 km through the New South Wales Government–led partnership NARCliM (NSW and ACT Regional Climate Modelling). NARCliM output was included in the historical era simulations using the hydrological model but was not available for projections at the time of the release. The aim is to include further downscaling models in future updates to the projections service.

Three bias-correction methods were implemented to improve the representation of local climate conditions and reduce biases relative to observed data. First, the output of the GCMs and downscaling model were scaled down from their original scale (about 150 × 150 km) to 5 × 5 km resolution using a conservative re-gridding method; then the bias correction was applied. Each of the bias-correction methods is designed to preserve various features of the climate signal such as trend, inter-annual variability or seasonality of a climate variable.

The ability of each ensemble member to simulate the future hydroclimate of the Monsoonal North region was assessed by evaluating its ability to reproduce the observations and observation-based model results of the 1976 to 2005 reference period. This evaluation let us identify any biases in the models that were likely to be carried forward into future projections. A range of evaluation techniques and statistics were used to evaluate the ability of the ensemble to simulate the hydroclimate of each individual region.

The following 3 bias-correction methods were used:

- ISIMIP2b, a quantile-based method that preserves the trend in the data (Hempel et al. 2013)
- QME, a quantile-based method that models the extremes well (Dowdy 2020)
- MRNBC, a method that preserves the interdependence among the variables as well the low-frequency characteristics (Johnson & Sharma 2012; Mehrotra & Sharma 2016).

The bias-corrected data was evaluated to assess the effectiveness of the bias-correction methods. The AWRA-L model (see Section 3.2) was then run with the bias-corrected climate data as input.

3.1 Ability to simulate the key climate drivers

The skill of the 4 National Hydrological Projections GCMs (among other GCMs) to represent the key large-scale drivers of Australia's climate was assessed previously by the Climate Change in Australia initiative (Moise et al. 2015). This assessment provided a basis for placing confidence in the model's projection for Australia and identified individual ensemble members or ensemble groups that may have significant performance issues in simulating a key aspect of climate variability.

Many CMIP5 GCMs have a bias in the Pacific Ocean whereby the ENSO signal extends too far towards Australia along the equator. This bias is minimal in the 4 National Hydrological Projections models selected; thus they represent the processes influencing climate variability in northern and eastern Australia reasonably well (Brown et al. 2016). A common bias seen in the eastern Indian Ocean in the Australian spring is relatively small in 3 of the models. However, CNRM-CM5 has this bias, which might limit the expected increase in the frequency of extreme positive Indian Ocean Dipole events and their expression through dry conditions in south-east Australia (Wang et al. 2017).

The 4 GCMs chosen for these projections, ACCESS1-0, CNRM-CM5, MIROC5 and GFDL-ESM2M (Table 3.1), were found to represent the weather-scale features influencing northern Australia well, and their future changes should be considered reliable. However, CMIP5 GCMs in general do not capture the eastward propagating sub-seasonal monsoon activity, cloudiness and precipitation linked to the Madden–Julian Oscillation (Moise et al. 2015).

Table 3.1. Details of selected global climate models

Climate model	Type	Institute	Country of origin	Reference
ACCESS1-0	Global	CSIRO and Bureau of Meteorology	Australia	Collier and 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)	USA	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)

For completion, MIROC5 fulfils the requirements for inclusion in our ensemble although it does not represent the weather features that are important for the southern Australian climate as well as some others and might be considered less reliable. However, its inclusion helps the National Hydrological Projections GCM ensemble embrace the range indicated by the full range of 42 CMIP5 models (Srikanthan et al. 2022).

3.2 Hydrological modelling: the Australian Water Resources Assessment Landscape model (AWRA-L)

The Bureau's operational Australian Water Resources Assessment Landscape model (hereafter AWRA-L) was used to project root zone soil moisture, potential evapotranspiration and runoff. AWRA-L is a daily semi-distributed water balance model based on a 5 × 5 km (0.05°) grid. It models hydrological processes separately for each spatial unit, called a hydrologic response unit (HRU). At each grid cell it simulates the flow of water through the landscape: precipitation entering the grid cell, passing through the vegetation and soil moisture stores, and leaving the grid cell through evapotranspiration, runoff or deep drainage to the groundwater (Figure 3.1). Each grid cell in AWRA-L is divided into 2 HRUs, these represent deep-rooted vegetation (trees) and shallow-rooted vegetation (grass). The spatial distribution of the HRUs remains static over time and does not reflect land use change.

The AWRA-L model is calibrated at the national scale to match streamflow, soil moisture and evapotranspiration observations from across the country. This calibration enables a nationally consistent dataset, but model evaluation results can vary between regions and landscape features (Frost & Wright 2018).

Model performance can be affected by the number of calibration catchments local to the region or representative of the landscape feature. AWRA-L better captures the runoff dynamics in wetter regions and periods, while discontinuous runoff regimes, consisting of long dry periods followed by short periods of extreme precipitation, are more difficult to characterise. A positive bias in runoff can result in areas with extended periods of no flows in central and northern Australia. Groundwater–surface water interactions are not well represented in AWRA-L, resulting in a drop in performance in areas where there is a high dependency on the contribution of baseflow to the generation of streamflow.

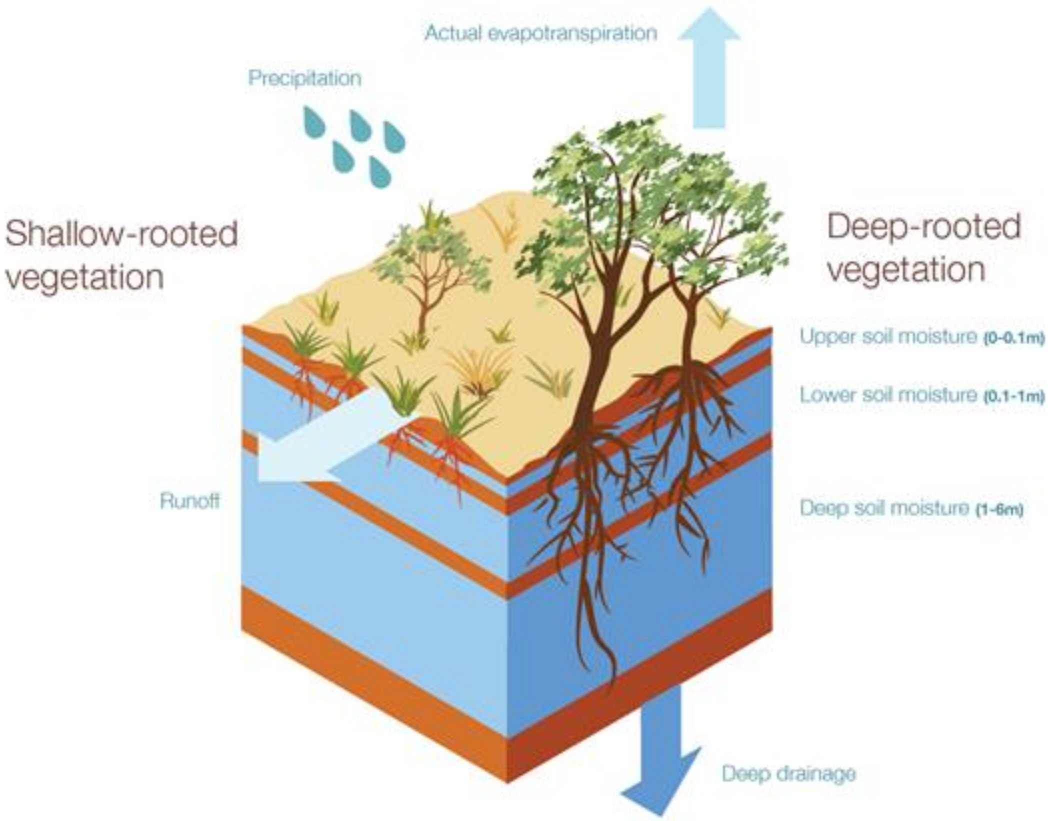


Figure 3.1. AWRA-L model grid cell with key water stores, fluxes and the hydrologic response units of deep- and shallow-rooted vegetation

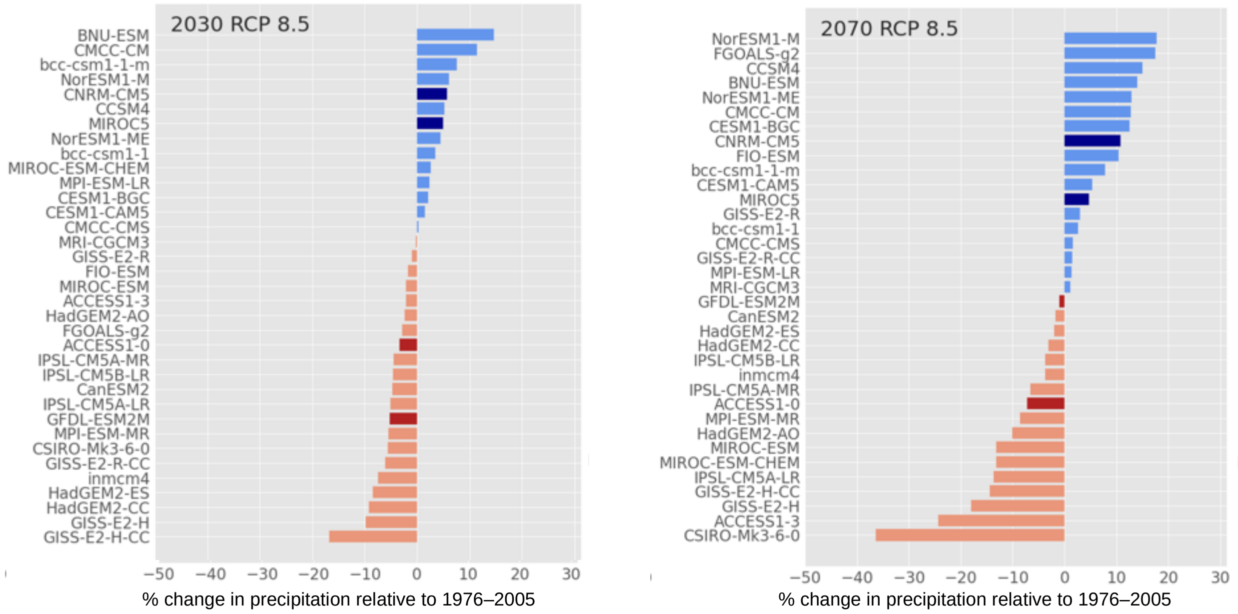
The Bureau's operational AWRA-L was chosen as the hydrological model based on the evaluation and benchmarking of the available national models presented in Frost & Wright (2018). Importantly, this evaluation considered runoff, soil moisture and actual evapotranspiration in the assessment of the models. AWRA-L was run independently using the bias-corrected GCM climate data as input. The lack of feedback between the GCMs and AWRA-L means that the potential role of increased carbon dioxide levels on vegetation growth and evapotranspiration rates are not modelled (Greve et al. 2017; Yang et al. 2019). Future land use changes and vegetation changes resulting from future temperature and water availability changes are also not considered in AWRA-L or the GCMs. Together these factors will grow in importance over time, adding an extra facet of uncertainty to the soil moisture and runoff projections later in the century. A detailed description of the quantification of the AWRA-L model uncertainty can be found in Azarnivand et al. (2022).

3.3 Ability to simulate the hydroclimate of the Monsoonal North region

The 4 GCMs were chosen to represent the range of future precipitation and temperature changes for Australia as described in the National Hydrological Projections technical report (Srikanthan et al. 2022). The 4 selected GCMs were compared to the entire ensemble of 42 CMIP5 Climate Change in Australia (CCiA) models to see how these models represent wet or dry futures (Figure 3.2). This provides an overview of how the selected GCMs rank relative to the full CMIP5 ensemble across Australia and respective climate variables.

The 4 global climate models chosen for these projections, ACCESS1-0, CNRM-CM5, MIROC5 and GFDL-ESM2M (Table 3.1), were found to represent Australia's weather-scale features well, and their future changes should be considered reliable (Grose et al. 2015). Two of the 4 GCMs project a Monsoonal North wetting trend while 2 project a decrease in precipitation over northern Australia. The full CMIP5 ensemble of 42 models projects an increase in temperature in the Monsoonal North region, and the selected 4 capture the central to lower end of this range (Srikanthan et al. 2022). Overall, the 4 GCMs are representative of the projected future climate in the

Monsoonal North with a tendency towards a wetter climate and not as much warming as the full suite of CMIP5 GCMs (see the technical report for more details, Srikanthan et al. 2022).



(a) (b)

Figure 3.2. Ranking of the Monsoonal North region precipitation projections for the GCMs used in this study (shown in darker colours) compared to the CCiA ensemble for RCP8.5 for (a) 2030 and (b) 2070. The horizontal bars indicate the change signal – the difference of the regional average quantity from the monthly pattern for the reference period (1976–2005)

Simulated hydroclimate data for the current climate (produced by the 16-member ensemble) is assessed by comparing it with observational datasets from AWAP (Jones et al, 2009). In addition, three outputs (soil moisture, runoff and potential evapotranspiration) obtained by forcing the AWRA-L model with AWAP and bias corrected data were also compared. Since the models are not perfect representations of the world, the simulated data will not exactly match the observed data. A certain tolerance level is used in assessing the model simulations. The precipitation and temperature observation networks are moderately distributed across the Monsoonal North region and are suitable for evaluation purposes. The evaluation of the ability of the ensemble members to replicate the reference period (1976–2005) observations and model runs revealed overall minimal bias in the Monsoonal North. Evaluation criteria, such as representing the seasonality of the climate variables, are found to be adequately preserved in all ensemble members, and they revealed overall minimal bias in the Monsoonal North. The biases in mean annual and seasonal precipitation are small for all the ensemble members except for projections of winter season precipitation by all GCMs applying MRNBC bias correction. In these cases, the bias is in the order of 10% (see Appendix Figure 7.1).

The ensemble members were able to produce the monthly precipitation pattern satisfactorily (less than 10% positive bias). The greatest deviations were produced by the QME bias-correction method as it corrects the bias using a seasonal time scale whereas the other methods use a monthly scale. For other climate variables, the biases in mean annual and seasonal daily maximum and minimum temperatures are small for most ensemble members (<0.1 °C) with the exception of less than 0.2 °C for the variables bias-corrected with ISIMIP2b. Most ensemble members tend to underestimate solar radiation levels but within an acceptable range of less than 4%. Wind speed is well captured by the ensemble members, the bias reaching 0.02 metres per second (m/s) in only a few cases (see Appendix Figure 7.9).

Biases in the hydrological variables, including potential evapotranspiration, soil moisture and runoff, are calculated by comparing the results produced by the ARWA-L model forced with observed climate inputs and those modelled by the ensemble for the 1976 to 2005 reference period. Annual and seasonal soil moisture were slightly overestimated in the ensemble; correcting with MRNBC produced the best result. Evaluating the mean annual and seasonal potential evapotranspiration revealed a small (<2.5%) negative bias (underestimation) in most ensemble members. The most accurate projection for potential evapotranspiration was again achieved by correcting with MRNBC, while QME did not preserve the monthly pattern well for the November and December months. The bias was greatest in the modelled runoff estimates for GFDL-ESM2M_QME (up to 50% positive bias) (see Appendix Figure 7.11). The lowest bias in runoff was achieved by correcting with the MRNBC bias-correction method and CCAM_ISIMIP2b. MRNBC preserved the monthly runoff pattern well while the other bias corrections produced less-accurate projections (up to 20 mm) of monthly runoff for January to March (see Appendix Figure 7.12).

The vegetation of the Monsoonal North is dominated by shrubs, heath and grasslands and is characterised by the shallow-rooted hydrological response unit in the AWRA-L model (Frost & Wright 2018). Some areas in the north with a savanna tree canopy are represented by the deep-rooted hydrological response unit. There are also significant areas dominated by rock and impermeable surface that are not modelled in AWRA-L version 6.1 but will be in version 7. AWRA-L is a nationally calibrated model with 32 of the 305 calibration catchments in the Wet Tropics region. The performance of the continentally calibrated AWRA-L model for the Monsoonal North is good based on the median monthly Nash–Sutcliffe coefficient of efficiency (NSE) (Nash & Sutcliffe 1970) greater than 0.6. Wasko et al (2021) analysed streamflow trends post 1970 for both streamflow observations and modelled runoff from the AWRA-L model. They found a combination of positive and negative trends in the runoff at 11 streamflow sites across the region. The AWRA-L model was able to match the trend direction for 82% of sites for annual volumes and 100% for summer flows compared to historical observations, all flows showed increasing trends for the summer period.

The runoff regime in the Monsoonal North region is discontinuous, with long periods between runoff events, making it difficult for the AWRA-L model to capture. The nature of precipitation in monsoonal Australia is that a significant proportion of our rainfall occurs as localised high-intensity, short duration events, which can be difficult to represent in a daily-based modelling approach. However, at a regional scale and considering the relatively flat topography of this region, with generally slower runoff, it may be that sub-daily rainfall intensity is inconsequential over large spatial extents. In addition, as most historic precipitation data has been read daily, there are few event-based rainfall gauges across the region to adequately perform a comparison at a temporal scale less than one day. Despite these recent increases in precipitation across most of tropical Australia, coastal regions of the tropical east coast have experienced decreases in annual precipitation.

In summary, the ability of the National Hydrological Projections ensemble members to simulate the hydroclimate for the Monsoonal North region is satisfactory. The evaluation shows that the bias-correction methods successfully adjusted the climate data, and this replicated the soil moisture and potential evapotranspiration. However, the QME method did not perform as well as other methods for runoff.

4 Available National Hydrological Projections storylines for the Monsoonal North region

Generally, projections provide a collection of plausible future ‘storylines’ rather than a forecast or likelihood of a specific outcome. Individually each ensemble member represents an internally consistent future storyline. Thus, while the ensemble members are based on slightly different physics, they all are built on plausible representations of physical processes. Individual ensemble members are the most appropriate method to represent this internal consistency and are a key element of establishing a storyline. No 2 ensemble members will follow the same changes in the many different climate features that can be considered.

The National Hydrological Projections used in this report allow for a unique region-wide assessment of projected hydroclimatic changes of the Monsoonal North region. Results below are drawn from the assessment of the 16-member ensemble of hydroclimatic variables. The projected hydroclimate for the region is presented in this chapter as a set of available plausible future changes of key hydrological variables or storylines. It presents a set of key figures representing the change in the hydroclimate into the future under 2 different representative concentration pathways and showing how this change varies within the Monsoonal North region.

In addition to the National Hydrological Projections storylines, additional climate storylines are available from previous Climate Change in Australia climate projections for the Monsoonal North region and are described in the Monsoonal North CCiA report (Moise et al. 2015). Some state-based datasets provide further projections information in parts of this region. For Western Australia, Department of Water (2015) provided projections based on 12 GCMs from an earlier generation of climate models (CMIP3) than those presented here, with 4 greenhouse gas emission scenarios. Scenarios used in this report differ, but RCP8.5 is similar to A1F1 and RCP4.5 has slightly lower emissions than the B2 scenario used in Department of Water (2015). Taking a similar approach to the storylines presented below (see Chapter 5), Department of Water (2015) described projections from a wet, mid and dry scenario and provided guidance on its applicability. Queensland projections information can be found on the Long Paddock website (Syktus et al. 2020). Queensland projections use 10 climate models in total. Each of the GCM outputs used in Syktus et al. (2020) is downscaled using CCAM to 50 km resolution, as used in the National Hydrological Projections. Queensland projections then downscale projections data to 10 km. Basic climate variables are provided as well as wind and potential evapotranspiration, but Syktus et al. (2020) does not provide other hydrological variables.

4.1 Interpreting the National Hydrological Projections storylines

The projected future conditions are represented by the degree of change relative to the conditions of the reference period (1976–2005). Each of the 16-member ensemble is run for this reference period and for the future. As described in Chapter 3, each ensemble member is evaluated on the basis of the differences between the modelled reference period and the observations. These differences inform our assessment of the change in conditions projected by each ensemble member for the future. The change can be presented in absolute values (e.g. millimetres of precipitation) or as a relative proportion of the mean for the region (e.g. a 10% increase in precipitation). There is significant value in interpreting both absolute and relative values depending on the application.

Chapter 3 outlines how an ensemble of GCMs and bias-correction methods has been used to develop a range of plausible future conditions. This spread in the 16-member ensemble represents a range of plausible future conditions that decision-makers can use to explore impacts. The median of the 16-member ensemble represents a mid-range view of those plausible futures. The results are communicated against a series of future 30-year periods, which are referred to by their midpoint. For example, the results reported against 2050 represent the average of the 2036–2065 period. This allows us to identify general trends into the future beyond annual fluctuations. Results from other projections are discussed to contextualise where these storylines fit in a broader understanding of plausible futures.

Spatial variations in the projected conditions are represented by the differences in ensemble median and only presented for the futures, representative concentration pathways and units that are most relevant to the key finding in the region. Inter-annual variability is visually represented by a single ensemble member (ACCESS1-0_ISIMIP2b) in the time series graphs. This single ensemble member time series should not be interpreted as a forecast for individual years; it is designed to model the extent to which the shorter-term climate drivers are likely to vary from the annual values.

Summary tables present key findings from multiple levels of evidence: projected results that describes the spread of the 16-member ensemble, concordance with historical trends reached by previous studies if available, and the assessment of the ability of the ensemble to simulate the hydroclimate in the region.

