Australian Government
Bureau of Meteorology

Southern Slopes — National Hydrological Projections Assessment report

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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).

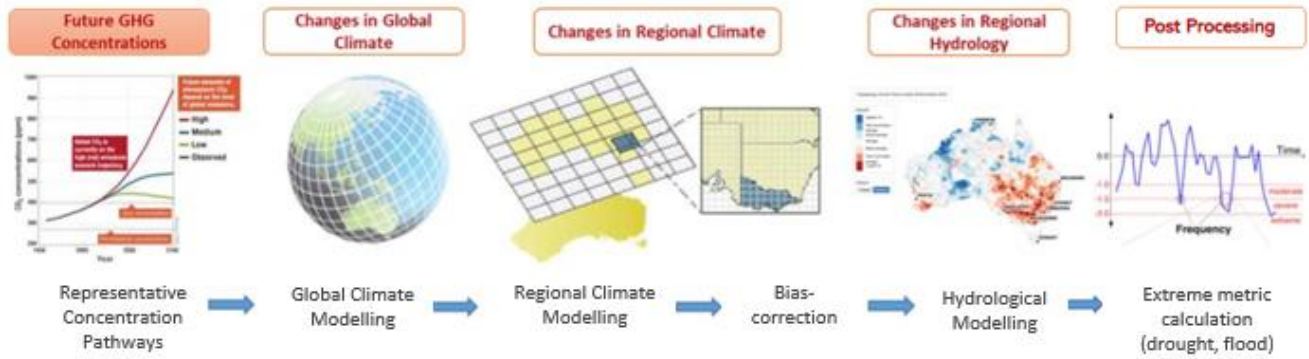

Figure 1.1. National Hydrological Projections workflow principles showing the processing steps: i) selecting representative concentration pathways, ii) running the 4 selected global climate models and also a regional climate model, iii) correcting the discrepancies between climate input and observation (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.

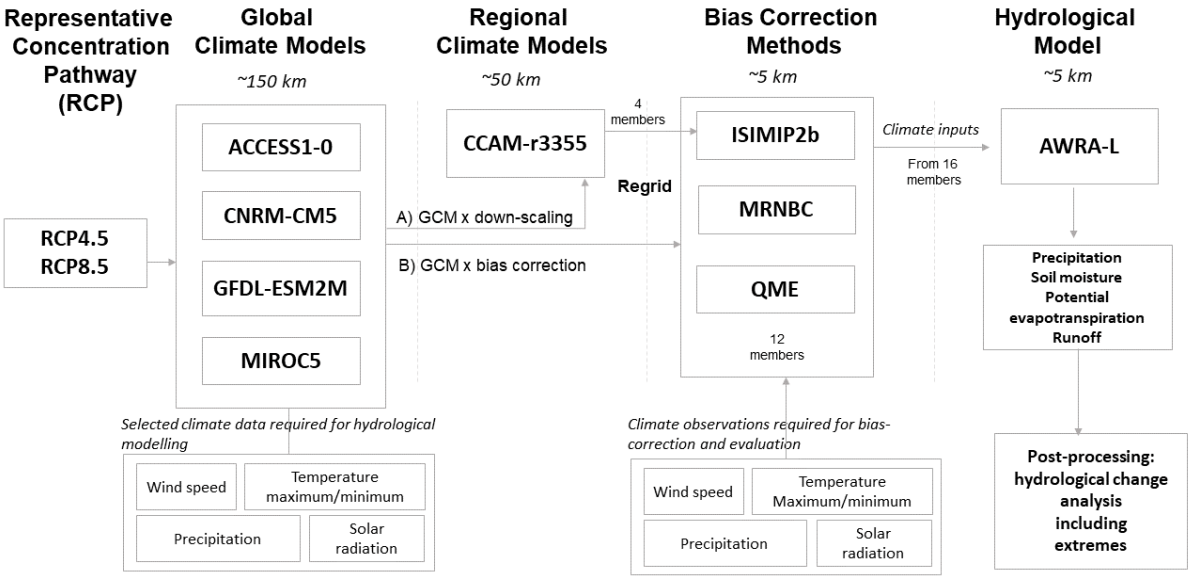

Figure 1.2. National Hydrological Projections showing details of the processing steps: i) 2 representative concentration pathways (RCP4.5 as medium and RCP8.5 as high) are selected, ii) 4 CMIP5 global climate models (GCMs) are selected, iii) path A – each GCM is downscaled by a regional climate model (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 Southern Slopes 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

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2. Regional description and hydroclimate of the Southern Slopes region

The Southern Slopes region consists of Tasmania, southern Victoria and south-east New South Wales (Figure 2.1). It is home to over 30% of Australia's population including about 5 million inhabitants of Melbourne, Australia's second-largest city. The region features expansive dryland agriculture, vast native forests and nationally significant wetlands as well as hydro-electric schemes.

The Southern Slopes region has 4 subregions: western Victoria (Vic West), eastern Victoria and south-eastern New South Wales (Vic East), western Tasmania (Tas West) and eastern Tasmania (Tas East) (shown in Figure 2.2). The most northerly portion of the region in New South Wales is defined by a climate zone transition, approximately at Wollongong, to the subtropical climate that is found in the East Coast region (Fiddes et al. 2021). The northern boundary follows the southern slope of the Great Dividing Range. Tasmania sits in the region's south.