4.2 Precipitation

The projected changes to precipitation for the Monsoonal North region show a large spread with both increases and decreases plausible (Figures 4.1 and 4.2). There is little difference between the 2 representative concentration pathways. The internal variability remains a source of year-to-year variability in projected annual precipitation totals. However, since we know the GCMs have a limited ability to represent key climate drivers associated with monsoonal precipitation, the lack of evident response to climate change forcing is considered a source of uncertainty rather than evidence that differences in emission pathways will not result in marked changes to annual precipitation.

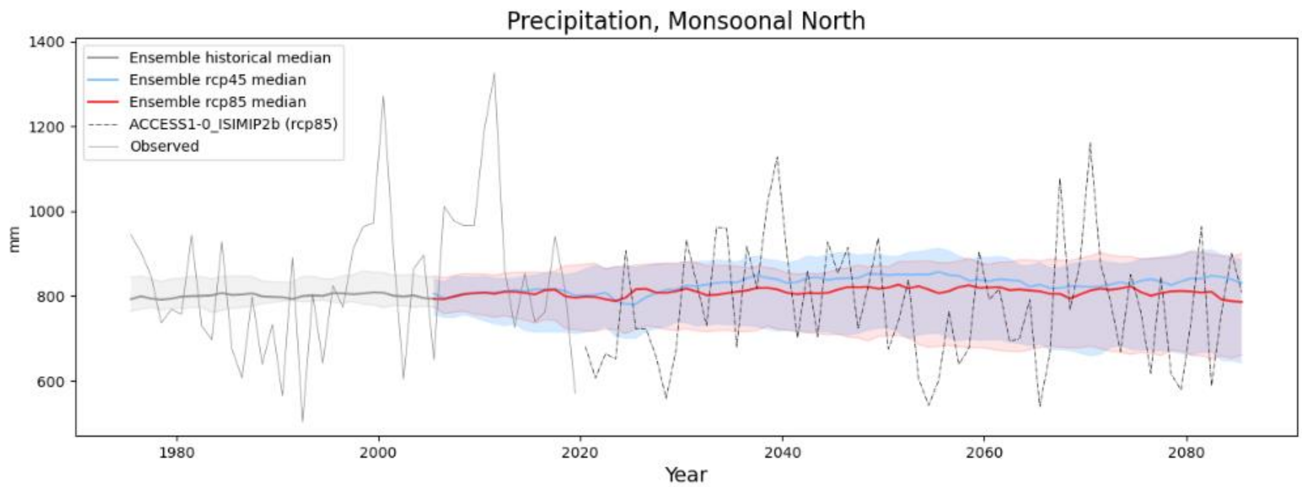


Figure 4.1. Annual modelled precipitation projected to 2099 by the 16-member ensemble for RCP4.5 (blue) and RCP8.5 (red) in the Monsoonal North region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. The time series for ACCESS1-0_ISIMIP2b (RCP8.5) is included (dotted line) to show the variability projected for an individual ensemble member. The grey line represents the observed historical median precipitation based on AWAP data

The median annual precipitation from the 16-member ensemble shows little change over time (Figure 4.2). However, the ensemble members project widely varying changes in annual precipitation, which makes the ensemble median a less reliable indicator of the change signal. Our ensemble shows that both large increases and decreases are considered plausible. The driest future storylines are represented by GCMs downscaled with the CCAM_ISIMIP2b bias-correction method. Ensemble members projecting the largest precipitation increases tend to be associated with CNRM-CM5 or MIROC5 GCM simulations.

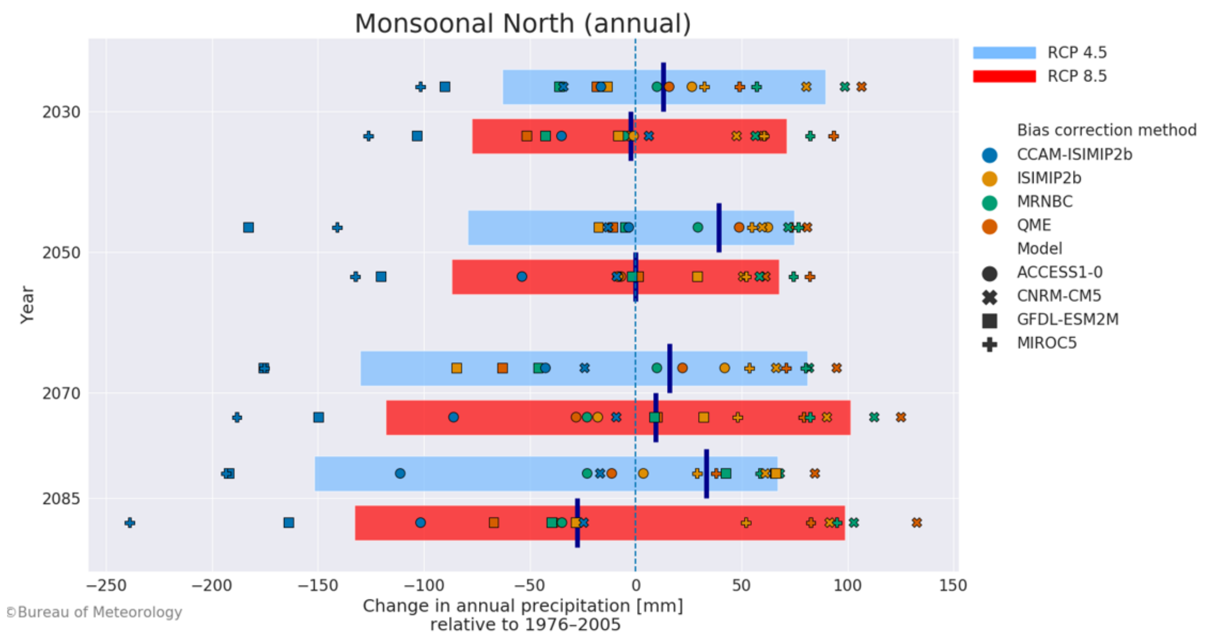


Figure 4.2. Change in annual precipitation (mm) projected by each ensemble member for 2030, 2050, 2070 and 2085 in the Monsoonal North region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentiles for RCP4.5. The dark blue line shows the ensemble median. The change is relative to the reference period (1976–2005)

The projected precipitation changes are not uniformly distributed across the Monsoonal North region (Figure 4.3), and while the ensemble median does not reliably indicate a particular direction of future change, spatially it gives a useful indication of the relative change signal across the region. There is a stronger drying signal in projected annual precipitation totals along coastal parts of the region and in the eastern subregion around the Gulf of Carpentaria. In contrast, a stronger signal for increasing precipitation is projected in the western part of the region.

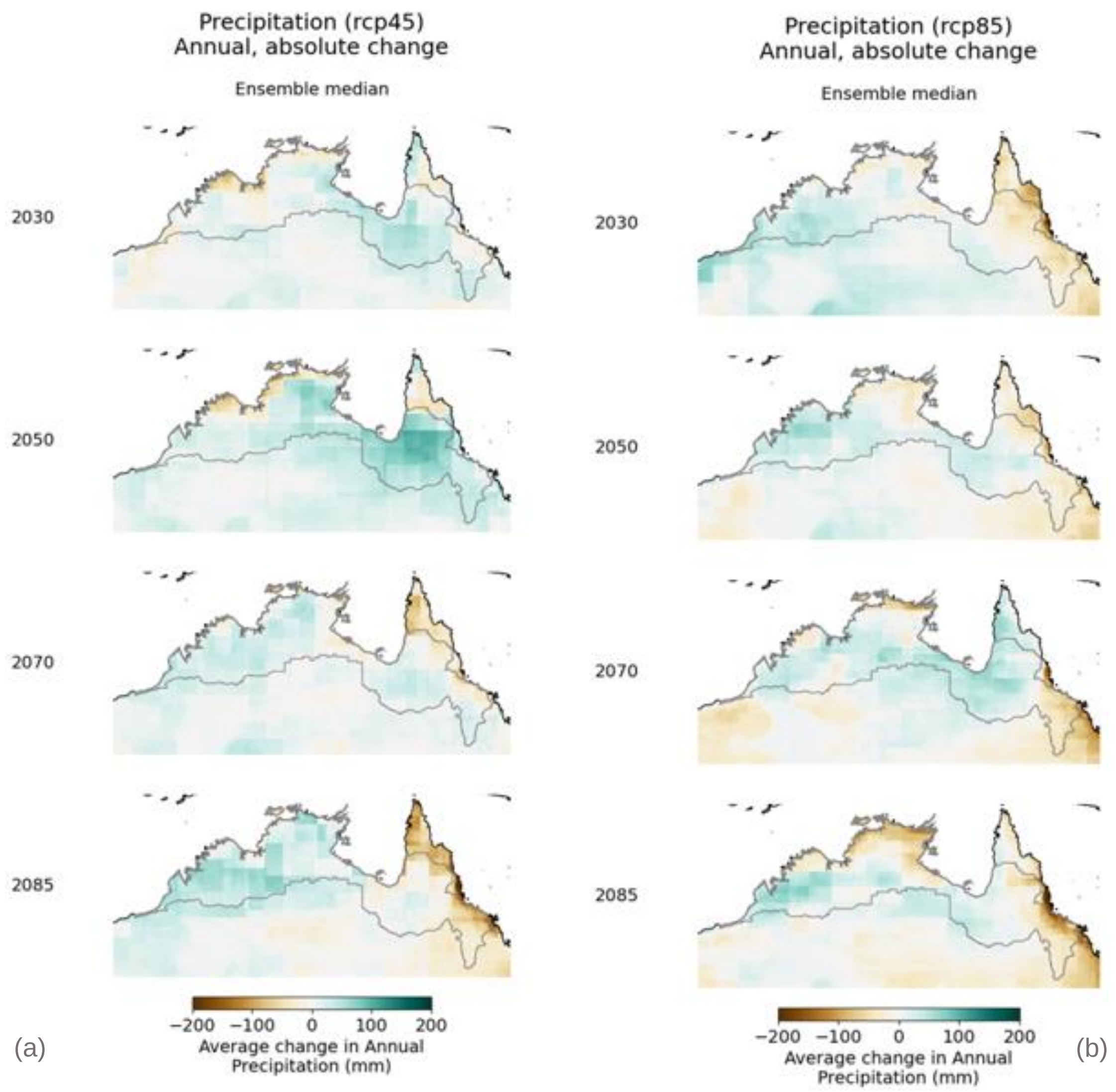


Figure 4.3. Absolute change (mm) (median) in annual modelled precipitation projected across the Monsoonal North region for 2030, 2050, 2070 and 2085 for (a) RCP4.5 and (b) RCP8.5. The change is relative to the reference period (1976–2005)

The median change in mean wet season precipitation for various future time periods shows a small increase (Figure 4.4). However, the wide distribution of wet season precipitation makes the median a not particularly reliable indication of change, and both large increases and decreases are considered plausible. The distribution of the ensemble members reflects the annual projections; decreases are projected by ensemble members bias corrected by the CCAM_ISIMIP2b method, and increases are associated with CNRM-CM5 and MIROC5 simulations. The median change to dry season precipitation projects a small decrease (Figure 4.4b).

Dry season precipitation amounts are relatively small compared to wet season precipitation, and the associated changes are on average less than 10% in relative terms (see summary Table 4.1). However, there is an influence of emission forcing with RCP8.5: by late century, most of the 16-member ensemble project decreases in dry season precipitation.

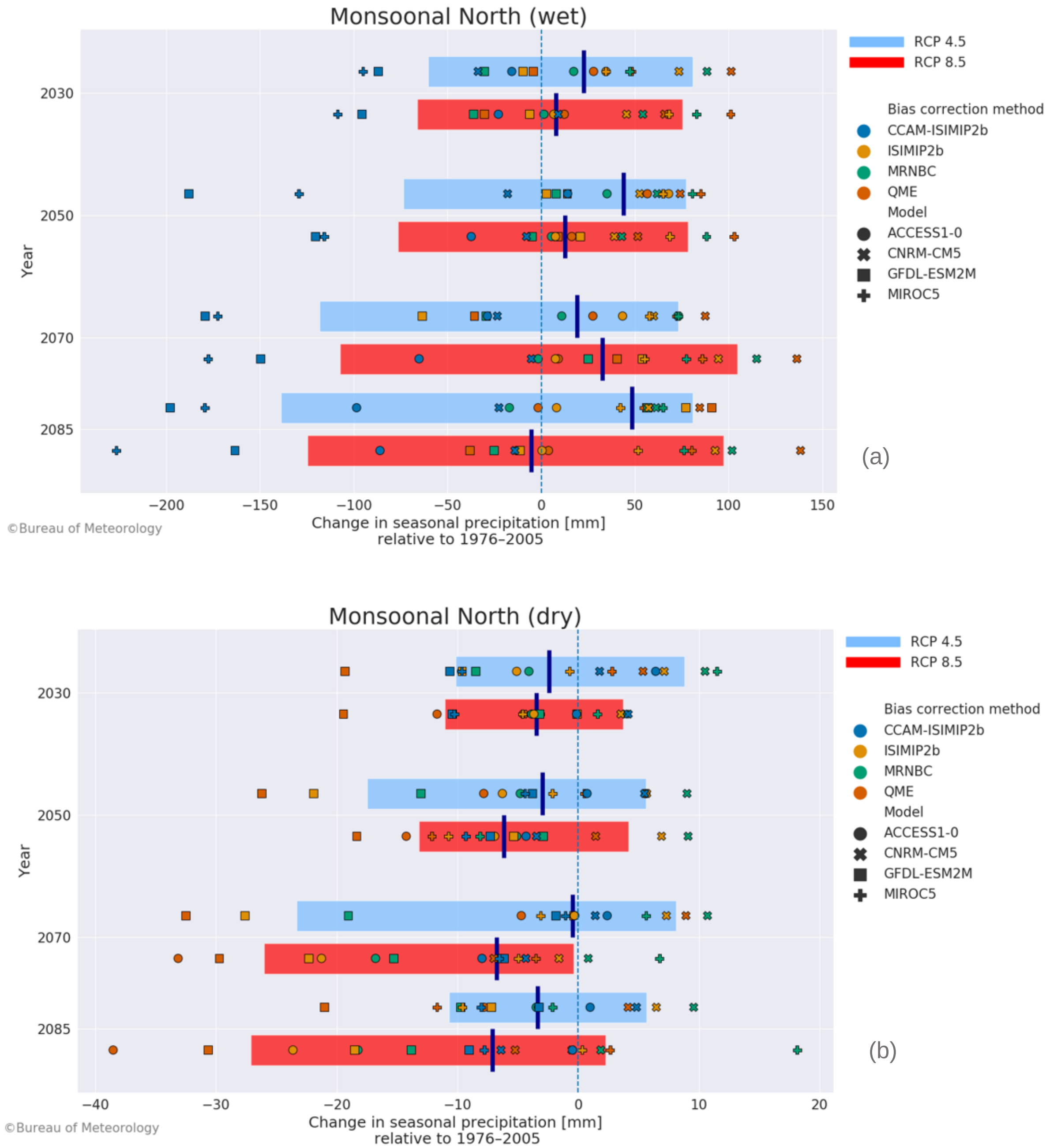


Figure 4.4. Absolute change in modelled precipitation (mm) projected by each ensemble member for (a) wet season (November–April) and (b) dry season (May–October) for 2030, 2050, 2070 and 2085 in the Monsoonal North region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentiles for RCP4.5. The dark blue line shows the ensemble median. The change is relative to the reference period (1976–2005)

Table 4.1. Assessment summary for precipitation in the Monsoonal North region

Feature	Largest plausible range of change	Additional evidence: plausible process	Additional evidence: ability to simulate	Summary statement
Wet season precipitation	RCP4.5 −198 to 101 mm/season (−26% to 13%) RCP8.5 −227 to 136 mm/season (−31% to 18%)	No observed trends in wet season precipitation and poor understanding of how wet season weather will change in a warming climate.	All GCMs are deemed suitable in representing ENSO events. However, models fundamentally disagree on projected changes to northern Australian summer rain in a warmer world. This is probably linked to uncertainty in circulation change at the largest scales (e.g. hemispheric changes) and might be sensitive to aerosol forcing. Also, GCMs may not adequately represent the influence of eastern seaboard topography on precipitation. GCMs vary in their response – some favouring an early, others a late monsoon season retreat – depending on each model’s circulation changes. This variation contributes to spread either side of the median.	The 16-member ensemble median projects a small decrease. Changes to wet season precipitation are highly uncertain in the Monsoonal North region, and both increases and decreases should be considered plausible. Natural climate variability is projected to remain the major driver of precipitation changes in the next few decades.
Dry season precipitation	RCP4.5 − 33 to 12 mm/season (−58% to 22%) RCP8.5 −39 to 9 mm/season (−56% to 17%)	Poor understanding of dry season precipitation.	All GCMs are considered suitable in simulating ENSO, which is key driver of dry season precipitation variability.	Both RCP4.5 and RCP8.5 project that both increases and decreases are plausible. Under RCP8.5 more ensembles point to a drier future. Median precipitation change is less than 10%. In absolute terms, all projected ranges of change are very small when compared to annual totals. Dry season precipitation is low compared to wet season precipitation.

4.3 Runoff

Projected changes to runoff feature a large spread, with both increases and decreases plausible. This large spread is driven by the projected changes to precipitation. Figure 4.5 shows the time series plot of the projected median of the mean annual runoff from the 16-member ensemble along with the annual runoff projected from ACCESS1-0_ISIMIP2b for RCP8.5.

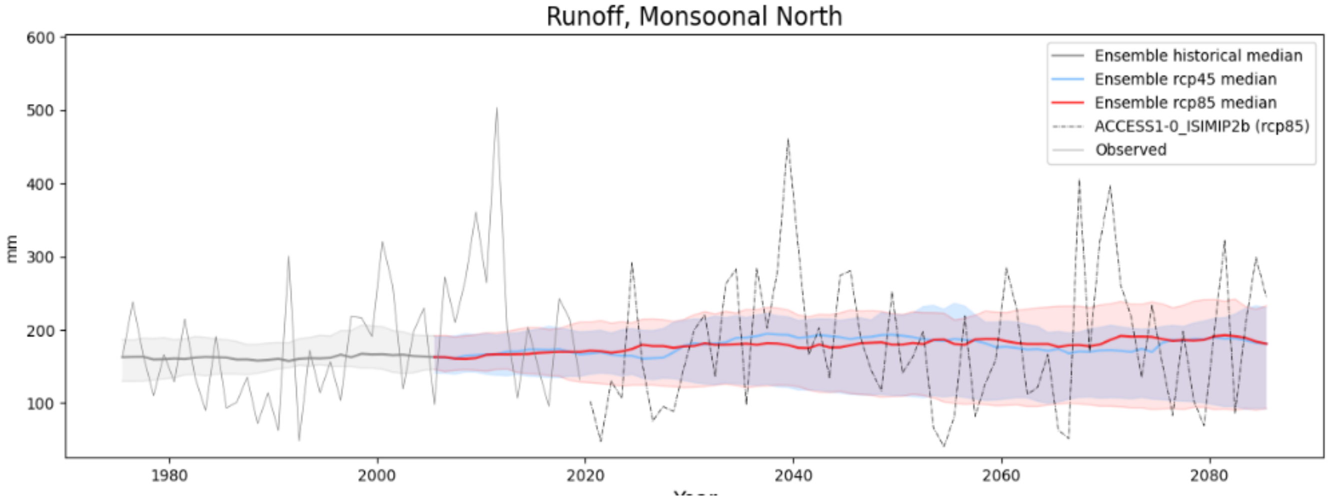


Figure 4.5 Annual modelled runoff (mm) projected to 2099 by ensemble members for RCP4.5 (blue) and RCP8.5 (red) greenhouse gas emission scenarios in the Monsoonal North region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. The time series for ACCESS1-0_ISIMIP2b (RCP8.5) is included (dotted line) to show the variability projected for an individual ensemble member. The grey line represents the modelled historical median runoff

The changes in annual runoff from the 16-member ensemble are shown in Figure 4.6. Median annual runoff is projected to increase for both representative concentration pathways and for each of the 4 time periods, but there is a wide spread between the storylines. Almost all storylines that project a decrease are downscaled and bias corrected with CCAM_ISIMIP2b. We do not know what features of the CCAM regional model lead it to project a different direction of change compared to all other bias-correction methods, but both increases and decrease in runoff are currently considered plausible. The remaining storylines all project increases, and the ensemble median is skewed towards the 90th percentile.

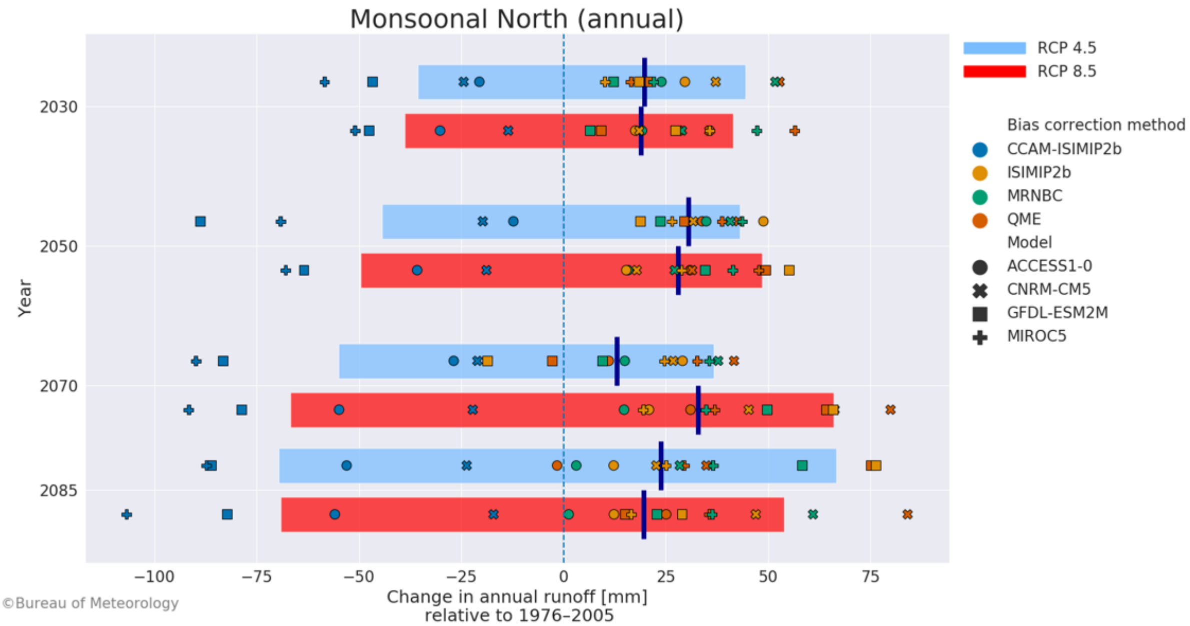


Figure 4.6. Absolute change in annual runoff (mm) projected by each ensemble member for 2030, 2050, 2070 and 2085 in the Monsoonal North region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentiles for RCP4.5. The dark blue line shows the ensemble median. The change is relative to the reference period (1976–2005)

The spatial distributions of the median change in annual runoff for the 2 representative concentration pathways over the 4 time periods are shown in Figure 4.7.

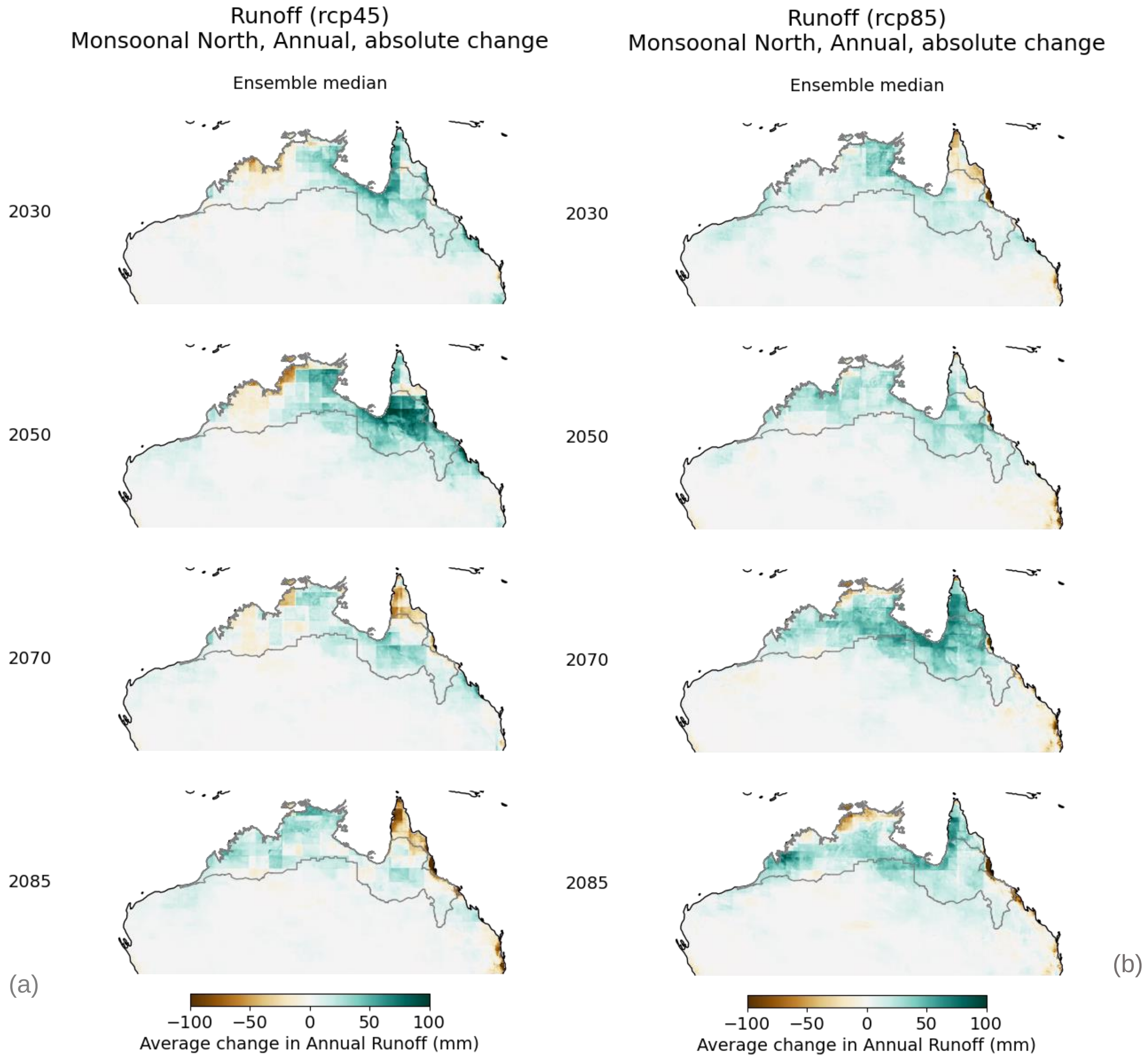


Figure 4.7. Absolute change (mm) (median) in annual modelled runoff projected across the Monsoonal North region for 2030, 2050, 2070 and 2085 for (a) RCP4.5 and (b) RCP8.5. This change is relative to the reference period (1976–2005)

Similar to projected changes in annual runoff, the median of the change in wet season runoff from the 16-member ensemble projects an increase (Figure 4.8a). A large spread of change is projected by the ensemble members, with both large increases and large decreases plausible. Almost all projected decreases are associated with models that are downscaled and bias corrected with CCAM_ISIMIP2b. There is no clear bias correction or GCM that consistently represents the larger runoff changes through various emission concentration or time periods.

The median change projected for dry season runoff is for little change early in the century and decreases towards the end of the century with a wider spread in ensemble results (Figure 4.8b). While the large spread of change values from the ensemble members indicates decreases and increases in the seasonal runoff are plausible, all projected changes are very small in absolute terms, especially when compared to runoff volumes generated in the wet season.

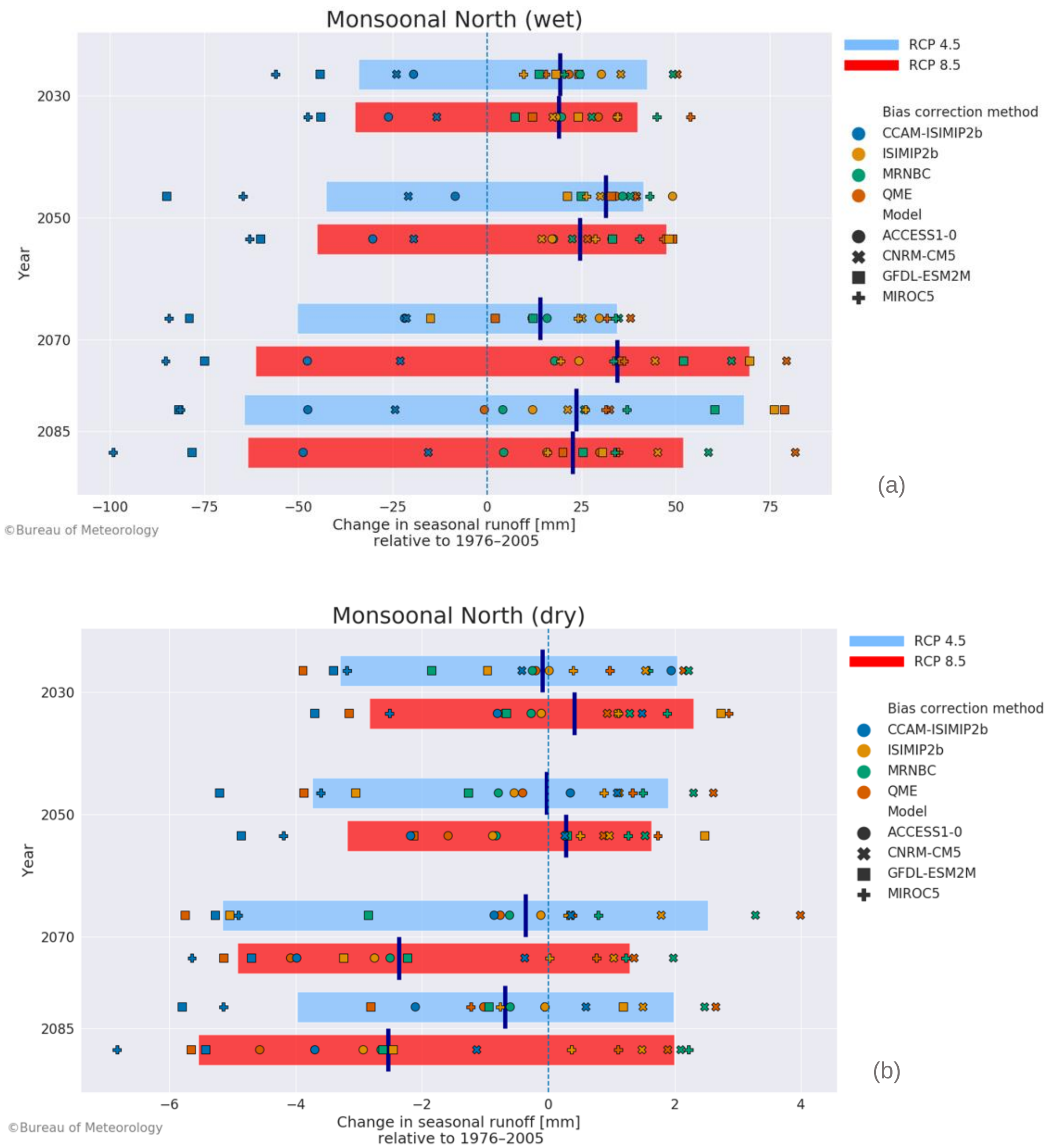


Figure 4.8. Absolute change (mm) projected by each ensemble member for (a) wet season (November–April) and (b) dry season (May–October) runoff for 2030, 2050, 2070 and 2085 in the Monsoonal North region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentiles for RCP4.5. The dark blue line shows the ensemble median. This change is relative to the reference period (1976–2005)

The summary assessment for runoff in given in Table 4.2.

Table 4.2. Assessment summary for runoff in the Monsoonal North region

Feature	Largest plausible range of change	Observed trends	Additional evidence: plausible process/ model reliability	Summary statement
Wet season runoff	RCP4.5 −85 to 79 mm/season (−62% to 49%) RCP8.5 −99 to 82 mm/season (−73% to 55%)	Increasing trend in wet season streamflow observed.	In the future more frequent high-intensity precipitation will occur, which is more likely to produce runoff, contributing to large average seasonal totals.	Large increases and decreases are projected for wet season runoff in all future time periods, with no significant difference between representative concentration pathways. Observed trends suggest increases may be more plausible. This is also consistent with increased runoff generated from higher intensity precipitation. However, the driest storyline is considered equally plausible as there is low understanding of how wet season rain-bearing climate drivers will respond to a warmer climate.
Dry season runoff	RCP4.5 −6 to 4 mm/season (−40% to 27%) RCP8.5 −7 to 3 mm/season (−50% to 18%)	Decreasing trend observed for dry season streamflow.		Increases and decreases are projected, with the ensemble median projecting little change. In absolute terms, the entire projected range is very small in comparison to wet season precipitation totals. No large difference between emission pathways.

4.4 Soil moisture

Annual root zone soil moisture is projected to decrease across the Monsoonal North region into the future, and the drying of soils is more pronounced under the high greenhouse gas emission scenario RCP8.5 than under RCP4.5 (Figure 4.9). Changes in soil moisture are strongly influenced by changes in precipitation and are more amplified due to large increases projected in potential evapotranspiration.

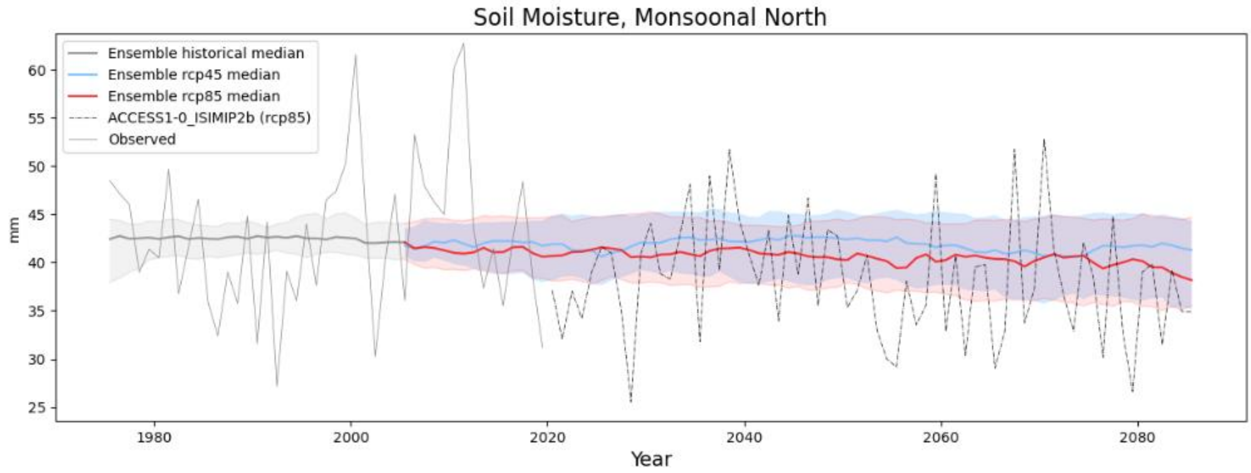


Figure 4.9. Annual modelled root zone soil moisture projected to 2099 by ensemble members for RCP4.5 (blue) and RCP8.5 (red) in the Monsoonal North region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. The time series for ACCESS1-0_ISIMIP2b (RCP8.5) is included (dotted line) to show the variability projected for an individual ensemble member. The grey line represents the modelled historical median soil moisture

Changes in future annual root zone soil moisture projected by the 16-member ensemble are shown in Figure 4.10. The median value of the change indicates a decrease in soil moisture later in the century.

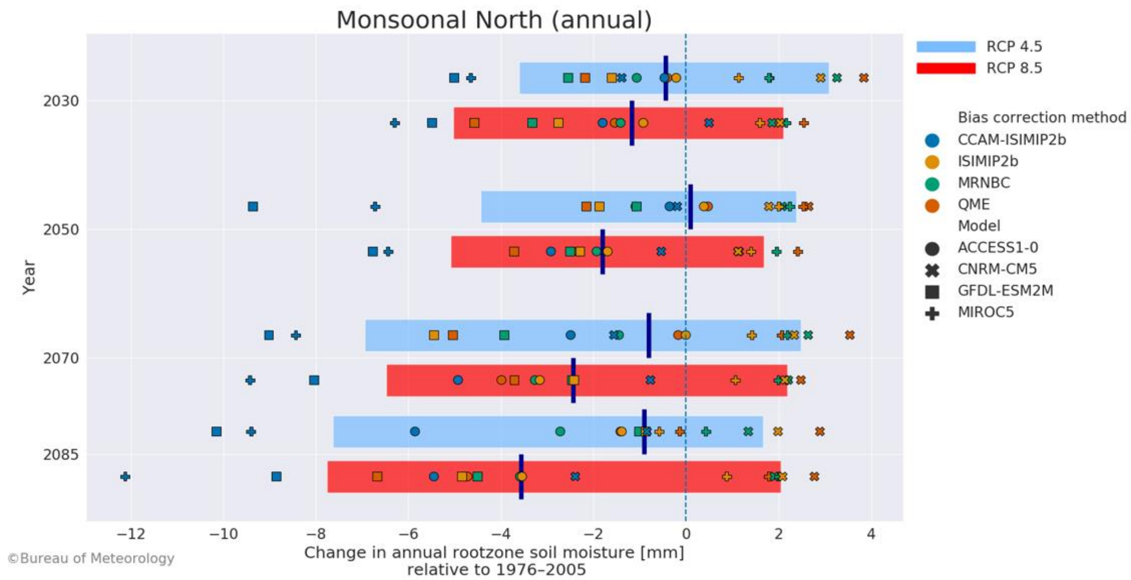


Figure 4.10. Absolute change (mm) in annual root zone soil moisture projected by each ensemble member for 2030, 2050, 2070 and 2085 in the Monsoonal North region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentiles for RCP4.5. The dark blue line shows the ensemble median. The change is relative to the reference period (1976–2005)

The eastern part of the Monsoonal North region is projected to become relatively drier in terms of root zone soil moisture than the western part (Figure 4.11), consistent with the projected changes in precipitation.

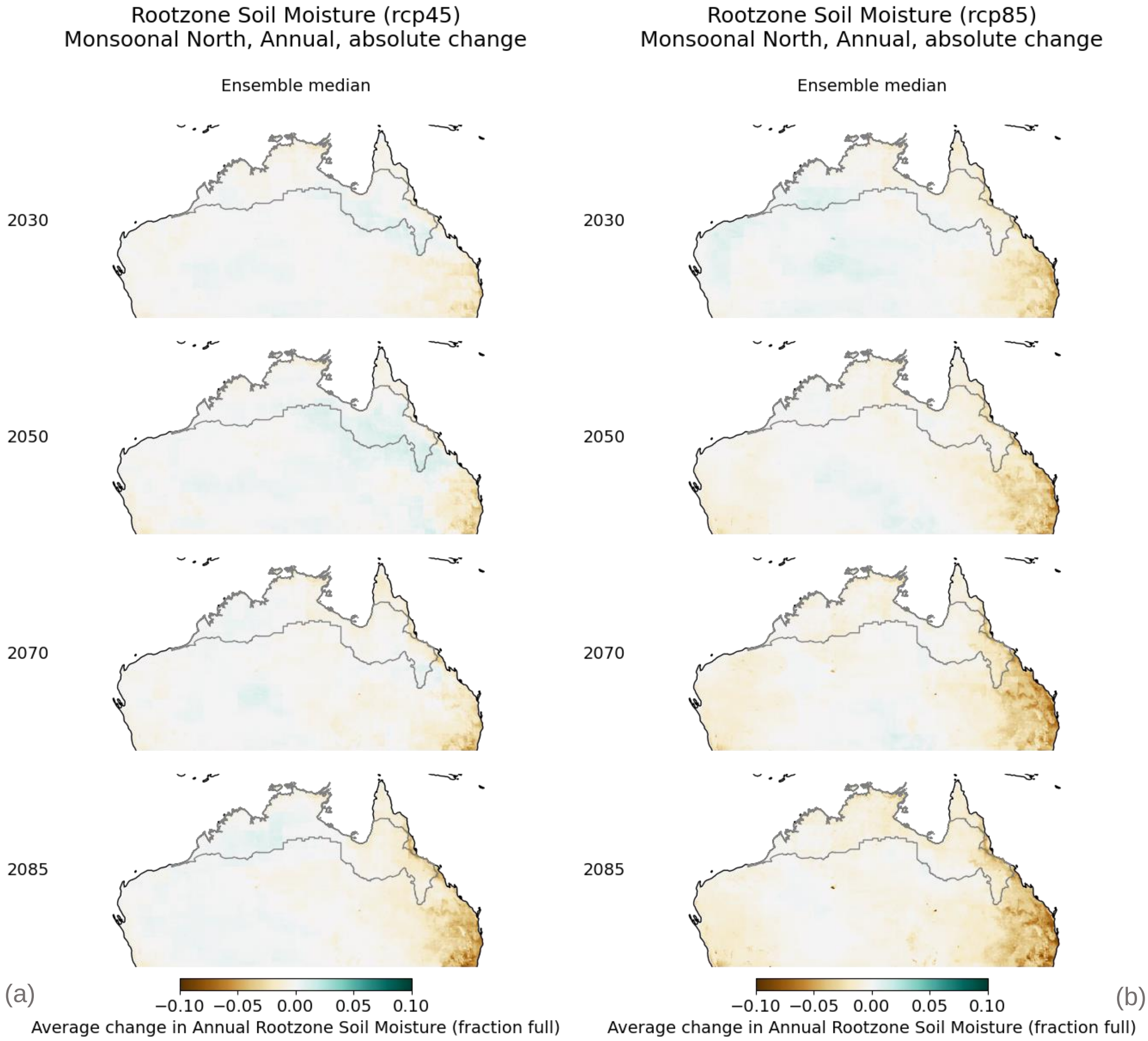


Figure 4.11. Absolute change (fraction full) (ensemble median) in annual modelled root zone soil moisture projected for 2030, 2050, 2070 and 2085 for (a) RCP4.5 and (b) RCP8.5 across the Monsoonal North region. The change is relative to the reference period (1976–2005). Fraction full (scale 0–1) is equivalent to (percentage full)/100 and represents the fraction of available water content in the root zone (0–1 m) soil profile