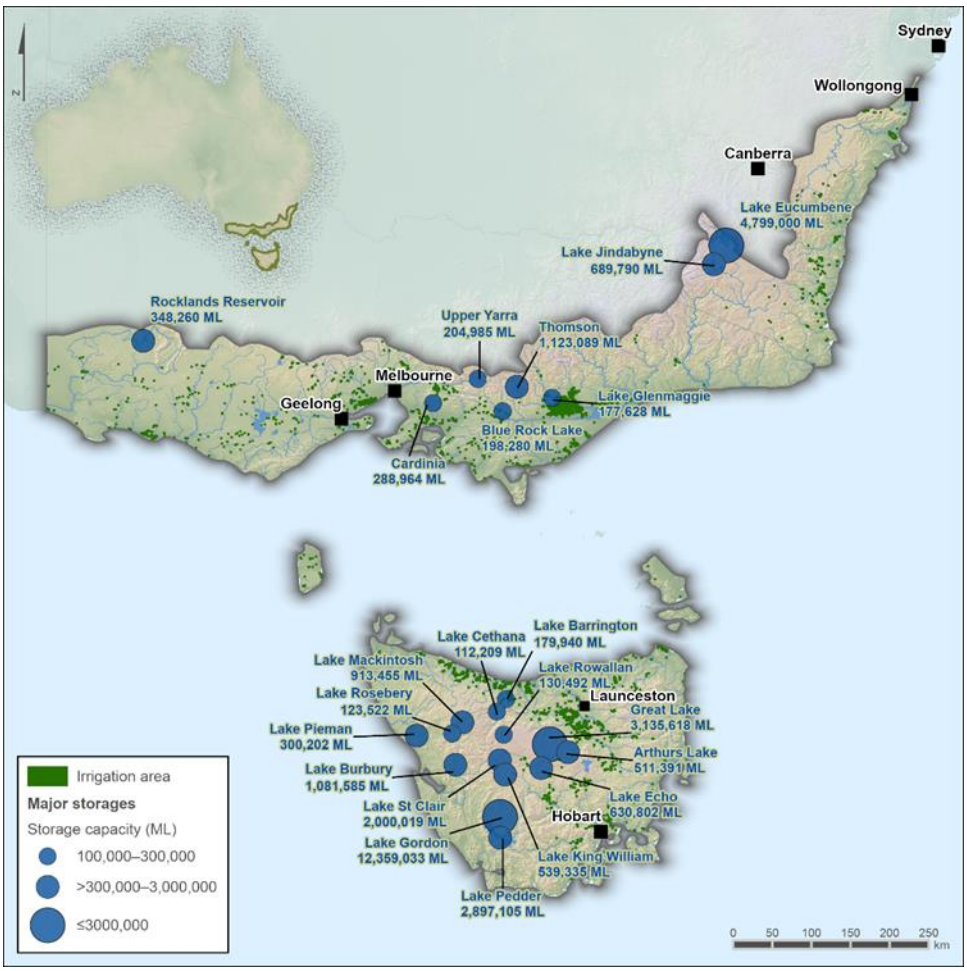

Figure 2.1 Southern Slopes region

The Vic West subregion is an important agricultural area that produces around 25% of Australia's milk and has important sheep and cattle grazing regions. The subregion also features extensive dryland cropping.

The suburbs of Greater Melbourne and the Port Phillip Bay catchment are in the eastern part of Vic West. In Vic East, dryland agriculture is important in East Gippsland and the New South Wales south coast. East Gippsland, Cape Otway, the NSW south coast and large parts of Tasmania feature extensive native and planted forests, which represent significant natural assets. Also in the east are large reservoirs, including some of the major surface water storages for Greater Melbourne, and Lake Eucumbene the largest reservoir in the Snowy Mountains Hydro-electric Scheme (Figure 2.1 shows the location of major storages and more details are given in Section 2.3).

The western side of Tasmania features extensive natural areas and is also home to many hydro-electric dams that generate significant electricity, supplying Tasmania and the mainland. Northern and eastern Tasmania host important agricultural regions, including on some of the most productive soils in Australia.

There are many nationally and internationally significant wetlands in the Southern Slopes region, scattered across Victoria and eastern Tasmania.

2.1. Climate

The climate of the Southern Slopes region is characterised by cool winters and hot summers, and there is a general trend for higher precipitation in the winter months. However, the climate and geography vary significantly across the region.

Western Tasmania is the wettest part of the region (Figure 2.2a), experiencing long-duration precipitation events, particular during winter. For example, the Gordon River in western Tasmania has the second-highest discharge rate in the country. Northern Tasmania receives shorter-duration precipitation events in mid to late autumn and winter from moist north-easterly airstreams, commonly associated with cut-off lows.

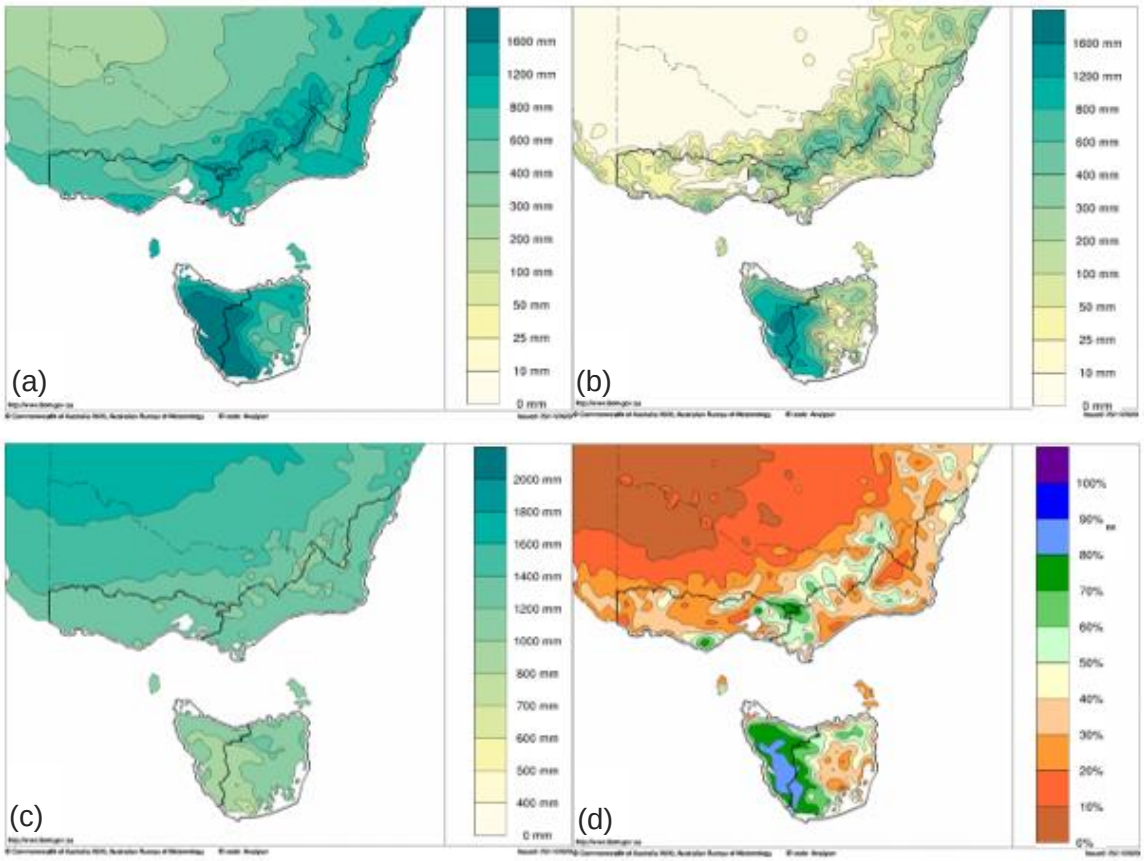

Figure 2.2. Southern Slopes region annual average hydroclimate (1976–2005) showing (a) observed precipitation and AWRA-L modelled values for (b) runoff, (c) potential evapotranspiration and (d) soil moisture. These graphs also show the 4 subregions: western Victoria (Vic West), eastern Victoria and south-eastern NSW (Vic East), western Tasmania (Tas West) and eastern Tasmania (Tas east)

Western Victoria experiences a Mediterranean climate with hot and dry summers as well as cool and wet winters. The western parts of the Southern Slopes region receive precipitation primarily from the interaction between the regular fronts and troughs embedded in the westerly flow and the mountainous topography of the south-west coast (Pepler et al. 2020). The annual cycle of this westerly flow, peaking in winter, drives the seasonal cycle of precipitation in these areas. This seasonal precipitation pattern drives the production of winter crops that are typically sown in autumn ahead of the cool season.

The extensive coastal temperate zones through Victoria, including Melbourne and the eastern part of the mainland alps, and western Tasmania are characterised by more consistent precipitation throughout the year. Other areas in eastern Victoria, south-eastern New South Wales and eastern Tasmania, are less influenced by the mid-latitude westerlies. A higher proportion of the precipitation in these regions instead comes from other systems such as extra-tropical cyclones, including cut-off lows (Pepler et al. 2020; Pook et al. 2014).

Precipitation across the region is relatively reliable. The sub-tropical ridge (STR), a climatological band of high pressure in the mid-latitudes, shifts north in winter, allowing more fronts and storms to cross Victoria. The STR shifts south in summer, leaving south-western Victoria with clear skies. The STR varies from year to year, and a stronger or more southerly ridge is associated with reduced westerly flow and therefore generally lower precipitation and warmer temperatures (Pepler et al. 2018; Timbal and Drosdowsky 2013).

Very wet and dry years are possible anywhere within the Southern Slopes region. The northern parts of the region, particularly the west and far east, experience high inter-annual variability in precipitation. The inter-annual variability in these regions in any given year is driven by an interplay between the modes of large-scale drivers such as the Indian Ocean Dipole (IOD), the El Niño–Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) (Hope et al. 2017). The high phase of SAM is when the storms in the westerlies contract towards Antarctica and there is generally higher atmospheric pressure over southern Australia. In winter, high SAM is associated with decreased precipitation over southern Australia, whereas high SAM in summer is associated with increased precipitation, particularly in the eastern parts of the region (Hendon et al. 2007).

Mean monthly precipitation, runoff and root zone soil moisture are shown in Figure 2.3. Western Victoria exhibits seasonality in precipitation, runoff and soil moisture while Vic East (eastern Victoria and south-eastern NSW) does not show much seasonality (Figure 2.3a, b). Runoff in both western and eastern Tasmania feature marked seasonality, reflecting higher precipitation in winter (peaking in August) and the lowest precipitation in February (Figure 2.3c, d). Precipitation seasonality in Tasmania is driven by fronts embedded in westerlies. Atmospheric blocking by high-pressure systems in the Tasman Sea influences the passage of westerly weather systems over the region and is negatively correlated with spring and autumn precipitation in western Tasmania (Risbey et al. 2009a, b) but positively correlated with precipitation anomalies in north-east Tasmania in most seasons (Pook et al. 2010). Blocking is correlated with the incidence of cut-off lows on the east coast of southern Australia (Cowan et al. 2013; Pepler et al. 2019; Pook et al. 2013; Ummenhofer et al. 2013).

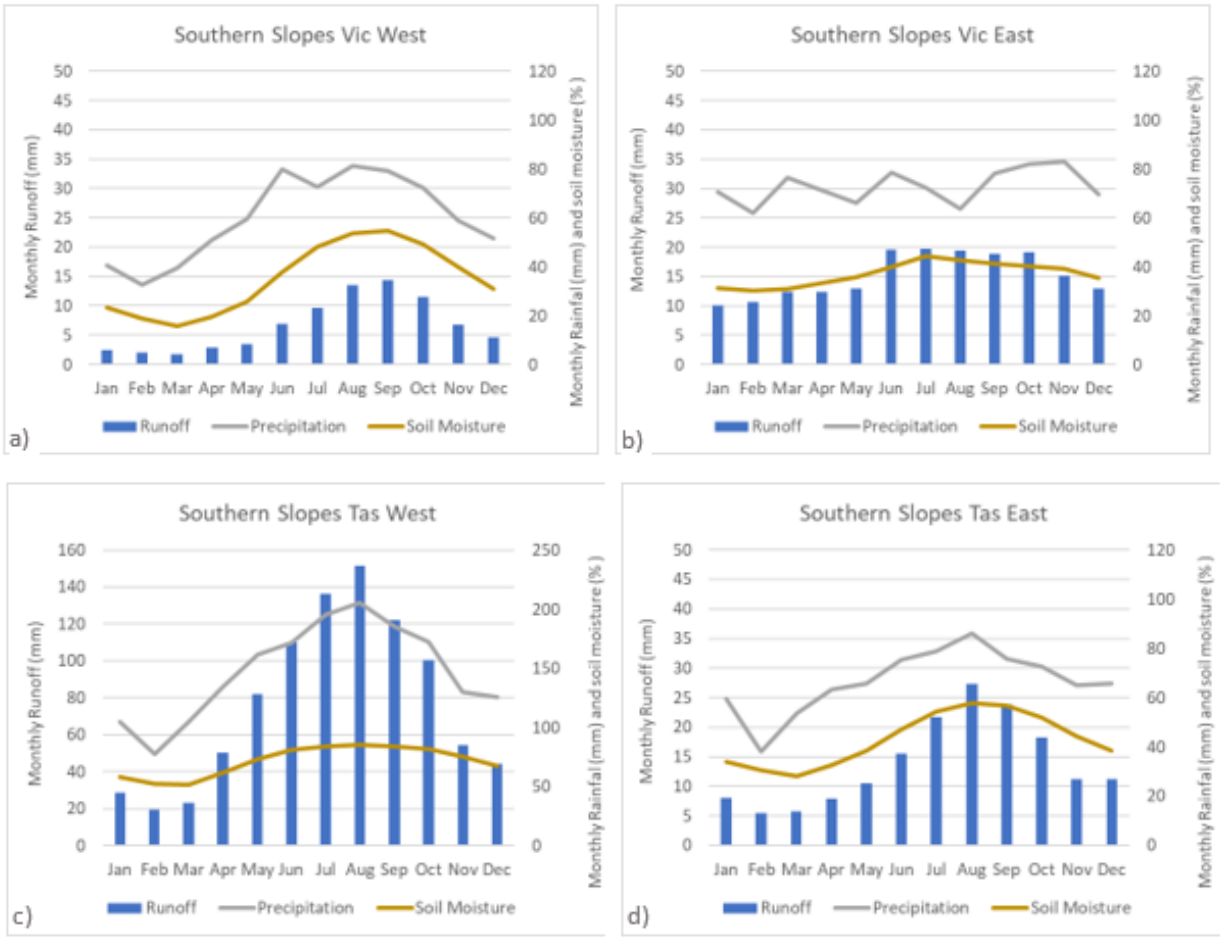

Figure 2.3. Monthly average observed precipitation, AWRA-L modelled runoff and soil moisture for (a) western Victoria (Vic West), (b) eastern Victoria and south-eastern NSW (Vic East), (c) western Tasmania (Tas West) and (d) eastern Tasmania (Tas East) subregions of the Southern Slopes region for the reference period (1976–2005)

While the highest precipitation, soil moisture averages and runoff volumes occur in winter, western Tasmania experiences little intra-annual variability in soil moisture (Figure 2.3c) in line with its cooler climate and lower evapotranspiration rates (Figure 2.4). Western Tasmania generates significantly more runoff annually than does eastern Tasmania (Figure 2.3c, d), again reflecting the spatial distribution of precipitation on the island. The diminished runoff in the east results from the warmer temperatures (Figure 2.4) associated with lower altitudes and the rain shadow caused by the alpine areas in the island's west. Almost all rivers and streams in Tasmania follow an annual cycle of peak flows in winter and spring and lowest flows in late summer.