The median changes in both wet and dry season root zone soil moisture for the Monsoonal North region show a decrease from the reference period (1976–2005) for almost all time periods under both representative concentration pathways (Figure 4.12). The summary assessment for soil moisture is given in Table 4.3**.**

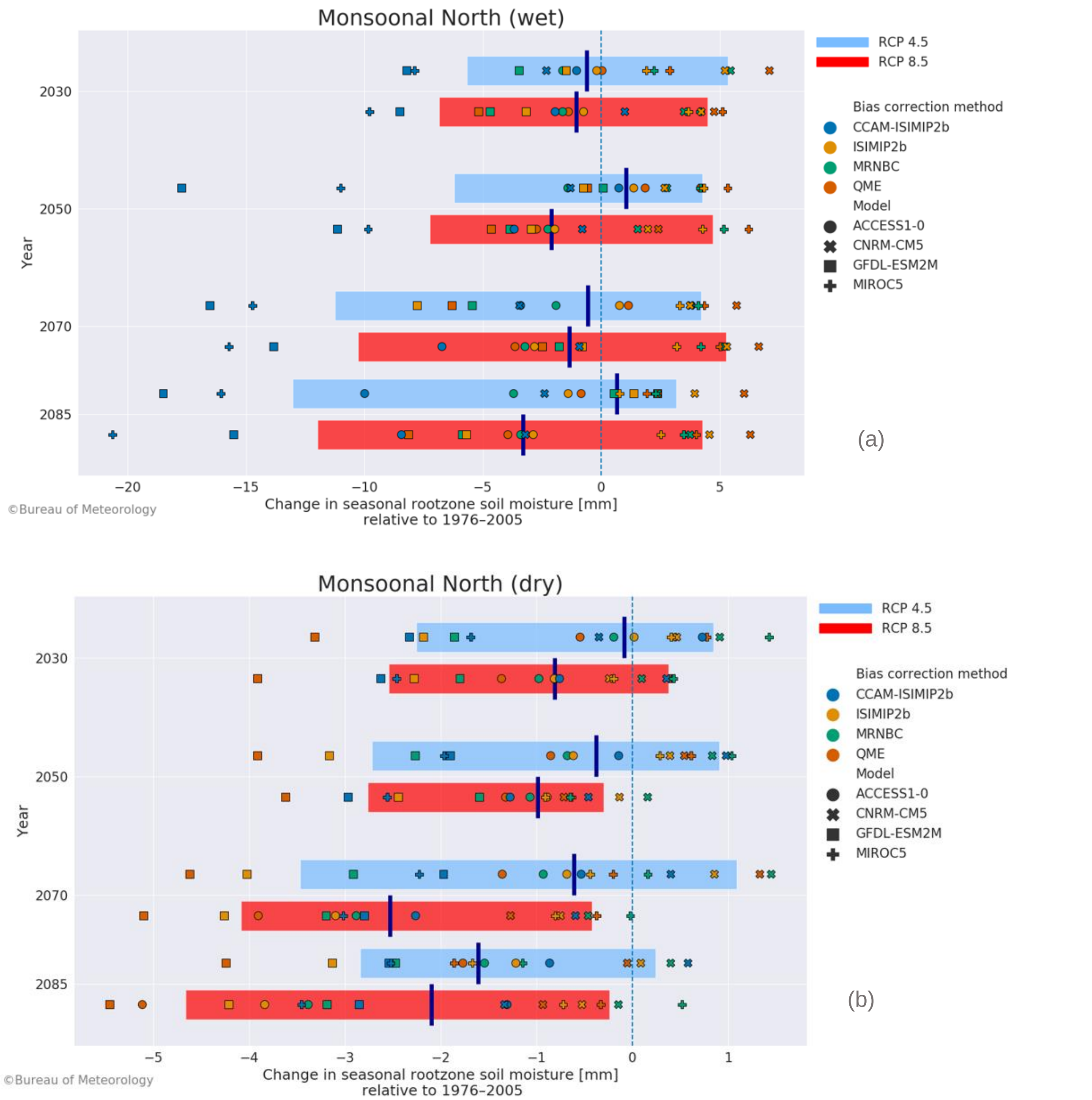


Figure 4.12. Absolute change (as fraction full of soil moisture capacity) projected by each ensemble member for (a) wet season (November–April) and (b) dry season (May–October) root zone soil moisture for 2030, 2050, 2070 and 2085 in the Monsoonal North region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentiles for RCP4.5. The dark blue line shows the ensemble median. The change is relative to the reference period (1976–2005)

Table 4.3. Assessment summary for root zone soil moisture in the Monsoonal North region

Feature	Largest plausible range of change	Additional evidence: plausible process/ model reliability	Summary statement
Wet season soil moisture	RCP4.5 −7 to 2 mm/season (−24% to 9%) RCP8.5 −8 to 2 mm/season (−27% to 8%)	Soil moisture conditions influence how much precipitation can infiltrate into and saturates soils; how much water is generated as runoff as well as how much water is available for plant uptake. Wet season precipitation is typically replenishing soil water stores. Increases in evapotranspiration can lead to decreases in soil moisture.	Both future increases and decreases in soil moisture are plausible. The wettest future storyline for wet season soil moisture is for increases of around 5%. The ensemble median storyline is for little change for both representative concentration pathways and all future periods. The driest storyline features mid-century decreases and large decreases late in the century and no significant difference between greenhouse gas emission pathways.
Dry season soil moisture	RCP4.5 −3 to 0 mm/season (−35% to 13%) RCP8.5 −2 to 0 mm/season (−41% to 5%)	Dry season soil moisture is largely driven by precipitation amounts in the preceding 3 months. Increases in evapotranspiration can lead to decreases in soil moisture and runoff.	The wettest future storylines for dry season soil moisture show little change. The median ensemble projects large decreases (10% to 20%). The driest scenario projects very large decreases (20% to 36%).

4.5 Potential evapotranspiration

In the hydrological cycle, evapotranspiration plays an important role, particularly in soil evaporation and crop transpiration. While precipitation is the key driver of water availability, potential evapotranspiration is an indicator of potential losses in the total water balance for a system, and a limiting factor in the amount of water available for use. While these trends in potential evapotranspiration do not tell us what the projected changes to the actual evapotranspiration rate are, the signal indicates that the region could see impacts including:

- an increase in crop water demand (through higher transpiration of plants)
- increased evaporation from soils following a higher depletion rate of soil moisture
- the potential for greater losses from surface water storages through evaporation.

Annual potential evapotranspiration (PET) is projected to increase in the future, consistent with projected increases in temperature. The time series of annual potential evapotranspiration for Monsoonal North from ACCESS1-0_ISIMIP2b is shown in Figure 4.13. This figure shows an increase in annual potential evapotranspiration in the future. The projected increase is greater for the higher representative concentration pathway: the mid-century increase under RCP8.5 is equivalent to the end-of-century increase under RCP4.5. Potential evapotranspiration is projected to increase in terms of annual potential evapotranspiration (Figure 4.14) and both wet and dry season potential evapotranspiration (Figure 4.16) as warming is projected to progress. The largest change is projected in the dry season (winter) potential evapotranspiration by 2085 for RCP8.5 (Figure 4.16). This increase in potential evapotranspiration is expected with rising temperature. Projected increases in potential evapotranspiration have a spatial gradient across the region (Figure 4.15) with slightly higher values inland, away from the moderating effects of the coastal regions. The summary assessment for potential evapotranspiration is given in Table 4.4**.**

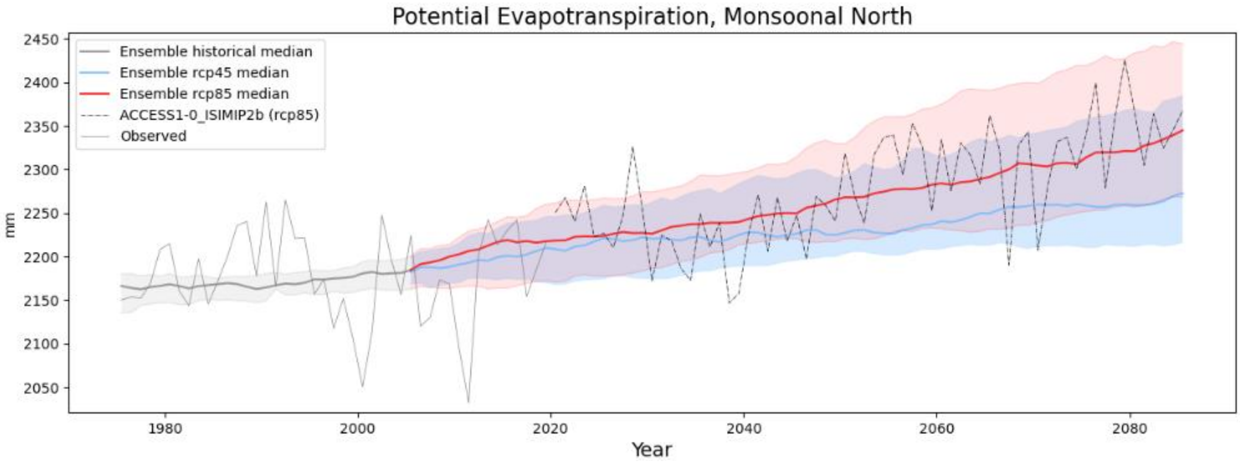


Figure 4.13. Annual modelled potential evapotranspiration (mm) projected to 2099 by ensemble members for RCP4.5 (blue) and RCP8.5 (red) in the Monsoonal North region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. The time series for ACCESS1-0_ISIMIP2b (RCP8.5) is included (dotted line) to show the variability projected for an individual ensemble member. The grey line represents the modelled historical median potential evapotranspiration

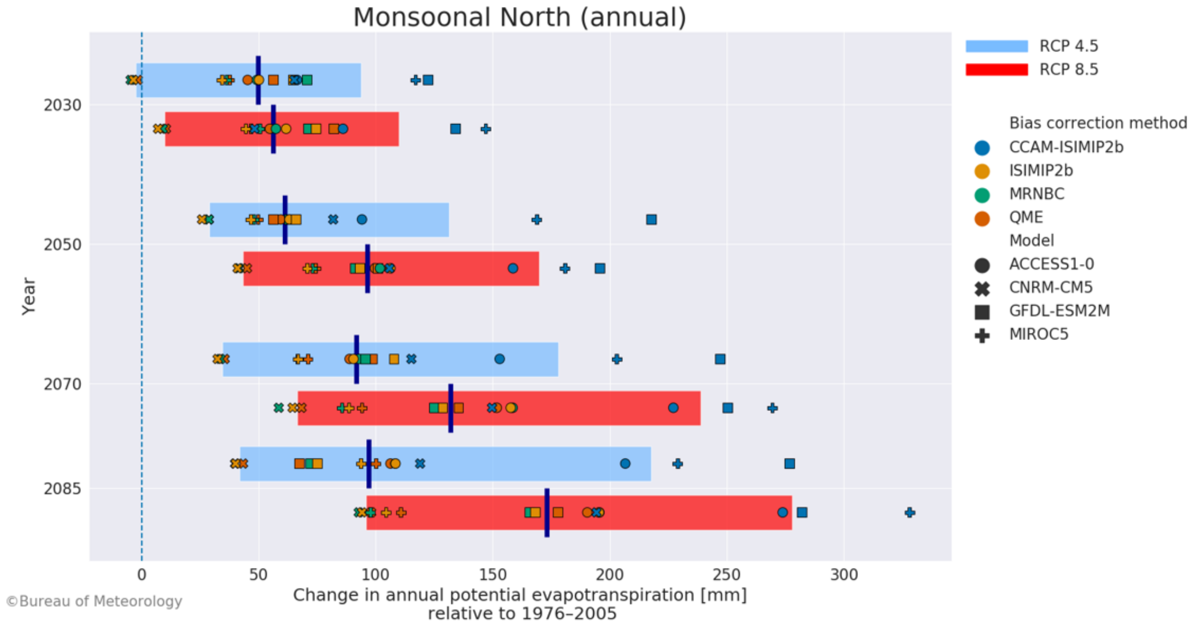


Figure 4.14. Absolute change (mm) in annual potential evapotranspiration projected by each ensemble member for 2030, 2050, 2070 and 2085 in the Monsoonal North region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentiles for RCP4.5. The dark blue line shows the ensemble median. The change is relative to the reference period (1976–2005)

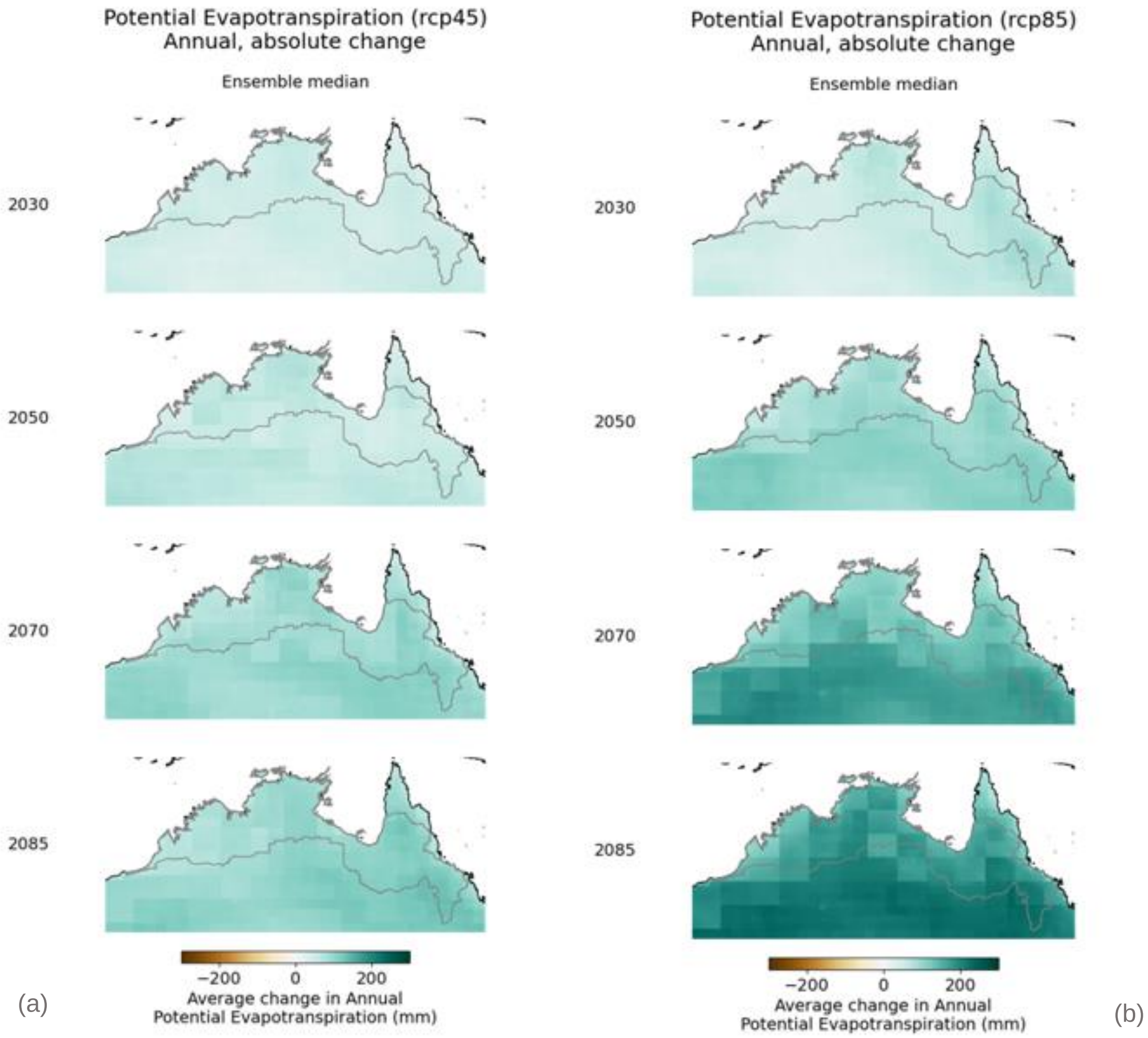
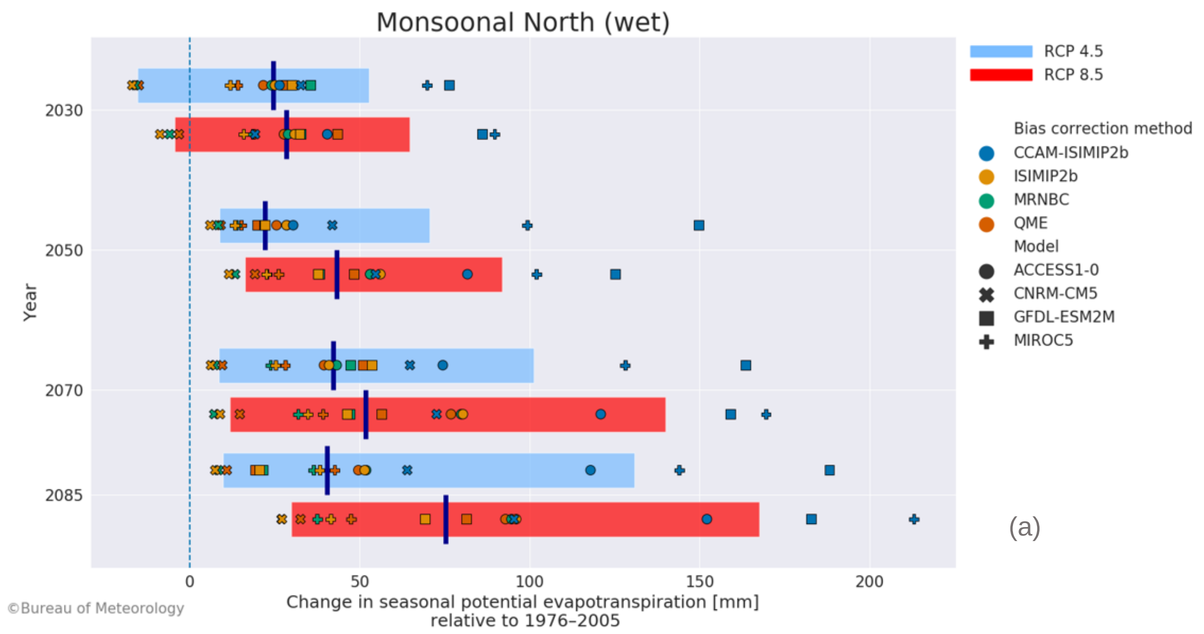


Figure 4.15. Absolute change (mm) (ensemble median) in annual modelled potential evapotranspiration for (a) RCP4.5 and (b) RCP8.5 for 2030, 2050, 2070 and 2085 across the Monsoonal North region. The change is relative to the reference period (1976–2005)



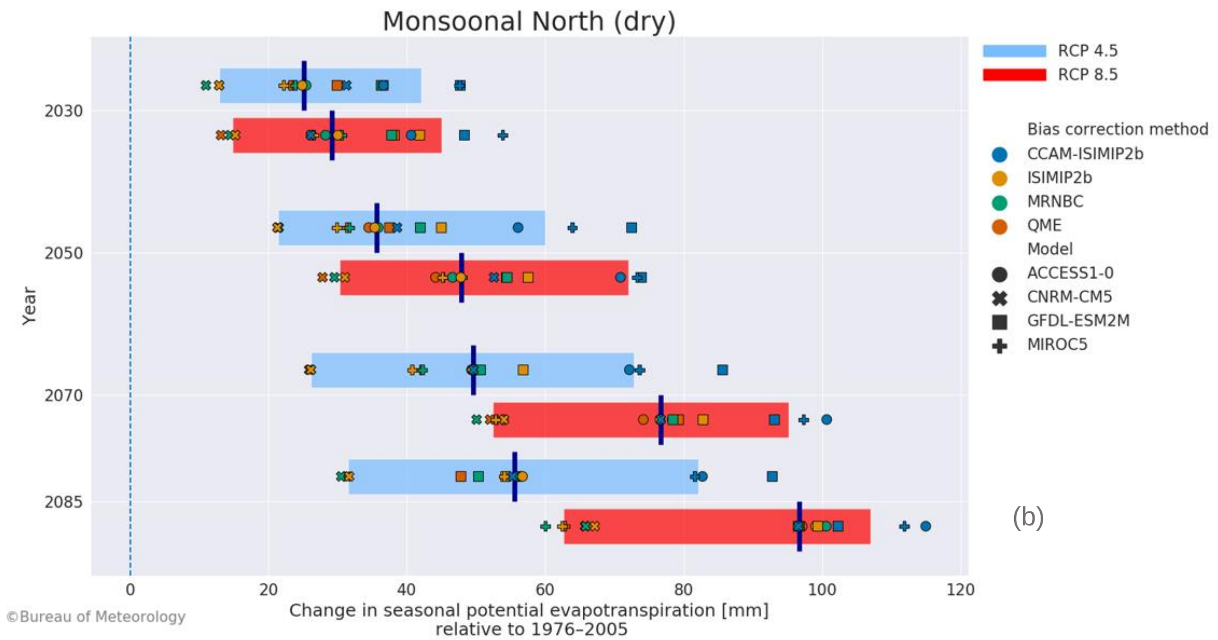


Figure 4.16. Absolute change (mm) in potential evapotranspiration projected by each ensemble member for (a) wet season (November–April) and (b) dry season (May–October) for 2030, 2050, 2070 and 2085 in the Monsoonal North region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentiles for RCP4.5. The dark blue line shows the ensemble median. The change is relative to the reference period (1976–2005)

Table 4.4. Assessment summary for potential evapotranspiration in the Monsoonal North region

Feature	Largest plausible range of change	Additional evidence: downscaling/ consistency of observations trends with projected trends	Additional evidence: plausible process/ model reliability	Summary statement
Annual potential evapotranspiration	RCP4.5 −5 to 286 mm/year (0% to 13%) RCP8.5 7 to 328 mm/year (0% to 15%)	Small increase observed in the recent past.	Warmer climate results in higher potential evapotranspiration.	Potential evapotranspiration increase is similar for both seasons. Storylines vary from little change in both emission pathways, and all future periods, to large increases. Magnitude increases in potential evapotranspiration are plausible with time.

4.6 Extreme events

Hydrological extremes, including floods and droughts, are among the costliest natural disasters in the world (Wasko & Nathan 2019). They pose risks to life, food security, infrastructure and energy supply. Future climate change is expected to bring a more variable precipitation pattern with longer dry spells and more frequent extreme events, such as flood-producing rain and cyclones (Easterling et al. 2000; Johnson & Murray 2004; Milly et al. 2002; Palmer & Räisänen 2002; Walsh & Ryan 2000). On the extreme dry end of the spectrum, prolonged absence of precipitation, for example, through a failure of the monsoon, may result in increasing dry spells. On the extreme wet end of the spectrum, an increase in extreme rains can exacerbate flooding events. Changes in the frequency, amount and duration of precipitation have serious impacts on sectors such as agriculture, water management and flood control (Alam et al. 2018). The ability to project future climate can help improve irrigation planning, flood planning, and design and management of hydraulic structures such as dams and stormwater drainage systems. This knowledge will also help us identify Australia's vulnerability to future droughts and improve resilience through mitigation actions.

4.6.1 Extreme precipitation and runoff

Earlier studies using observations and projections have shown an increase in the frequency of extreme precipitation events in the Australian region (Alexander & Arblaster 2009; Rafter & Abbs 2009; Wasko & Sharma 2017). In a warming climate, heavy precipitation events are likely to increase in magnitude due to the increased moisture-holding capacity of a warmer atmosphere (Sherwood et al. 2010; Yin et al. 2020). Such excessive precipitation events may enhance the potential risk of flooding, depending on antecedent conditions. However, Wasko & Nathan (2019) found that, in Australia as in many other parts of the world, soil moisture deficits that are first re-filled during precipitation events commonly reduce flood magnitudes, despite increasing precipitation extremes. Therefore, in this project, we estimated projected future flood scenarios based on both precipitation and runoff.

Characterising changes in flood frequency and intensity at a large spatial and temporal scale is challenging; flood risk often depends on local topography, sub-daily precipitation intensity and antecedent conditions. We calculated a set of threshold-based indicators using precipitation and runoff to capture changes in flood risk on a broad scale.

The changes on the extreme wet end of the spectrum are determined using 3 indicators: the projected annual mean and maximum daily precipitation and runoff, and the 20-year return period precipitation and runoff estimated using the generalised extreme value (GEV) distribution. The GEV distribution is generally used to represent the rare events (Bali 2003).

Projections show an increase compared with the reference period in the maximum daily and 20-year return period of both precipitation (Figure 4.17) and runoff (Figure 4.18) for 2030 and 2070 under both representative concentration pathways (RCP4.5 and RCP8.5). Mean daily precipitation and runoff show more moderate increases, although mean daily runoff tends towards a marked increase across both representative concentration pathways. This pattern (an increase in all indicators) differs from the projections for almost all other National Hydrological Projections assessment regions and could reflect an overall shift in monsoonal precipitation patterns. The magnitudes of the simulated changes in extreme precipitation indicators depend heavily on the representative concentration pathways, the given ensemble member and the time period in question. Therefore, the magnitude of change is uncertain. This could be because smaller-scale systems that generate extreme precipitation are not well represented by GCMs (Fowler & Ekström 2009). In the Monsoonal North region, the RCP8.5 scenario for 2070 has a larger ensemble member spread than the same time period for RCP4.5.

In summary, the results suggest that daily mean precipitation is projected to increase only slightly overall, but extreme precipitation is projected to show a stronger increase (Figure 4.17). However, the magnitude and timing of the future change in intensity of wet extremes from natural climate variability of the region cannot be projected with certainty.

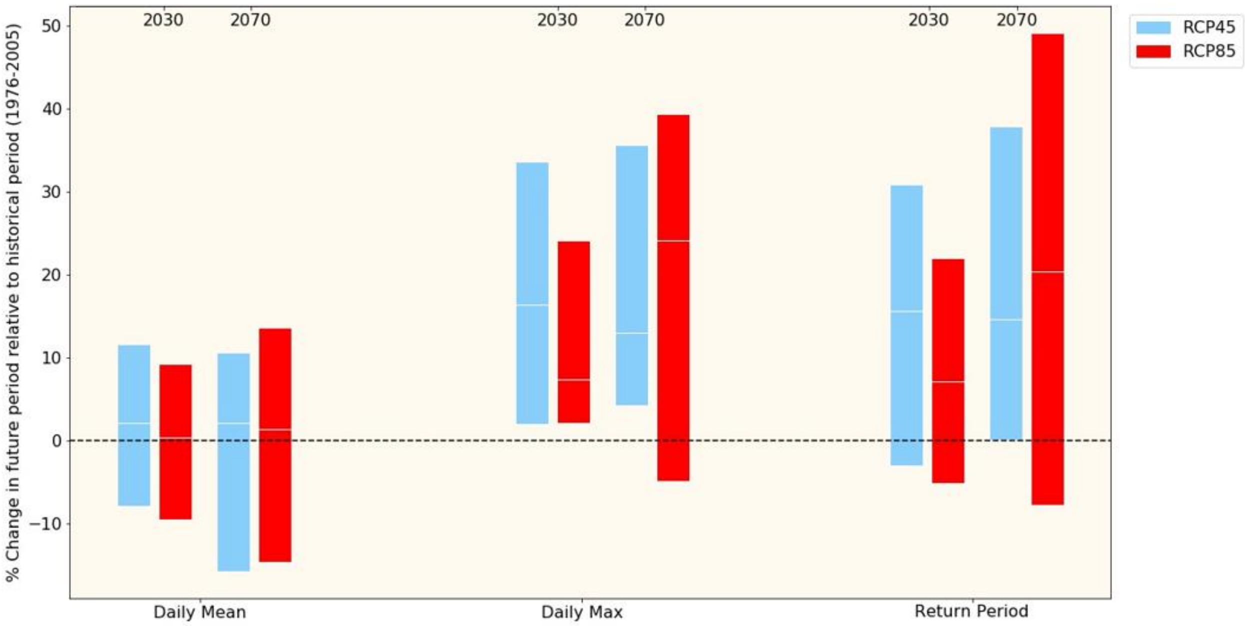


Figure 4.17. Future extreme wet analysis based on modelled precipitation shown by changes (%) in mean daily precipitation, maximum daily precipitation and 20-year return period of the annual maximum precipitation for 2030 and 2070 in the Monsoonal North region. The red bars show the 10th to 90th percentiles for RCP8.5. The blue bars show the 10th to 90th percentiles for RCP4.5. The white lines show the ensemble median. The change is relative to the reference period (1976–2005)

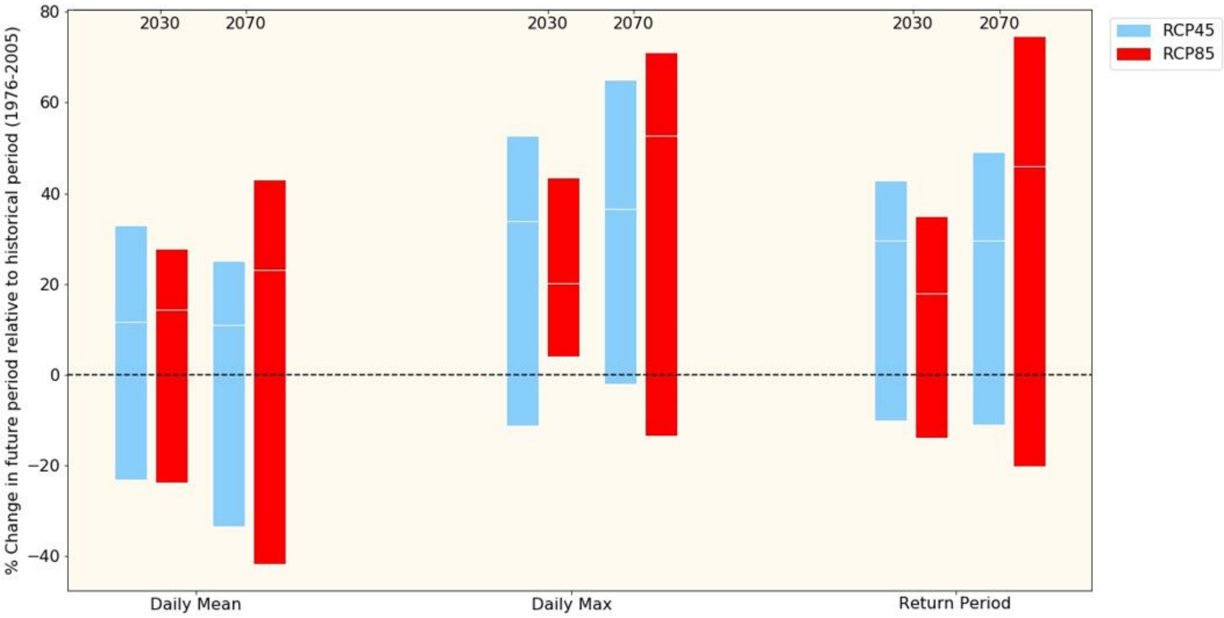


Figure 4.18. Future extreme wet analysis based on modelled runoff shown by changes (%) in mean daily runoff, maximum daily runoff and 20-year return period of the annual maximum runoff for 2030 and 2070 in the Monsoonal North region. The red bars show the 10th to 90th percentiles for RCP8.5. The blue bars show the 10th to 90th percentiles for RCP4.5. The white lines show the ensemble median. The change is relative to the reference period (1976–2005)

4.6.2 Dry landscape conditions

To gain a greater understanding of future extreme dry conditions or droughts and the range of socioeconomic impacts, it is important to combine multiple lines of evidence encompassing climatological and hydrological extreme dry states. Projected extreme meteorological, hydrological and agricultural dry conditions were investigated using 3 separate indicators. A meteorological extreme dry state refers to when an area is 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. Analysis of future conditions must also take into account different time frames, as hydrological dry states arise over a longer time period than meteorological and agricultural extreme dry periods (which can include 'flash droughts'). Hydrological dry states result from prolonged spells of below-average precipitation and the subsequent below-average runoff. However, a reduction in precipitation may result in a decrease in water available for stock or a depletion of topsoil moisture needed to grow crops. This will impact agriculturalists sooner than it will cause disruption to the whole hydrological system.

In this study, projected precipitation, runoff and soil moisture data was used to represent these 3 types of droughts: meteorological, hydrological and agricultural. This lets us capture the potential impacts on key sectors of agricultural and water-sensitive industries. The indicators are used as a proxy for drought, noting that they should be taken as an indicative estimate of drought conditions because many other factors involved in determining whether a region is in drought have not been included in this analysis.

As the various types of extreme dry conditions or droughts arise over different time frames, our analysis addresses short-term to long-term durations by calculating the median extreme dry condition duration (short, moderate, long or prolonged). An extreme dry condition is defined by applying a threshold quantile of 15% of the historical period to future projections. We use percentile thresholds to determine drought periods as this method involves no assumptions about the data distribution. Using the 15th percentile as the drought threshold means that any month below this 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) and is commonly used to characterise ‘moderate’ droughts (McKee et al. 1993). We use this threshold to ensure we have a sufficient number of drought events 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). The 15% threshold definition is applied separately for each indicator and for each different time period. Figure 4.19 and Table 4.5 show that various characteristics of the extreme dry condition were evaluated, namely, the future change in the cumulative duration of the short, moderate, long and prolonged extreme dry spells and the change in the spatial extent of the area undergoing short, moderate, long, and prolonged extreme dry conditions compared to the historical reference period (1976–2005). Using the defined drought metrics, the average percentage of time spent in drought in the future was also calculated and is presented below in Table 4.5.

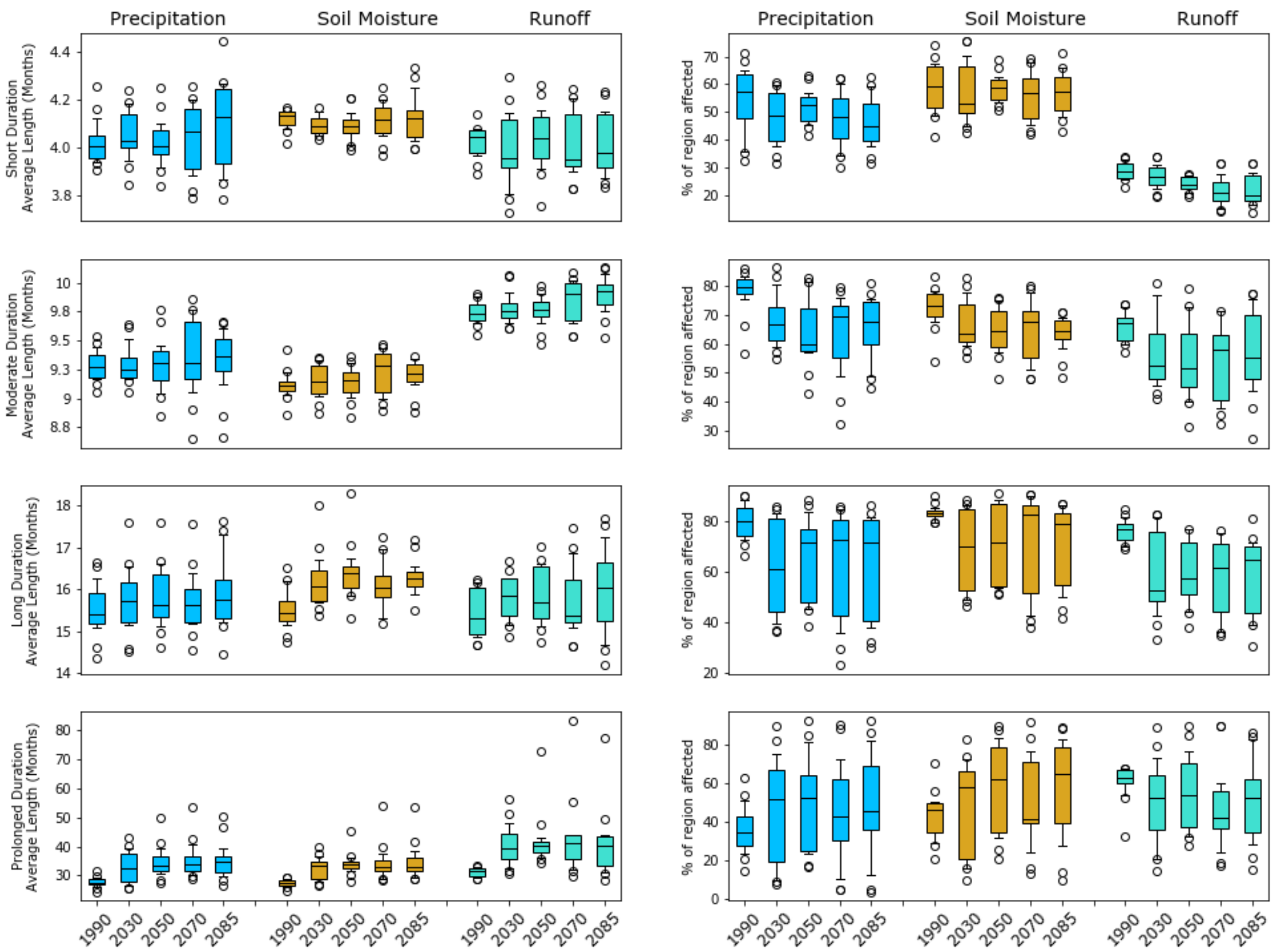


Figure 4.19. Change in projected median drought lengths (left) and percentage of total area affected by extreme dry conditions (right) for modelled precipitation (meteorological drought indicator), modelled soil moisture (agricultural drought indicator) and modelled runoff (hydrological drought indicator) in the Monsoonal North region. The box plots show the median, 10th and 90th percentiles and outliers. They are presented for short-term, moderate, long-term and prolonged drought durations. The change is relative to the reference period (1976–2005)

Table 4.5 Summary of the primary results shown in Figure 4.19

Duration (months)	Drought type	Projected result	Impact
Short (3–6 months)	All types	Little change in average duration projected for all drought types but up to a 15% decrease in spatial extent of drought. A wider ensemble member spread is shown in the change in spatial extent than in duration.	Projected flash droughts (as represented by 3–6 months duration) remain similar on average compared to the historical reference period. Higher variability is plausible for the drought-affected regions, tending towards a decrease in the area affected.
Moderate (7–11 months)	All types	Little change in average duration projected for all drought types but up to a 15% decrease in spatial extent of drought. A wider ensemble member spread is shown in the change in spatial extent than in duration.	Projected moderate droughts remain similar to the historical reference period. Higher variability is plausible for the drought-affected regions, tending towards a decrease in area affected.
Long-term (12–23 months)	All types	Little change on average is projected for all drought types. The largest increase is shown in the agricultural drought duration (about 7%) but up to a 20% decrease in spatial extent of drought. A wider ensemble member spread is shown in the change in spatial extent than in duration.	Projected long-term droughts to increase, which could have negative implications for river health, water-dependent industries and agricultural systems in the future.
Prolonged (>24 months)	Meteorological drought	Projected up to about 30% increase in time in drought, varying across the future time periods. Projected increase in area under meteorological drought by up to about 20%, varying across the future time periods.	Projected increases in prolonged periods of low precipitation are plausible with an intensification of precipitation-deficient areas in the future.
	Hydrological drought	Projected up to about 25% increase in time in drought, varying across the future time periods. Projected decrease in area under hydrological drought by up to about 20%, varying across the future time periods.	Projected increase in prolonged periods of low-runoff states, which could lead to water supply shortages and insufficient environmental flows in the future.
	Agricultural drought	Projected up to about 30% increase in time in drought, varying across the future time periods. Projected increase in area under agricultural drought by up to about 15%, varying across the future time periods.	Projected increases in prolonged soil moisture deficits are plausible, with an increase in drought-affected areas towards the end of the century. This could lead to impacts on crop and pasture growth as well as natural vegetation growth in the future.

In summary, increases in future multi-year extreme dry conditions in the Monsoonal North region are projected, where the spatial extent of areas affected by multi-year extreme dry conditions is variable and uncertain across all indicators. Increases in areas under meteorological and agricultural drought are projected but decreases in areas under hydrological drought are plausible. Short-term to long-term droughts are projected to remain similar to the historical reference period.

5 Exploring future water resource impacts: applying selected storylines to the Monsoonal North region

Projection results feature many sources of uncertainty, including uncertainty over future trajectories of atmospheric greenhouse gas concentrations, how a warmer climate will lead to changes in hydroclimatic features and feedback loops, and how well climate models will represent those features. Acknowledging these uncertainties, the National Hydrological Projections 16-member ensemble provides a unique opportunity to examine the impacts of plausible future changes on Australia's hydroclimate and its water resources. Projections provide a collection of possible future storylines rather than a forecast or likelihood of a specific outcome.

While the National Hydrological Projections 16-member ensemble does not represent every possible future outcome (e.g. of the CMIP5 climate models) for every possible future emissions profile, the ensemble members do represent a selection of internally consistent plausible hydroclimatic futures, or storylines, that let us investigate hydrological responses and inform adaptation planning. Storylines can be used to tie the projections results to a specific impact (Shepherd et al. 2018). We have selected single ensemble members that represent changes to hydrological features that define a selection of storylines for the Monsoonal North region.

5.1 Exploring water-sensitive impacts

Changes to water supply and demand storylines are explored below. In the Monsoonal North, the key climate features that relate to water resource impacts are runoff in the wet season and changes to soil moisture in the dry season. We use the Burdekin River catchment to assess changes to water security in the far east of the region.

Wet season runoff fills the storages, so changes to wet season runoff in the Burdekin Falls Dam catchment can be taken as a proxy for changes in the reliability of storage filling. In absolute terms, changes to dry season runoff volumes are extremely small compared to the volumes generated in the wet season and are therefore not considered significant when discussing changes to annual water availability.

Estimates of changes to water demand at an annual level are most sensitive to changes in dry season soil moisture. Changes to dry season soil moisture will drive increases or decreases in water demand in irrigation areas and urban centres. Dry season soil moisture is a critical indicator for pastoral agriculture such as the beef industry. Wet season soil moisture is also important for demand, but most wet season soil moisture changes are projected to change little, and only a few extreme storylines show a decrease. The entire Burdekin River catchment is used to represent changes in demand for the region.