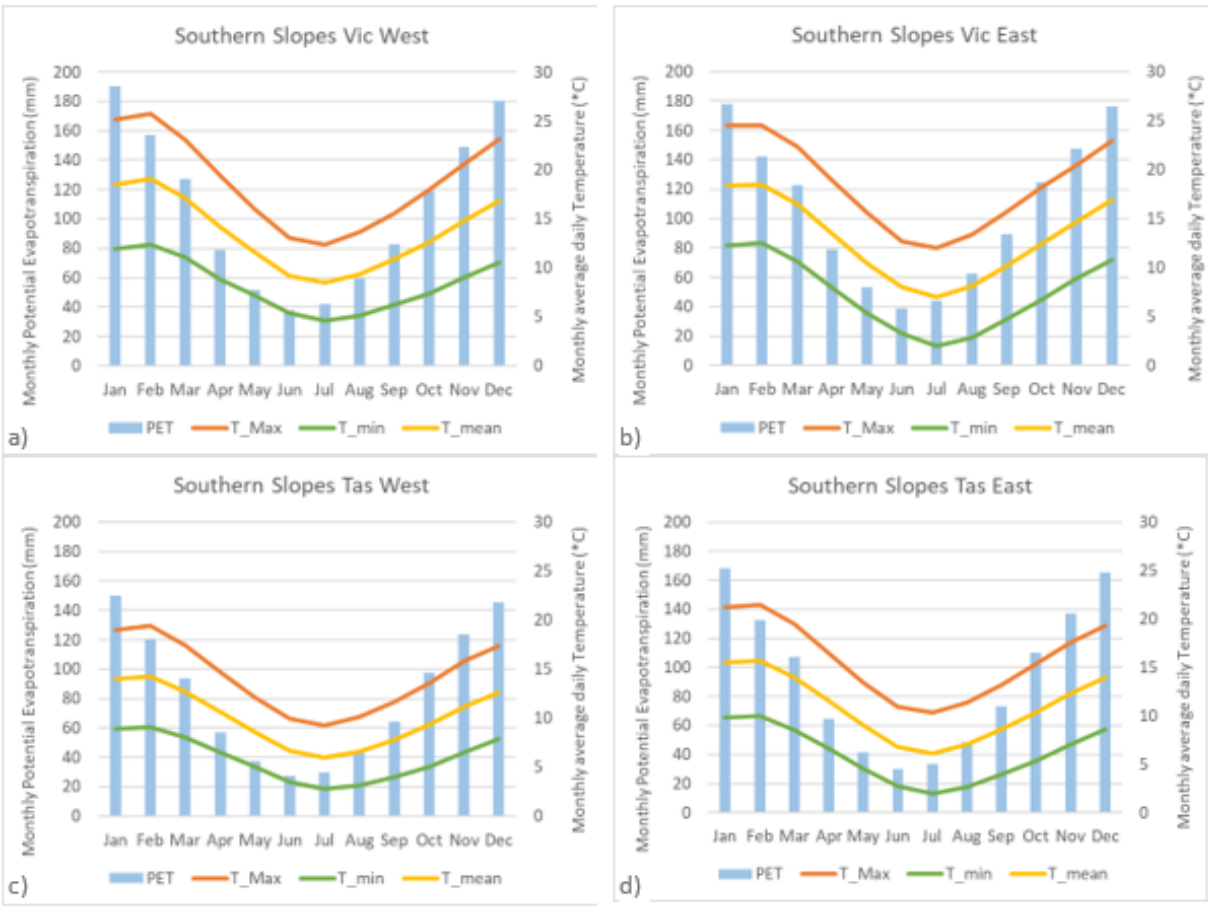

Figure 2.4. Monthly average observed temperature and AWRA-L modelled potential evapotranspiration (PET) for (a) western Victoria (Vic West), (b) eastern Victoria and south-eastern NSW (Vic East), (c) western Tasmania (Tas West) and (d) eastern Tasmania (Tas East) subregions of the Southern Slopes region for the reference period (1976–2005)

2.2. Recent hydroclimatic trends and condition

Changes to long-term mean annual precipitation, year-to-year variability and severity of multi-year dry periods are key risks to planning and water management. Observed trends to these climate features over the historic records, and also in more recent decades, are an important foundation from which to interpret projection results in later sections.

In recent decades, autumn precipitation has decreased across much of the region, including Tasmania, and winter and spring precipitation has been observed to decrease in the east of the mainland (CSIRO and Bureau of Meteorology 2020; Bureau of Meteorology 2021) but not in Tasmania. This is thought to be associated with an intensification of the sub-tropical ridge, which results in stronger high-pressure systems over the region that block the moisture-laden fronts from bringing rain to the region. This intensification of the STR is thought to be a result of anthropogenic climate change (Nyugen et al. 2015), and more changes to the STR are expected as a result of additional warming (Grose et al. 2015a).

There is no long-term trend in terms of mean annual precipitation in the region; recent annual decreases are associated with recent prolonged dry periods (i.e. the Millennium drought). Both wet and dry periods have occurred in the region (Figure 2.5).