5.2 Establishing representative storylines

To determine plausible storylines reflecting the range of changes to water availability, changes to wet season runoff for each ensemble member are plotted against changes to dry season soil moisture (Figure 5.1). This plot shows that a number of storylines can be established that represent the extreme conditions from the perspective of changes in water supply and drivers of demand (Table 5.1).

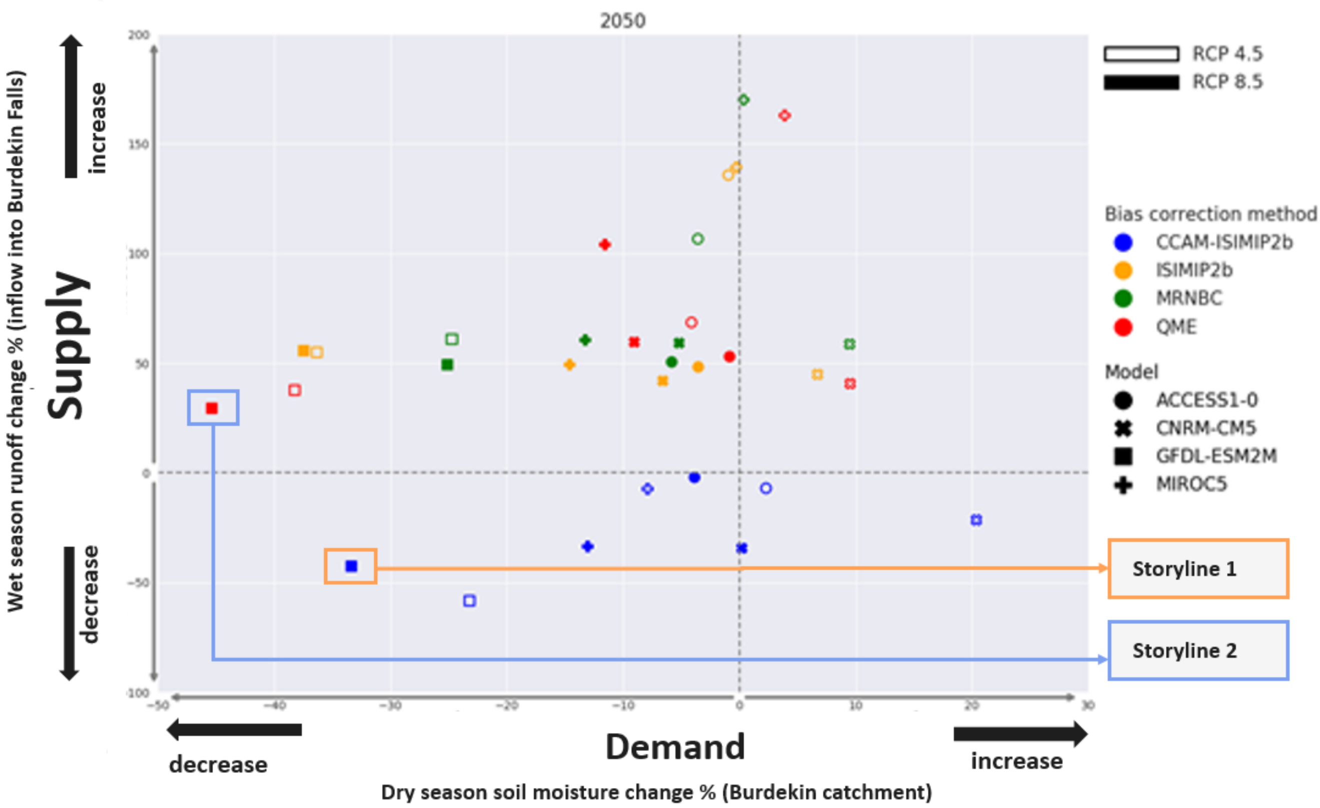


Figure 5.1. Projected changes to wet season runoff vs projected changes to dry season soil moisture. Wet season runoff is used as a proxy for changes to water supply and dry season soil moisture is a proxy for changes to demand

Table 5.1. Storylines for exploring changes in water supply and drivers of demand

Storyline	Impacts to be explored
Large decreases in wet season runoff, decrease in dry season soil moisture (GFDL-ESM2M_CCAM_ISMIP2b RCP8.5)	Large decreases in wet season runoff reduce water availability, while decreases in dry season soil moisture increase demand on irrigated water.
Very large decreases in dry season soil moisture, increases in wet season runoff (GFDL-ESM2M_QME RCP8.5)	Decreases of around 15% to 20% in dry season soil moisture and increases to wet season runoff by 25%. The largest decrease is represented by GFDL-ESM2M_QME; therefore, the largest increases in dry season demand are likely under this storyline.
Increase in dry season soil moisture and decrease in wet season runoff (CNRM-CM5_CCAM_ISMIP2b RCP4.5)	20% increase in dry season soil moisture with around 20% decrease in wet season runoff. Increases in dry season soil moisture could see increases in pasture to support rain-fed agriculture and reduce demand on irrigated water.
Large increase in wet season runoff, little change in dry season soil moisture (MIROC5_MRNBC)	This storyline is particularly favourable to water managers as it sees a large increase in wet season runoff. Dry season soil moisture is projected to decrease by around 5%, which is classified as little change.

The first 2 storylines are discussed in more detail below. They were selected because of their potential impact on water resource availability due to a projected reduction in wet season runoff and dry season soil moisture. The relationship between changes to variables and impacts associated with increases in wet season runoff are discussed to give a picture of how the other storylines would also face impacts.

5.2.1 Storyline 1: Large decreases in wet season runoff and decreases in dry season soil moisture (GFDL-ESM2M_CCAM_ISIMIP2b RCP8.5)

This storyline represents the largest decreases in wet season runoff (32%) and therefore the largest projected decreases in water supplies based on seasonal totals. This storyline is based on the GFDL-ESM2M climate model downscaled by the CCAM_ISIMIP2b bias-correction method (GFDL-ESM2M_CCAM_ISIMIP2b). Ensemble members downscaled with CCAM_ISIMIP2b project larger increases in potential evapotranspiration than do other ensemble groups; they also project the largest decreases in wet season precipitation and soil moisture, which drive the decreased runoff.

This storyline is around the 75th percentile of all ensemble results for changes to dry season soil moisture. Projected changes to dry season soil moisture are projected to be plausible since these are driven largely by increases in evapotranspiration (about 9%) and decreases in precipitation (about 18%).

A decrease of 32% in wet season runoff could result in less reliable filling of storages in the wet season, so water supply could become more vulnerable under this future storyline. A decrease in soil moisture, an indication of larger demands through the dry season, would compound the issue of decreased water availability under this storyline compared to current conditions. The projected decrease in dry season soil moisture will also decrease water availability for pasture growth, indicating that industries like beef cattle may be vulnerable to this plausible future change.

Many surface water and groundwater stores in northern Australia are characterised by a cycle of annual filling in the wet season followed by depletion from consumptive use and irrigation during the dry season (though noting that some storages need multiple years to reach full capacity). Despite the large inter-annual variability of precipitation characteristic of northern Australia (particularly in the early wet season), water storages in the Monsoonal North region tend to fill reliably. This is due to the typically high intensity of precipitation events, which generate significant volumes of runoff and fill many water storages within the first few precipitation events of the season. While current physical water availability consistently exceeds water demand in northern Australia, future surface water supplies will face dual and compounding pressures from a less reliable source of water (less wet season runoff) and faster depletion of stored water (as indicated by decreases in soil moisture and increased evapotranspiration). With the water resources depending heavily on annual filling, a single year of below-average precipitation can quickly drive a region into a state of water scarcity. The results here do not assess changes to reliability, such as changes in year-to-year variability. However, noting the large natural variability in precipitation for the region, it can be assumed that this storyline would also result in more frequent years of extreme dry and that these extreme dry periods will be more intense in terms of water deficits. Projected year-round increased evapotranspiration means greater direct losses from stored water. The projected increase in evapotranspiration, which experiences very high rates in the north, will reduce water storage opportunities.

5.2.2 Storyline 2: Very large decreases in dry season soil moisture, increase in wet season runoff (GFDL-ESM2M_QME RCP8.5)

This storyline describes the largest decrease (about 22%) in dry season soil moisture and is therefore the storyline with potentially the largest increase in dry season demand. The large decreases in dry season soil moisture are driven partly by increases in potential evapotranspiration (PET) for this ensemble member (about 4%), related to increased temperature. However, this ensemble member is around the median value for all ensembles. Projected decreases in precipitation (39.5%) from this storyline are the largest of any storyline.

Wet season runoff is projected to increase by about 25% in this storyline. Other ensemble members feature storylines with large projected increases in wet season precipitation and runoff; for example, ACCESS S1-0 projects increases in wet season runoff between 20% and 50%. Despite increased wet season runoff, this wet storyline is unlikely to result in increases in water availability. Storages in northern Australia already reliably fill in most wet seasons, so a storyline projecting increases in wet season runoff, with insignificant changes in dry season runoff, will not increase water availability without increases in storage capacity. However, an increase in runoff could also mean more frequent spill over of dams, which would need to be managed.

Additionally, the projected increase in wet season runoff could suggest the projected increases may be driven by higher intensity events. This could result in more frequent and more severe inundation in low-lying areas, impacting on road closures and, for example, interrupting critical supply chains for pastoralists.

Similarly, increased recharge to some groundwater aquifers might not lead to more groundwater availability in the future as these aquifers do already fill at capacity under the present wet season condition. Some karstic aquifers on the other hand do have the potential to accommodate larger recharge in this storyline. In conclusion, despite increases in wet season. runoff, this storyline does not necessarily translate into increases in water availability in this region, while at the same time water demand is projected to be higher. Mitigation planning for those extreme events should be considered.

5.2.3. Conclusions

National Hydrological Projections for changes to precipitation, soil moisture, runoff and evapotranspiration can be useful indicators for a range of water-sensitive impacts, such as water availability for the environment and human consumption, inflows and demands on water storages, and soil moisture for rain-fed agriculture or as a risk factor for bushfires. Using a storylines approach, we have used the National Hydrological Projections to interrogate potential changes to water security as an example of how impact risks can be assessed with these data. Each of the 16 ensemble members represents a plausible future storyline with respect to future changes to water security. Results from other projections are discussed to contextualise where these storylines fit in a broader understanding of plausible futures.

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8 Appendix: Evaluation of bias-correction methods

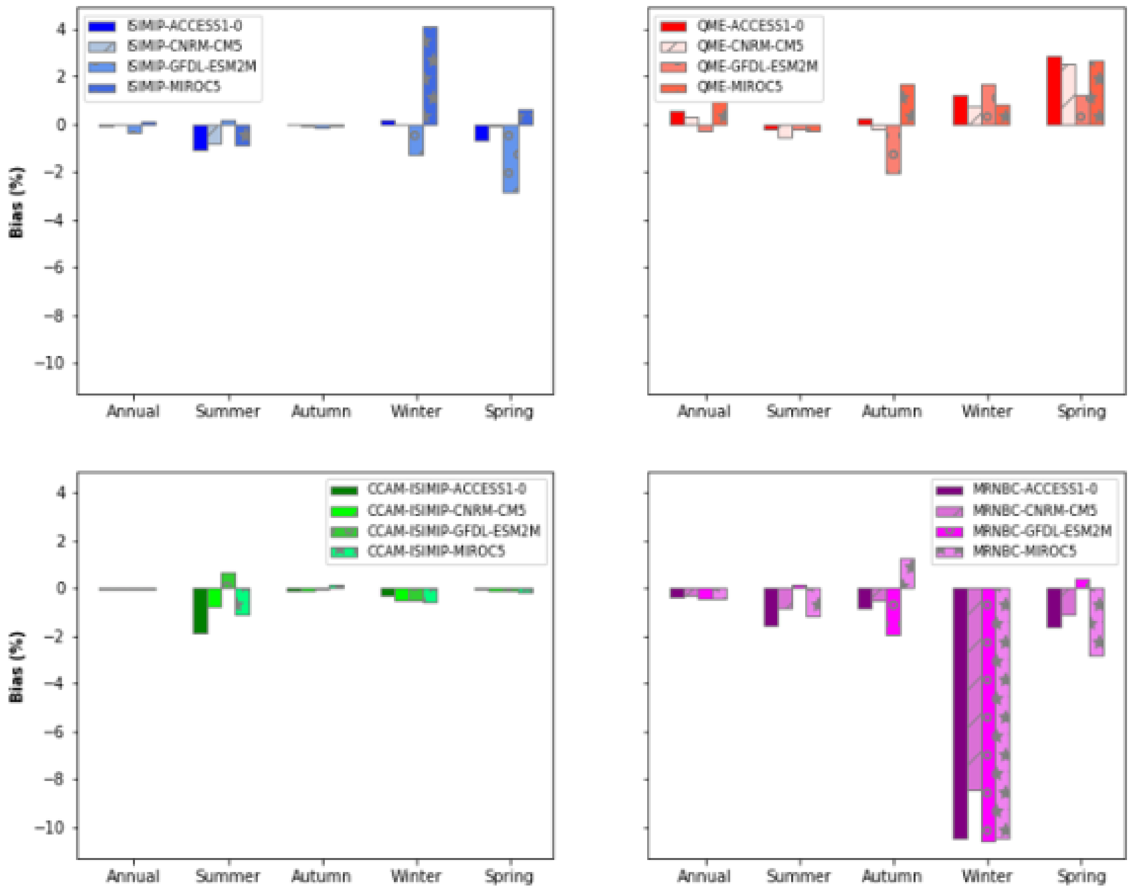

Figure 7.1. Bias (%) in mean annual and seasonal precipitation for the 16-member ensemble and observed (AWAP) data of the Monsoonal North region

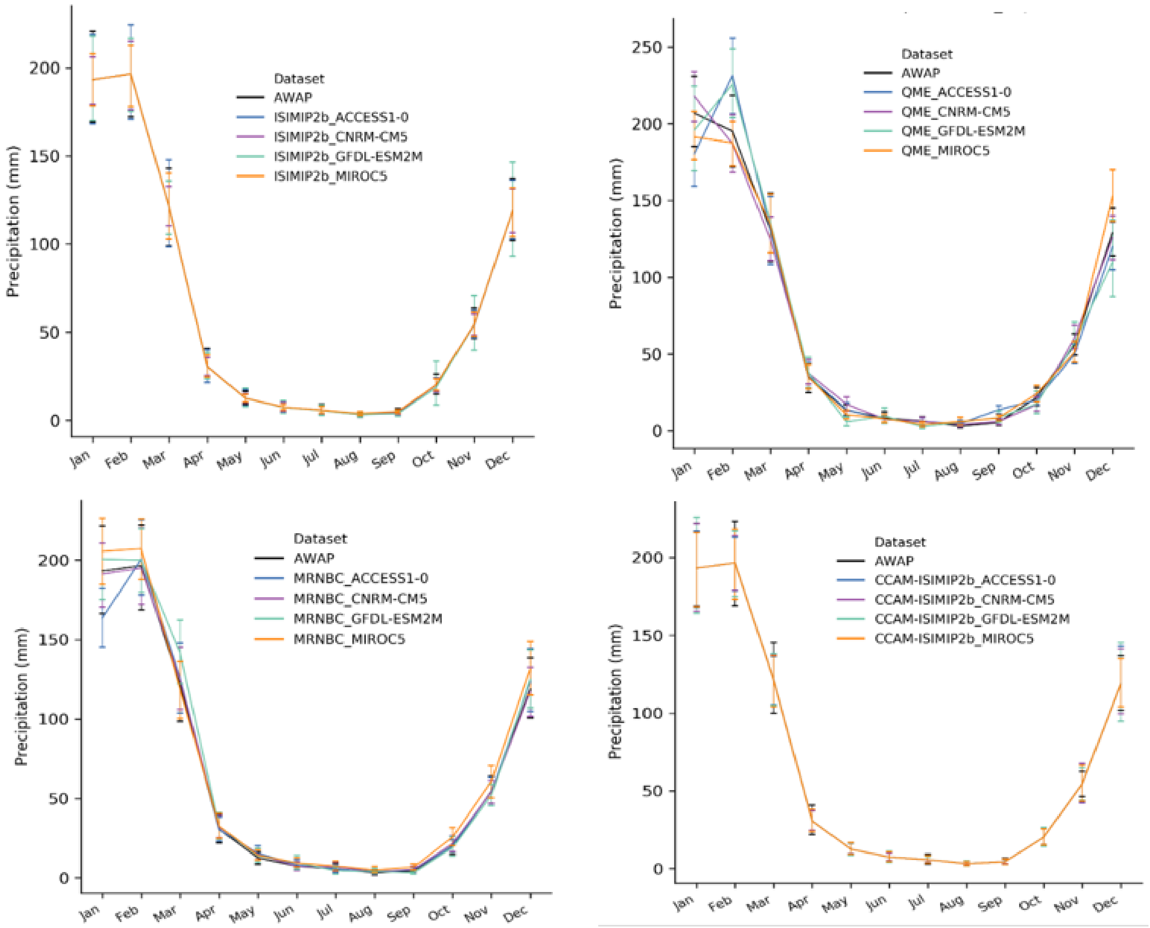

Figure 7.2. Comparison of the mean monthly precipitation (mm) for the 16-member ensemble and observed (AWAP) data of the Monsoonal North region (1976–2005)

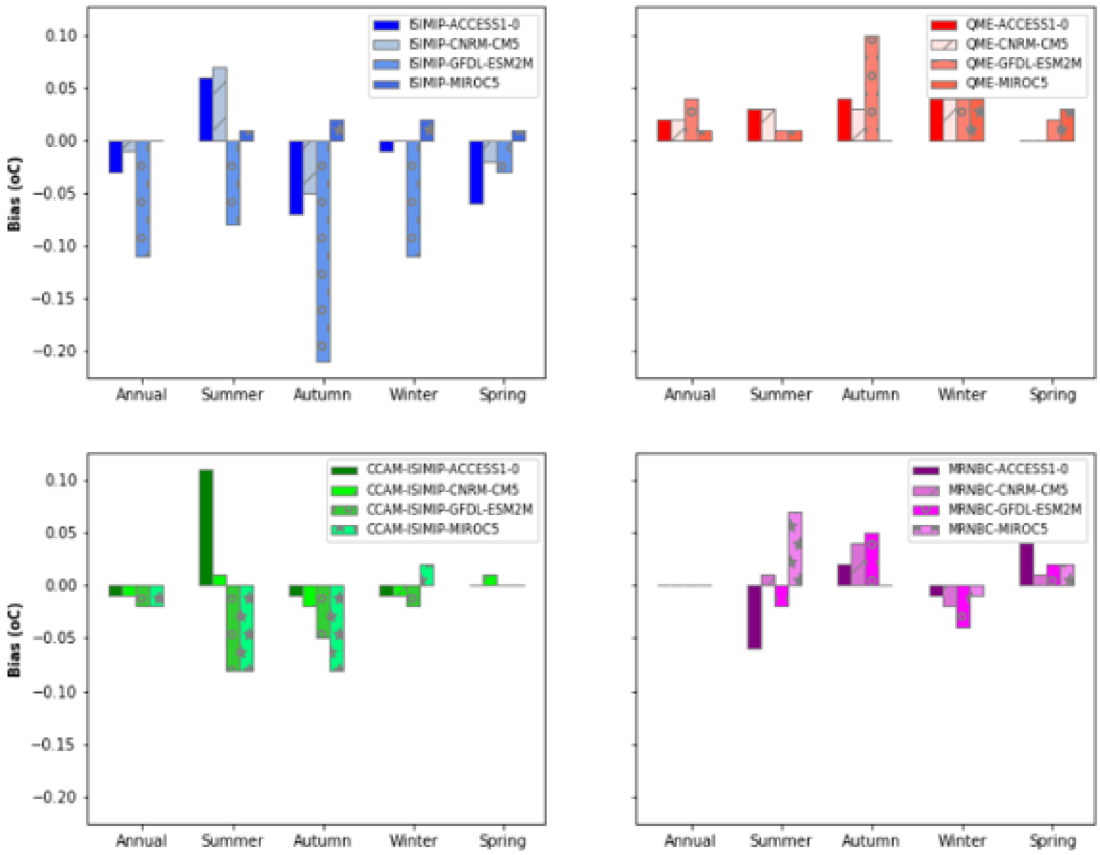

Figure 7.3. Bias (°C) in mean annual and seasonal maximum temperature for the Monsoonal North region