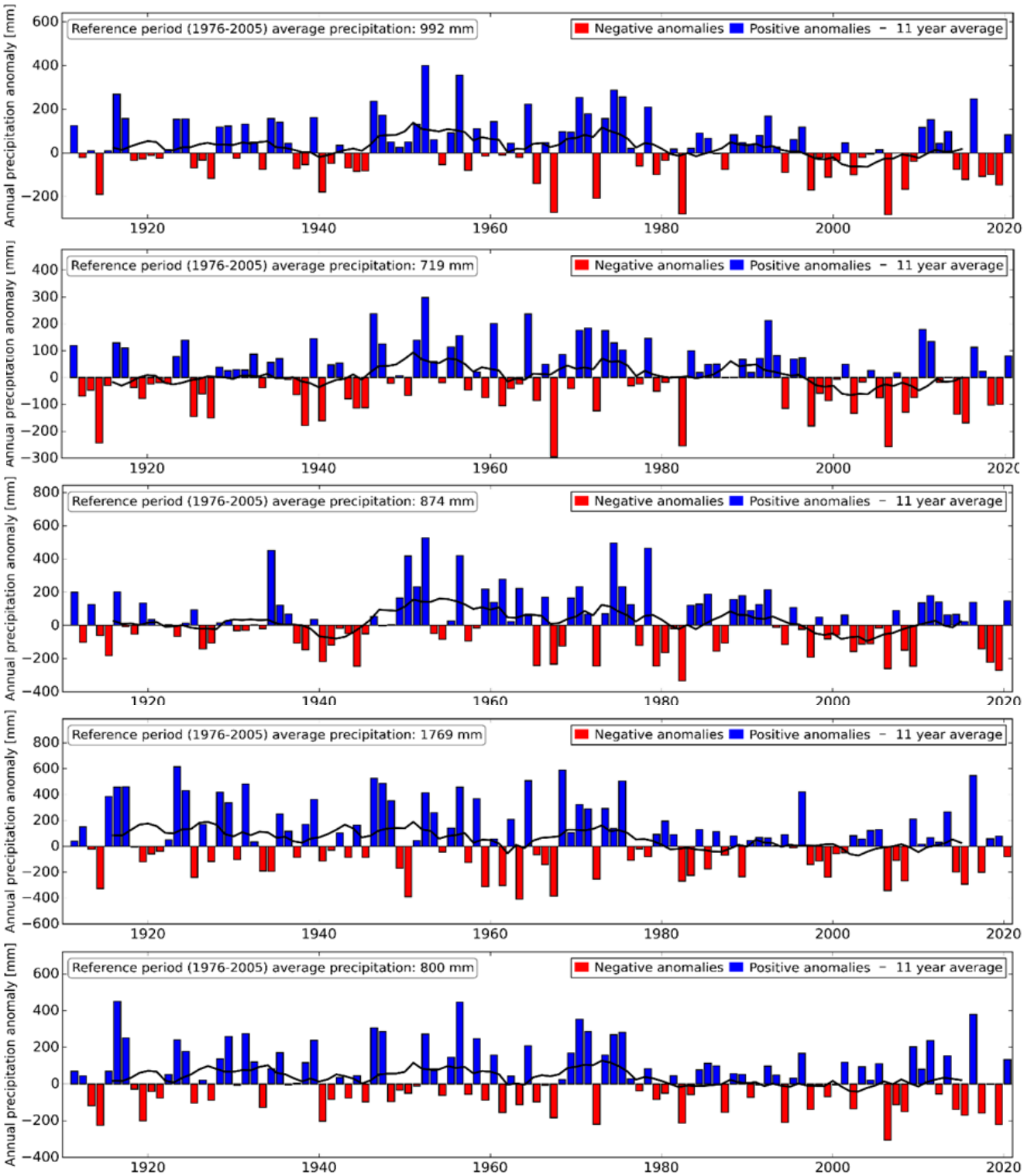

Figure 2.5. Annual anomalies in precipitation relative to the reference period (1976–2005) mean for (a) the whole Southern Slopes region and (b) western Victoria (Vic West), c) eastern Victoria and south-eastern NSW (Vic East), (d) western Tasmania (Tas West) and (e) eastern Tasmania (Tas East) subregions

Runoff exhibits large variability, and years of high and low runoff match years of high and low precipitation for all Southern Slopes subregions (Figures 2.5 and 2.6).

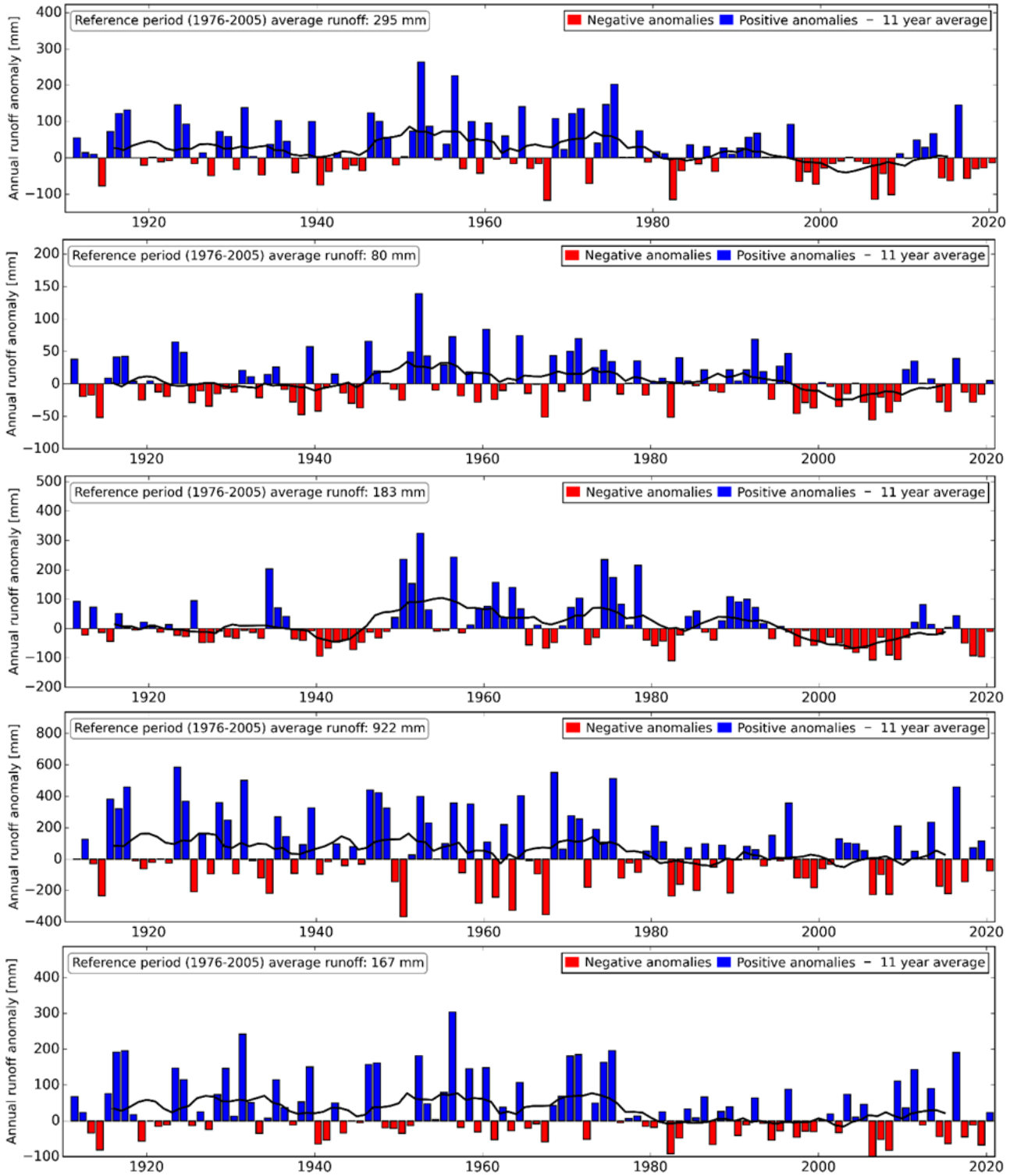

Figure 2.6. Annual anomalies in AWRA-L modelled runoff relative to the reference period (1976–2005) mean for (a) the whole Southern Slopes region and (b) western Victoria (Vic West), c) eastern Victoria and south-eastern NSW (Vic East), (d) western Tasmania (Tas West) and (e) eastern Tasmania (Tas East) subregions

Wasko et al. (2021) analysed 33 streamflow sites within the Southern Slopes region for trends in seasonal flow. These trends are calculated from gauged data commencing in the 1970s for most sites. They found a decrease in streamflow in 29 sites (88%) in summer, 32 sites in autumn (97%), 26 sites in winter (79%) and 30 sites (90%) in spring. These results are consistent with a broader trend for decreases in streamflow observed for southern Australia (Zhang et al. 2016).

Changes in precipitation–streamflow relationships were observed in many catchments in south-eastern Australia during the prolonged Millennium drought (Saft et al. 2015; Peterson et al. 2021). These changes led to disproportionately large reductions in streamflow compared to what was expected based on precipitation changes alone. The change in annual precipitation–streamflow relationship is thought to be the result of changes in internal catchment processes (Döll & Zhang 2010; Saft et al. 2016), but it is not fully understood what the processes are or why only some catchments were affected by this phenomenon. For hydroclimate projections, this adds uncertainty to the catchment response in a changing climate.

As for precipitation and runoff, soil moisture shows a decrease since the mid-1990s associated with the onset of the Millennium drought, and annual average soil moisture volumes are highly variable, reflecting high year-to-year precipitation variability (Figure 2.7). However, recent soil moisture in Victoria has seen more drier years since the late 1990s (within the reference period) than in earlier times, particular during the Millennium drought.

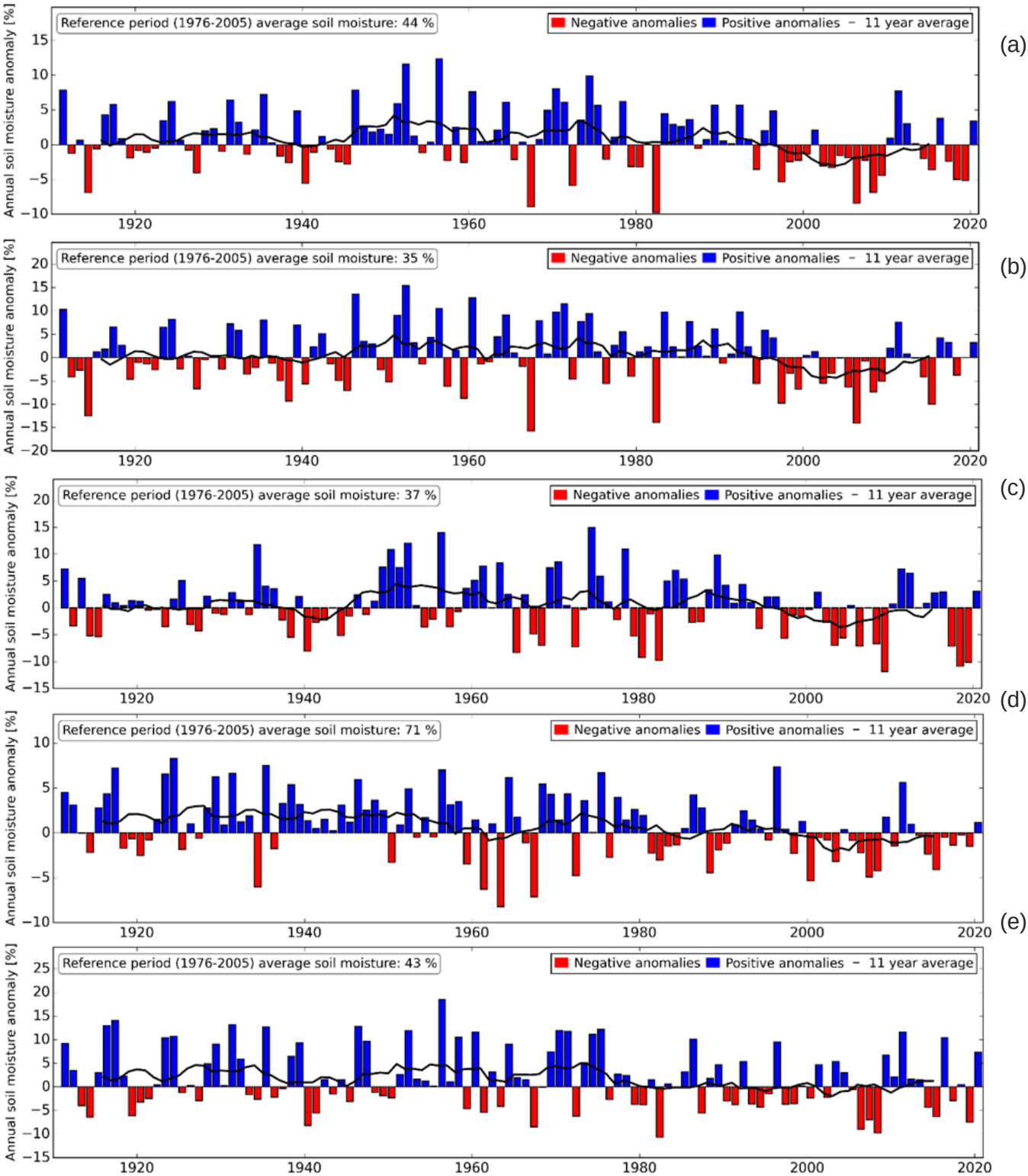

Figure 2.7 Annual anomalies in AWRA-L modelled soil moisture relative to the reference period (1976–2005) mean for (a) the whole Southern Slopes region and (b) western Victoria (Vic West), c) eastern Victoria and south-eastern NSW (Vic East), (d) western Tasmania (Tas West) and (e) eastern Tasmania (Tas East) subregions

Over the past 50 years, Australia has seen an increasing number of precipitation events (measured over an hour or day) exceeding previous levels (Guerreiro et al. 2018), and daily precipitation annual maxima have increased over the last century (Alexander & Arblaster 2017). Increases in extreme sub-daily precipitation are evident in the east and west of Victoria, but no change is evident in the central part of the region (Osburn et al. 2021).

Wasko et al. (2021) investigated observed flood magnitudes in the Southern Slopes region. Flood magnitudes have only increased for the rarest and largest precipitation events while common flood events showed a decreasing trend in flood magnitudes. However, a greater number of heavy precipitation events will not necessarily result in increased flooding because decreased soil moisture (associated with increases in temperature and subsequent evapotranspiration) could reduce flood magnitudes. The potential intensity of short-duration, high-intensity precipitation extremes is expected to increase in this region as temperatures increase, but the availability of moisture can potentially limit that increase (Jakob et al. 2020).

Time series plots of potential evapotranspiration anomalies for the Southern Slopes region are shown in Figure 2.8. A significant increase in potential evapotranspiration is observed over the past 2 decades in both Tasmanian subregions, Vic West and the Southern Slopes region overall. Vic East shows a slight increase since about 2010.

The region has experienced a trend towards increased mean annual surface temperatures in all subregions. Surface air temperatures in the region have been increasing since national records began in 1910, and particularly since 1960. Between 1910 and 2013, the mean temperature across the 4 subregions rose by between 0.8 °C and 1.0 °C (Grose et al. 2015a).

Additionally, the number of extreme heat days per year have been observed to increase across the entire region (Bureau of Meteorology 2021), as have the number of days per year with high fire danger for all parts of the region, but especially in southern New South Wales. This increased fire risk is related to changes in temperature, relative humidity and soil moisture content (CSIRO & Bureau of Meteorology 2020).