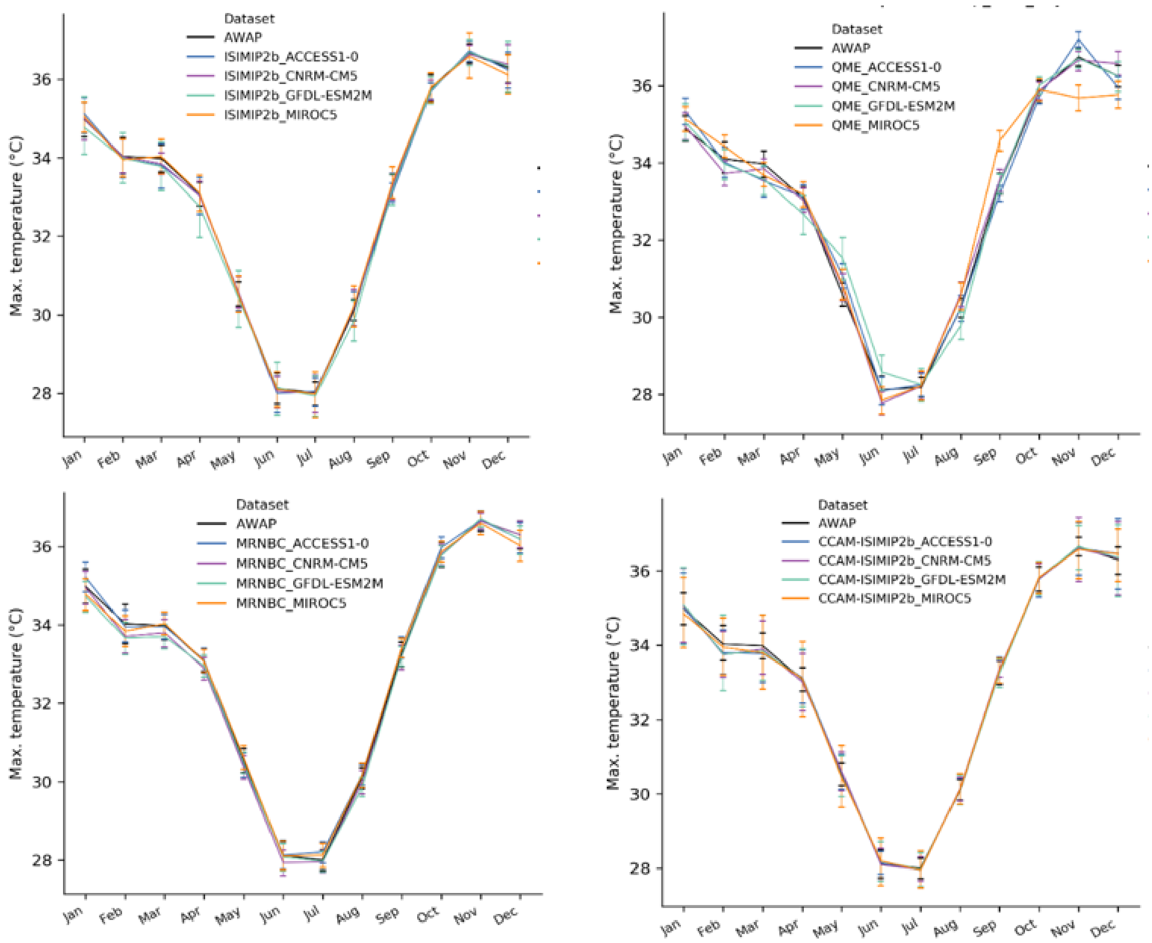

Figure 7.4. Comparison of the mean monthly maximum temperature (°C) for the 16-member ensemble and observed (AWAP) data for the Monsoonal North region (1976–2005)

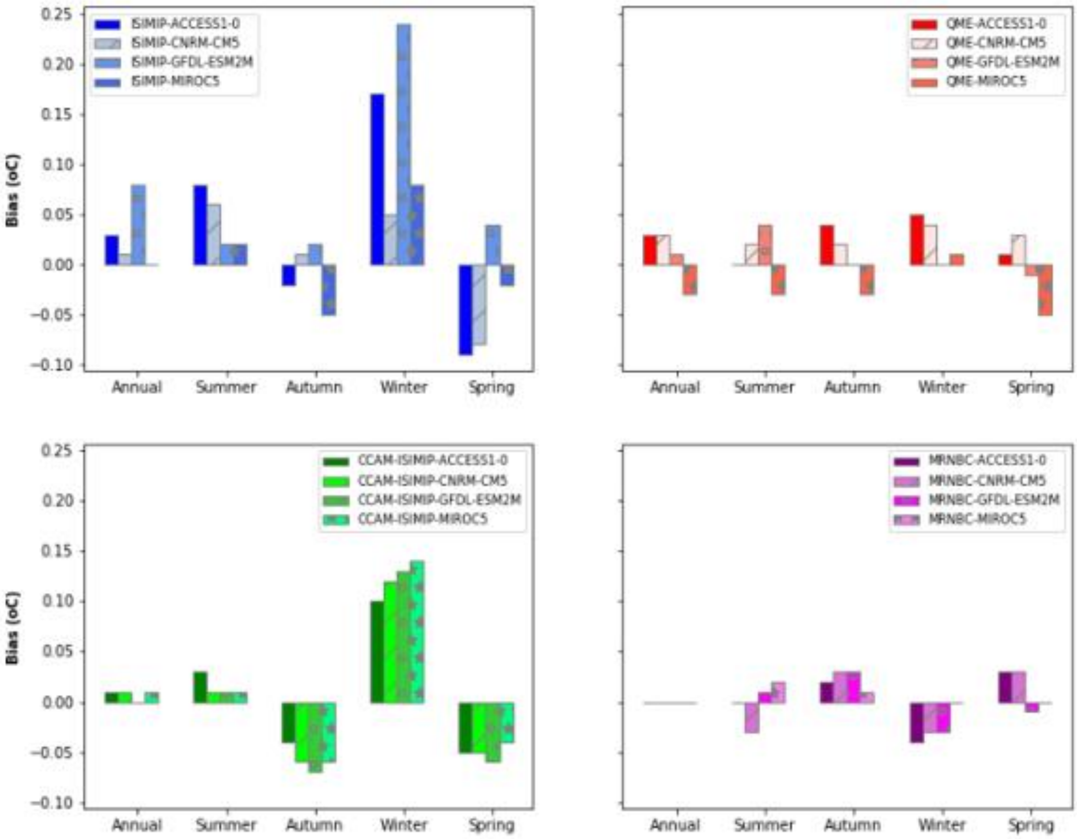

Figure 7.5. Bias (°C) in mean annual and seasonal minimum temperature for the Monsoonal North region

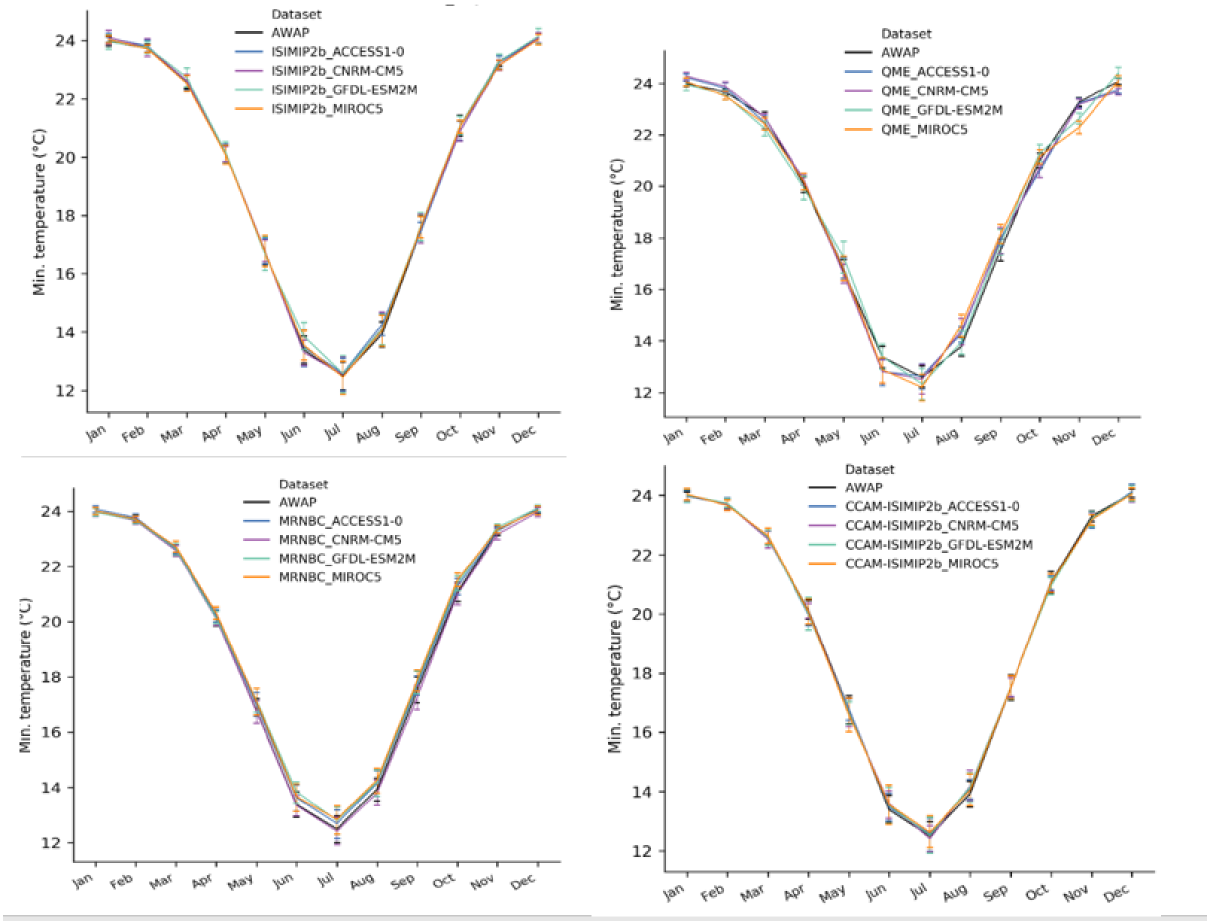

Figure 7.6. Comparison of the mean monthly minimum temperature (°C) for the 16-member ensemble and observed (AWAP) data for the Monsoonal North region (1976–2005)

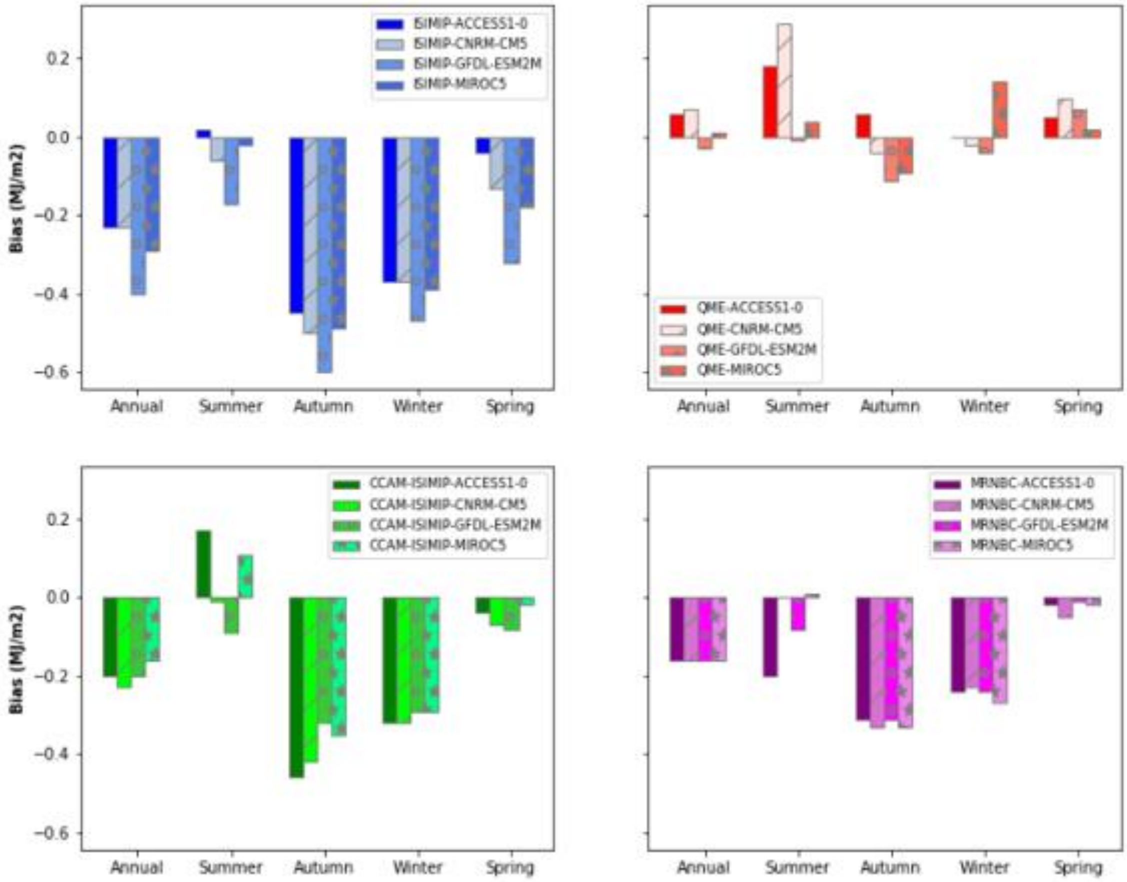

Figure 7.7. Bias (megajoules per square metre, MJ/m^2) in mean annual and seasonal solar radiation for the Monsoonal North region

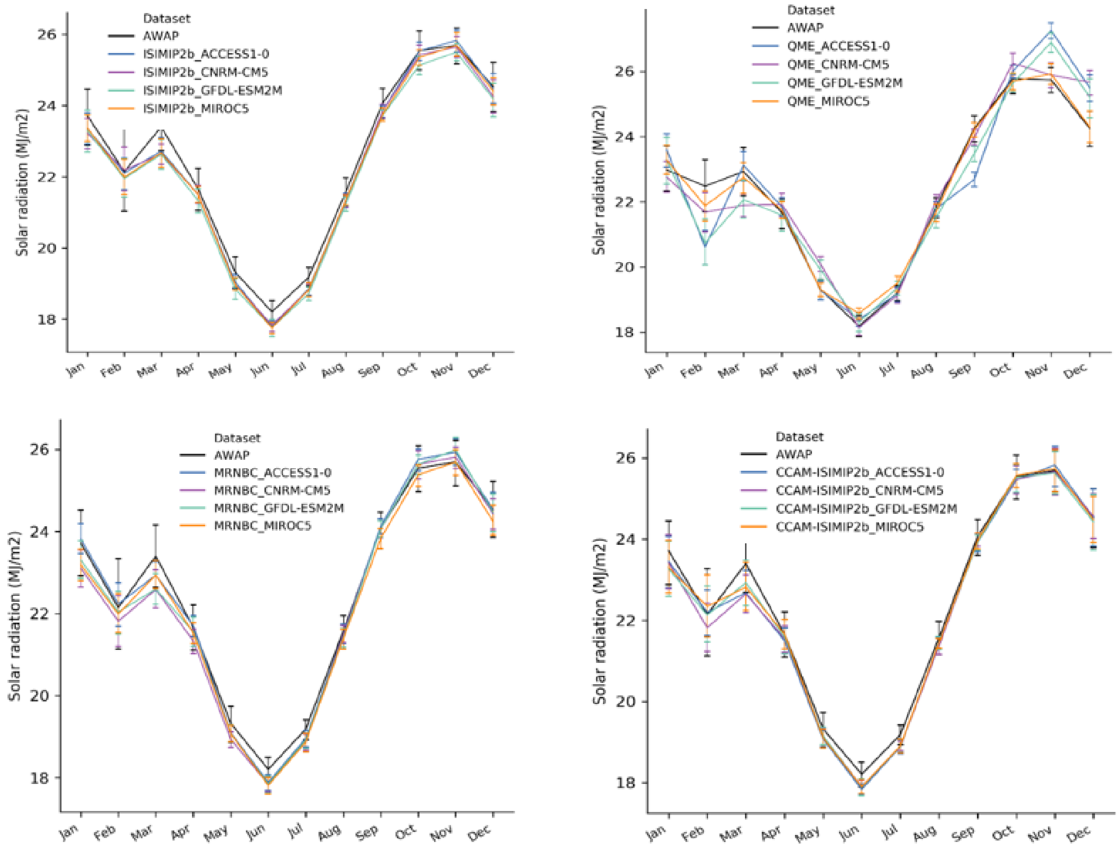

Figure 7.8. Comparison of the mean monthly solar radiation (MJ/m²) for the 16-member ensemble and observed (AWAP) data for the Monsoonal North region (1976–2005)

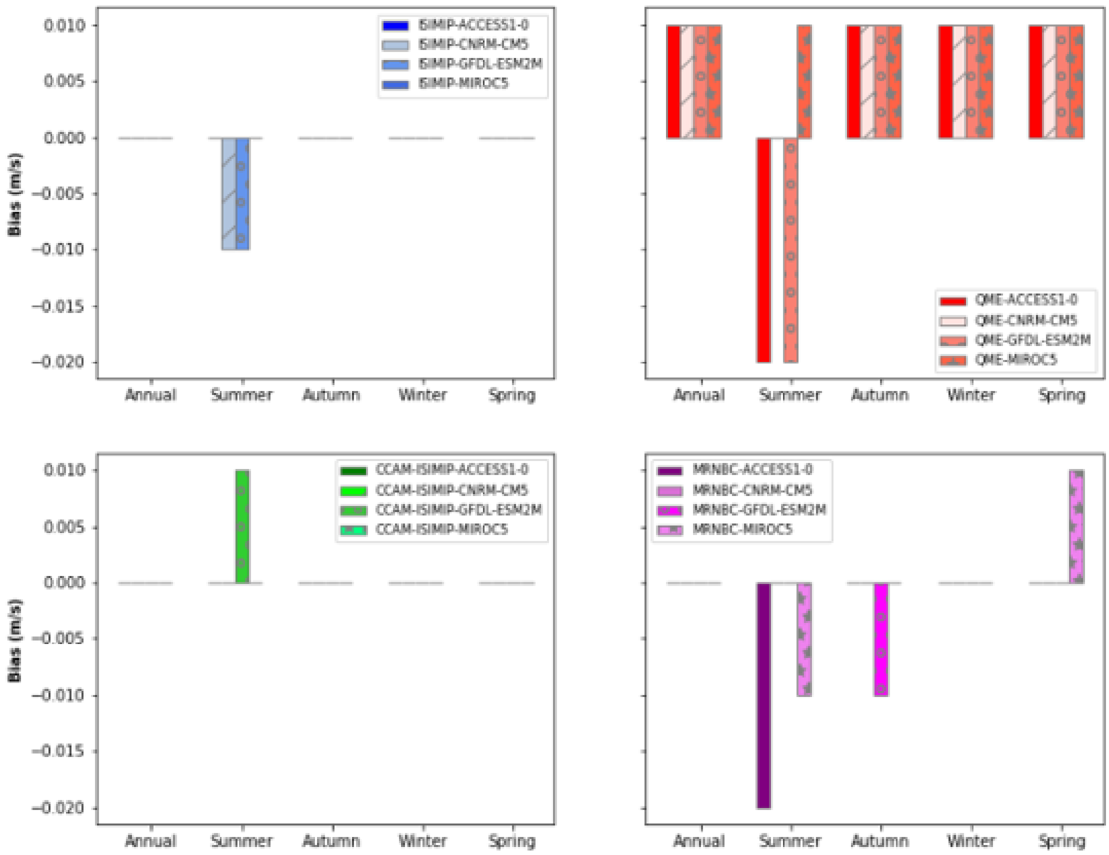

Figure 7.9. Bias (m/s) in mean annual and seasonal wind speed for the Monsoonal North region

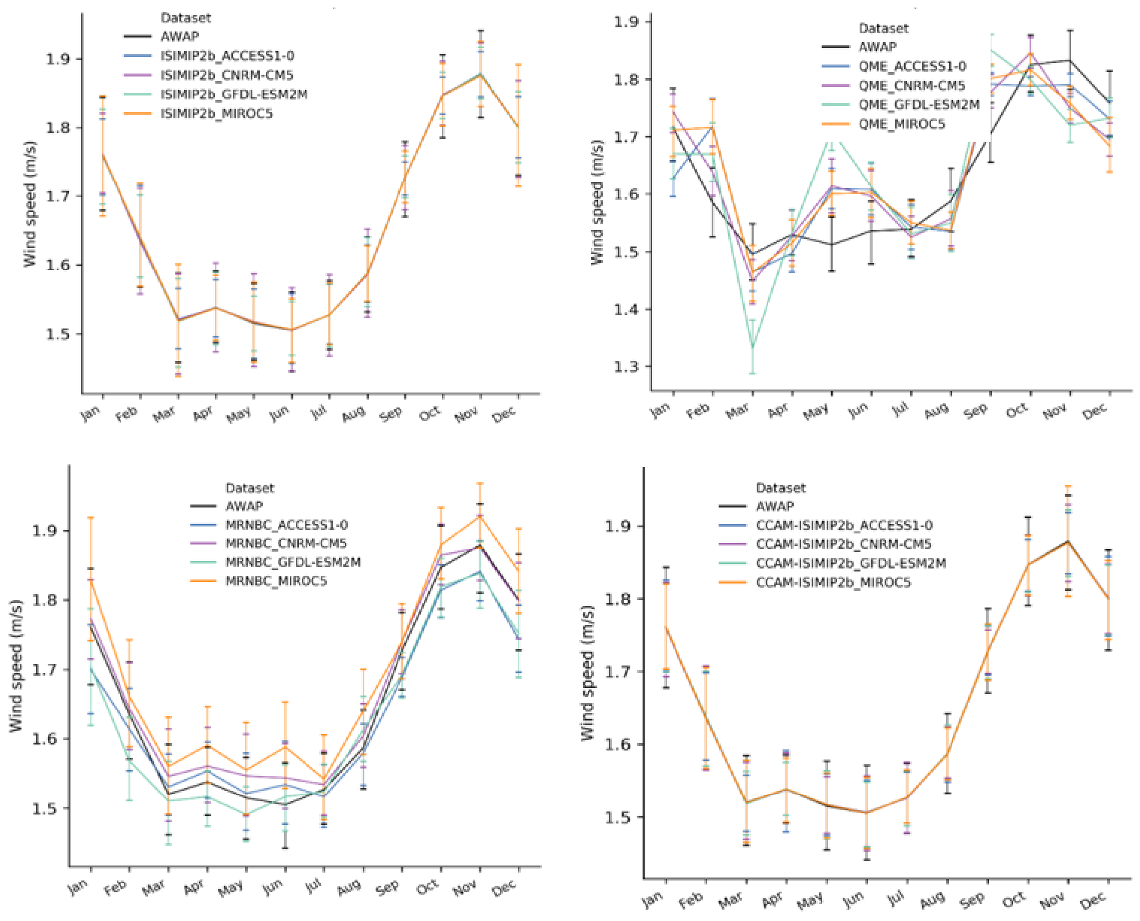

Figure 7.10. Comparison of the mean monthly wind speed (m/s) for the 16-member ensemble and observed (AWAP) data for the Monsoonal North region (1976–2005)

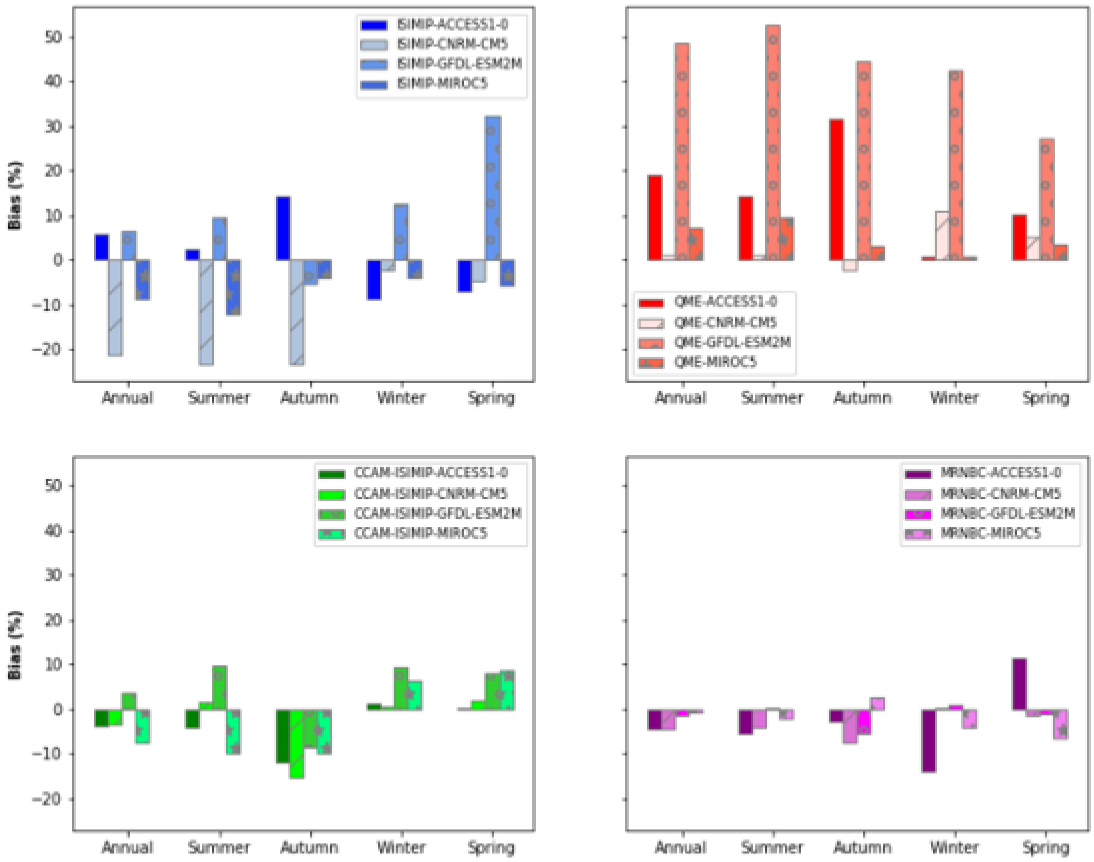

Figure 7.11. Bias (%) in mean annual and seasonal runoff for the Monsoonal North region

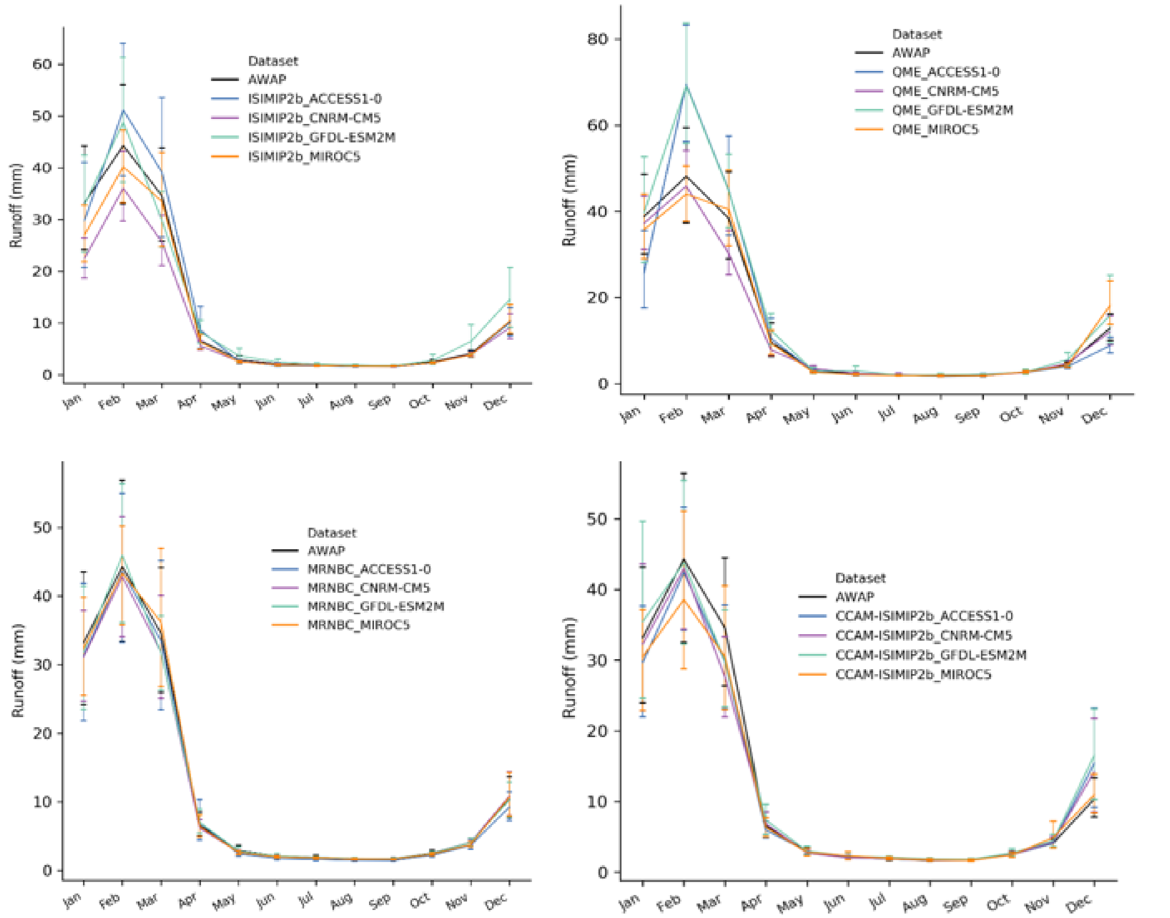

Figure 7.12. Comparison of the mean monthly runoff (mm) for the 16-member ensemble and observed (AWAP) data for the Monsoonal North region (1976–2005)

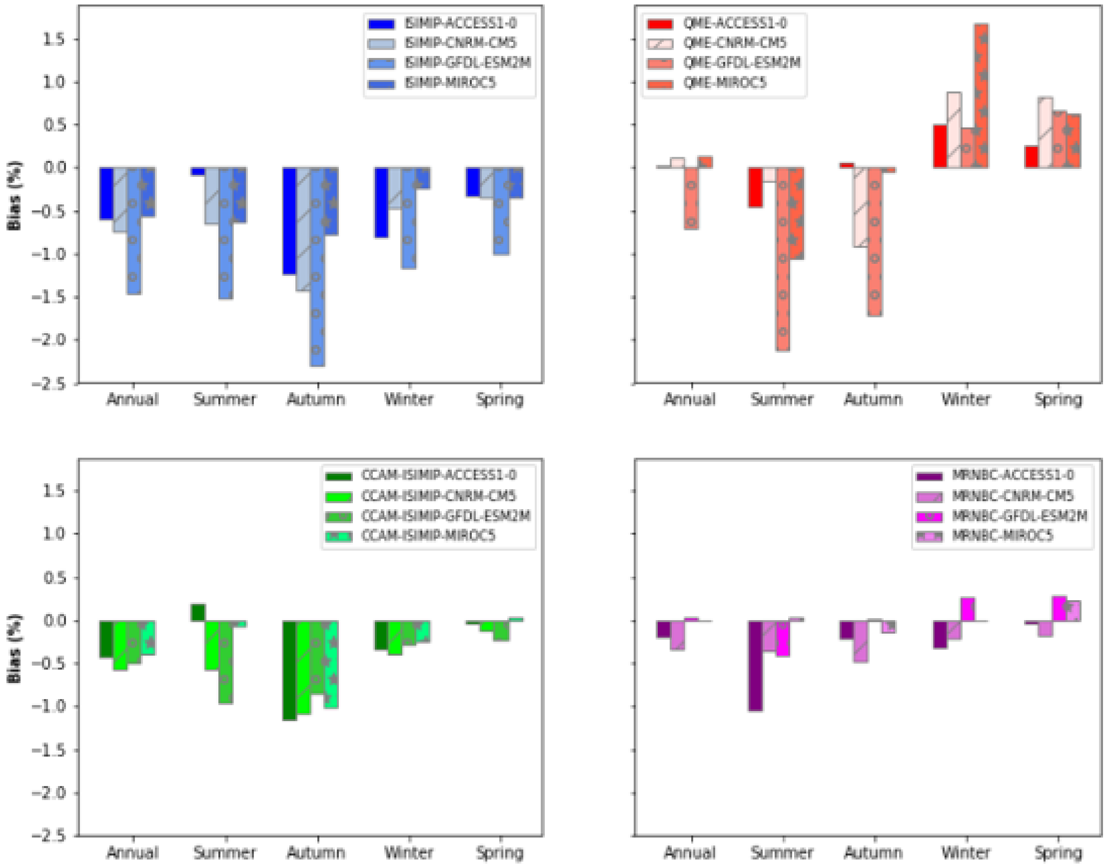

Figure 7.13. Bias (%) in mean annual and seasonal potential evapotranspiration for the Monsoonal North region

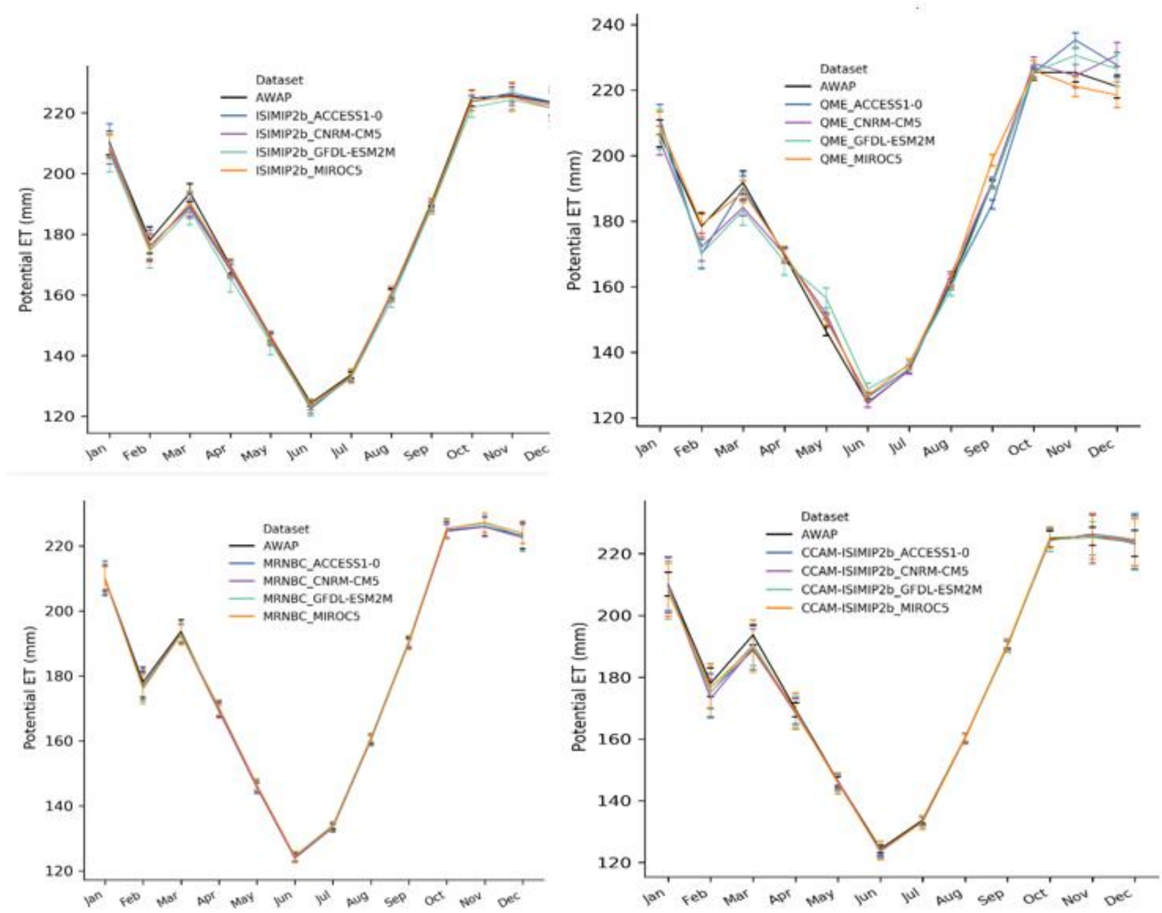

Figure 7.14. Comparison of the mean monthly potential evapotranspiration (mm) for the 16-member ensemble and observed (AWAP) data for the Monsoonal North region (1976–2005)

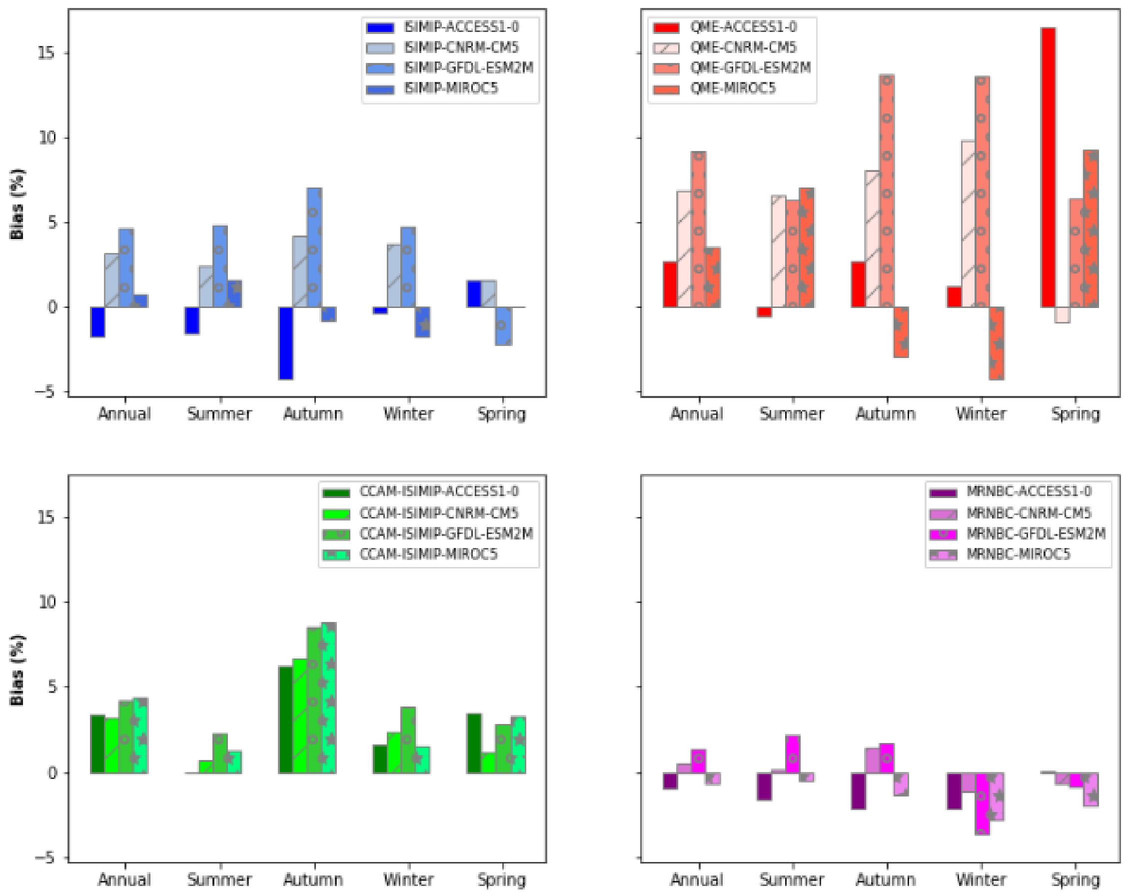

Figure 7.15. Bias (%) in mean annual and seasonal soil moisture for the Monsoonal North region

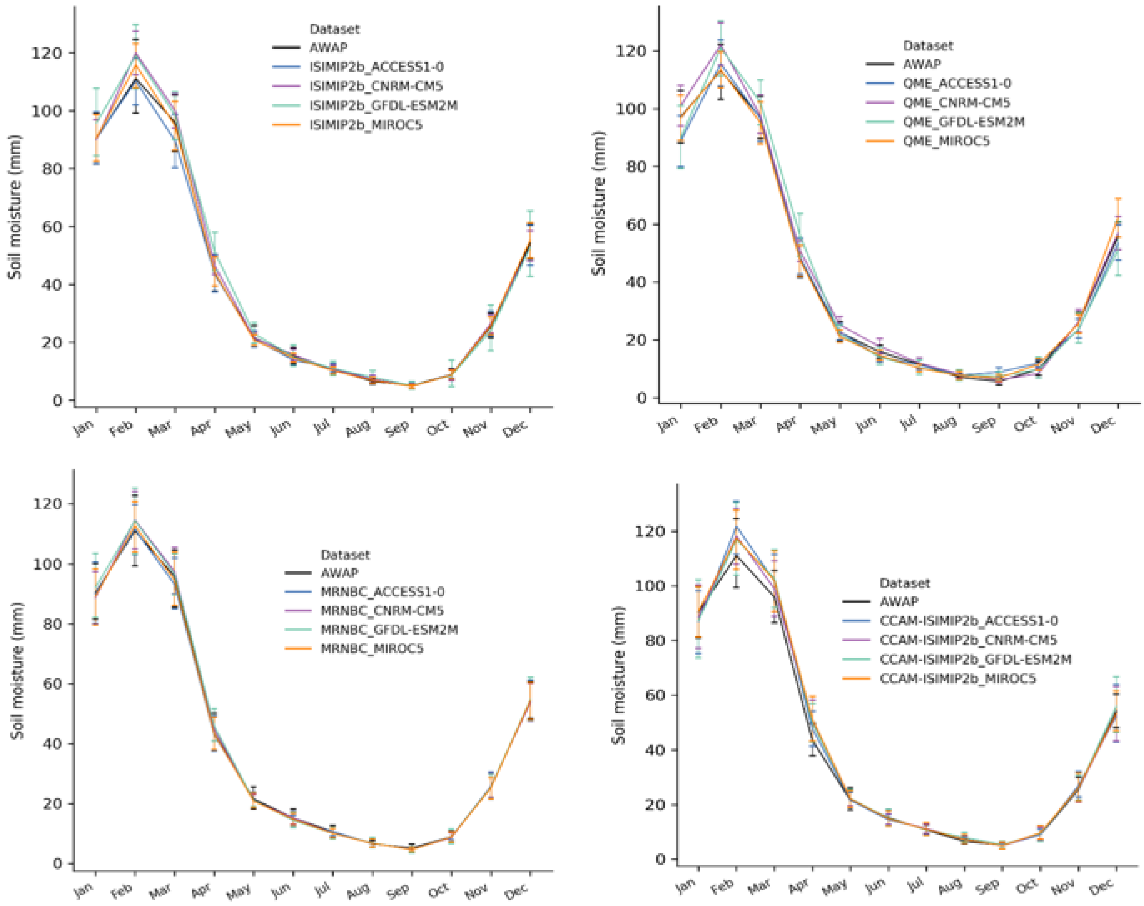

Figure 7.16. Comparison of the mean monthly soil moisture (mm) for the 16-member ensemble and observed (AWAP) data for the Monsoonal North region (1976–2005)