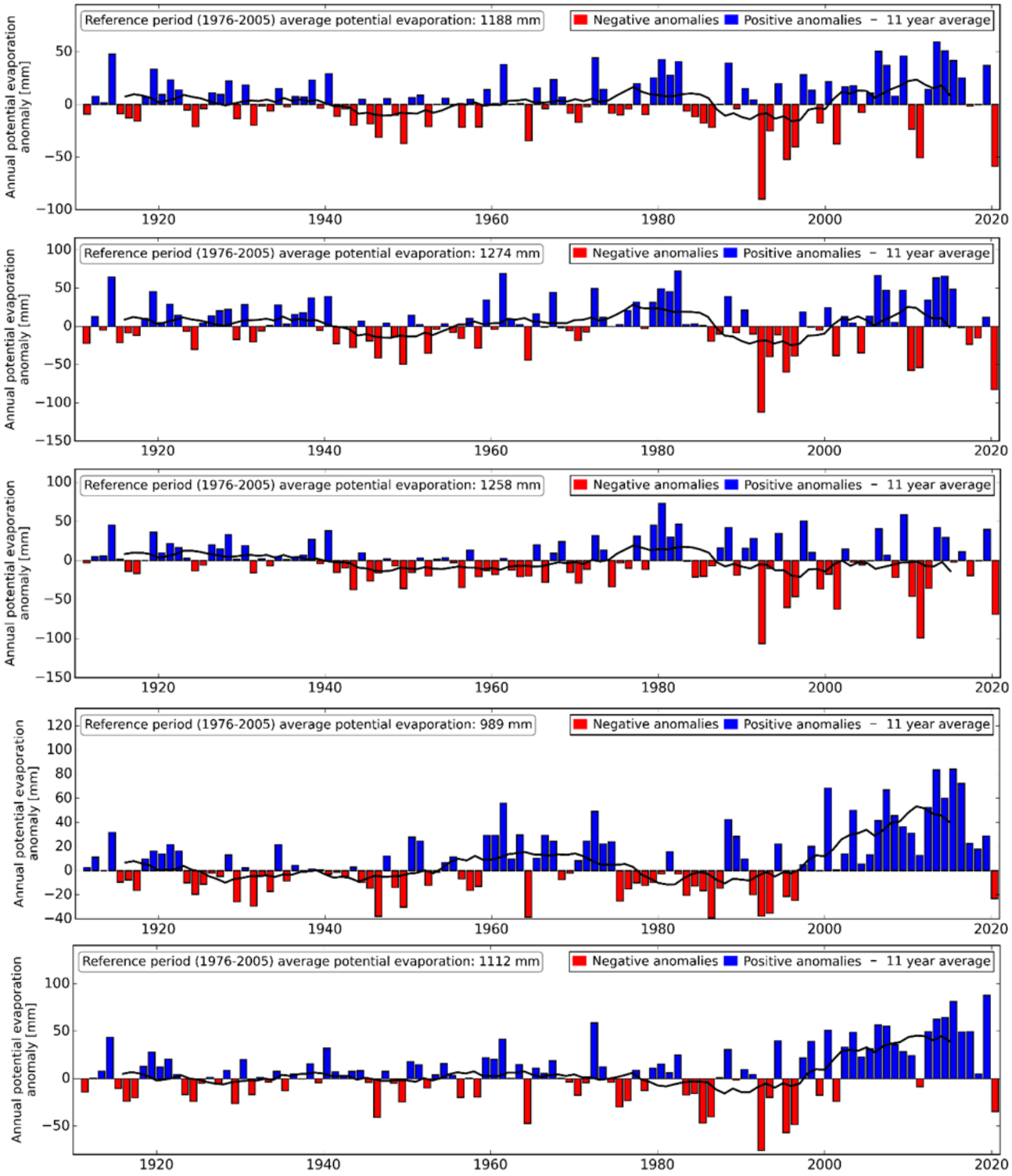

Figure 2.8 Annual anomalies in AWRA-L modelled potential evapotranspiration relative to the reference period (1976–2005) mean for (a) the whole Southern Slopes region and (b) western Victoria (Vic West), c) eastern Victoria and south-eastern NSW (Vic East), (d) western Tasmania (Tas West) and (e) eastern Tasmania (Tas East) subregions

2.3. Water availability and management

Hydrology and water resources vary considerably across the region due to large climate and geographic variability. The alpine areas of Victoria and western Tasmania feature high precipitation and lower average temperatures and evapotranspiration, so these headwater catchments generate most of the runoff in the region. Most of the runoff on the mainland portions of the region occurs in the winter and shoulder months. This cool-season runoff is important for filling surface water storages and groundwater recharge that provide water for use in the drier warm season. Groundwater systems in the Southern Slopes region vary in salinity and type. There are fractured and porous groundwater systems of low to moderate productivity throughout the region and also porous groundwater systems with high productivity in the Victoria's south and south-west. Changes to groundwater recharge could impact the productivity and salinity of such systems, particular high-productivity systems and systems in areas with a high dependency on groundwater (such as the south-western part of south-western Victoria).

On the mainland, the storages in these regions include the largest storage supplying drinking water to Melbourne (Thompson Dam) and also the largest dam in the Snowy Mountain hydro-electric scheme (Lake Eucumbene) (Figure 2.1). Water for consumptive use can be also sourced from Victoria's desalination plant at Wonthaggi, which was declared operational in December 2012. Western Tasmania has nationally significant hydro-electric dams under the responsibility of Hydro Tasmania that supply power to Tasmania and the mainland. Overall water management includes the release of environmental flows to sustain environmental assets, such as fish habitat or significant wetlands.

Changes to runoff could affect the reliability of these storages, adding to the region’s sensitivity to climate fluctuations affecting water availability, urban and rural water supply and agricultural production.

The hydrology in the western region is characterised by a large peak in runoff over winter and spring, and extremely low runoff in summer and autumn, with many rivers and streams experiencing very low flows. This combined with an increase in temperature and hot days, has already required cropping practice in this part of the region to respond to changing climate risks. In western Victoria, changes in the timing of precipitation and temperature patterns have affected dryland agriculture by increasing the risk associated with crop planting decisions. For example, the west has experienced a shift in peak precipitation from the spring to the summer. This mean less water is available for crops in the flowering and growing stages, reducing yields.

3. Ability to simulate hydroclimatic conditions of the Southern Slopes region

Assessing how well climate and hydrological models simulate key elements of the hydroclimate for Australia and the Southern Slopes 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 Southern Slopes region in the context of the 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 Projections 2019 work 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 Southern Slopes 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 Australian 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 (Grose et al. 2017). 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)

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.

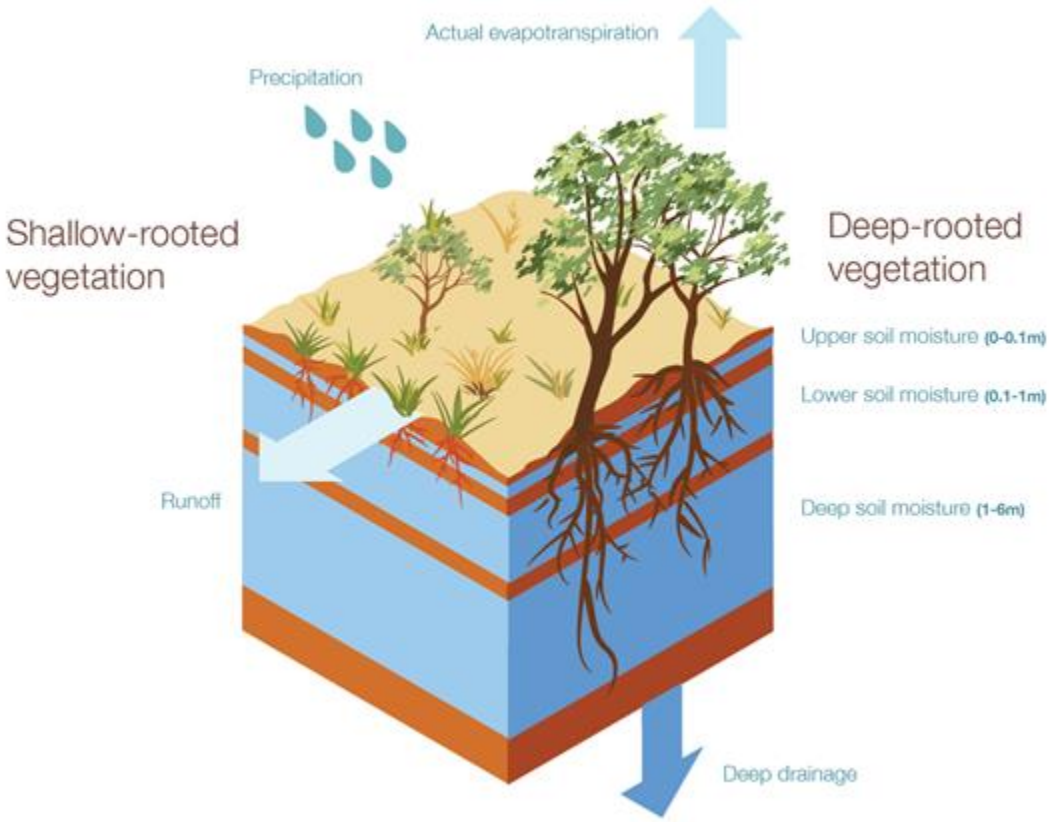

Figure 3.1. AWRA-L model grid cell with key water stores, fluxes and the hydrologic response units of deep- and shallow-rooted vegetation

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 Southern Slopes 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. 2015b).

In the Southern Slopes region, the 4 selected GCMs tend to represent central conditions within the range of conditions represented by the whole suite. That is, many of the other CMIP5 climate models project wetter and also much drier conditions, so the full scale of plausible futures for this region cannot be explored in this report.

Note that RCP4.5 for 2030 and 2070 are the only scenarios in which the 4 GCMs capture almost the full range of change in precipitation. While all 42 CMIP5 GCMs project an increase in temperature in the Southern Slopes region, the selected 4 capture the central to lower end of the range.

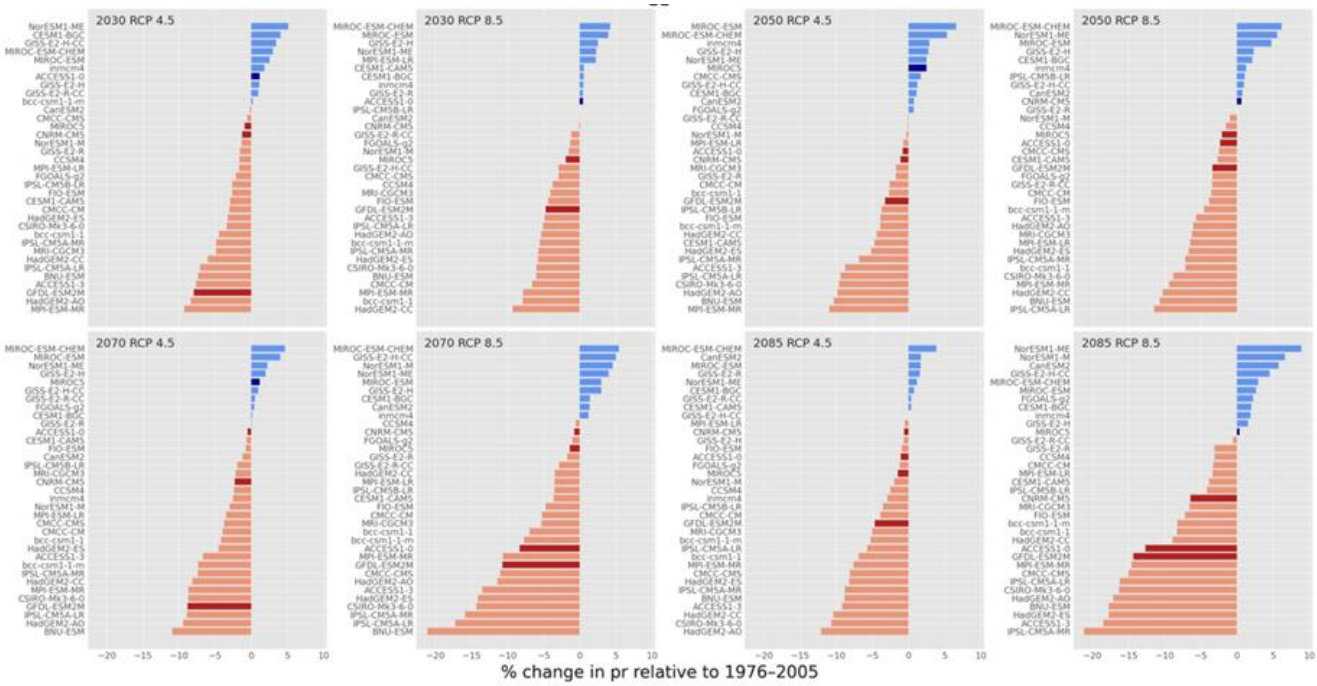

Figure 3.2. Ranking of the Southern Slopes region precipitation projections for the GCMs used in this study (shown in darker colours) compared to the CCiA ensemble for RCP4.5 and RCP8.5 for 2030, 2050, 2070 and 2085. The horizontal bars indicate the change signal – the difference of the regional average 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 the Australian Water Availability Project (AWAP) (Jones et al. 2009). In addition, 3 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 network and the interpolated AWAP grids (Jones et al. 2009) provide a good representation of the spatial variability of precipitation (including extreme precipitation) in regions such as the central eastern seaboard of Australia where there is a high density of observations (e.g. Dowdy et al. 2015). There is good coverage of precipitation and temperature observation networks across the Southern Slopes region and the observational data are suitable for the evaluation purpose.

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 Southern Slopes region. Evaluation criteria, such as representing the seasonality of the climate variables, are found to be adequately preserved in all ensemble members. Results show a tendency for ensemble members corrected with QME and MRNBC methods to feature positive and negative mean precipitation biases of around 1%, respectively, across all seasons (Appendix Figure 8.1). There is a consistent small negative bias (<4%) in maximum temperature for ISIMIP2b (Appendix Figure 8.3). For the other 3 bias-correction methods, the bias is both positive and negative and very small (<0.5%). In contrast, minimum temperature has a small consistent positive bias for ISIMIP2b except for 3 cases (>10%) (Appendix Figure 8.5). The bias in minimum temperature is small (<2%) for the other 3 bias-correction methods. Solar radiation (Appendix Figure 8.7) and surface wind speed (Figure 8.9) have very small biases (<1%).

There are some seasonal precipitation biases for individual ensembles or ensemble groups; for example, ensembles that are bias corrected by MRNBC underestimate winter precipitation. This bias does not change the key trends or messages for the ensemble set. Nevertheless, users should note these biases in studies that require selecting an individual ensemble – such as developing representative scenarios or representing year-to-year variability.

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 (Appendix Figures 8.11 to 8.16). The ensemble overall tends to underestimate soil moisture in the Southern Slopes region – MRNBC has the smallest bias in soil moisture and replicates the climatology (Figure 8.15). Simulations of potential evapotranspiration show a bias range between −2% and 2% (except for 6% in winter for one of the ensemble members) (Figure 8.13), which means the simulations are reliable. Runoff biases are the largest of any variable: most ensemble members feature positive (overestimate) or negative (underestimate) biases between 5% and 10% (Figure 8.11). The bias-corrected regional climate model CCAM_ISIMIP2b and the GCMs bias-corrected with MRNBC tend to underestimate runoff by 5% to 10%. In contrast, GCMs corrected with ISIMIP2b and QME produce both underestimates and overestimates. All ensembles average a bias of around 5% for winter runoff, but some ensembles have a bias up to 10%, which is still in the acceptable range.

The vegetation and landscapes of the Southern Slopes region are well represented in the AWRA-L model. The forested areas of the Victorian alpine regions and large areas of Tasmania are well represented by the deep-rooted hydrological response unit and the flatlands by the shallow-rooted or grass vegetation. Only regions representing urban and irrigation areas are not included in the AWRA-L model set-up. Of the 305 calibration catchments nationally, 68 of them are in the Southern Slopes region, so the model is well tuned to this area (Frost & Wright 2018). The performance of the continentally calibrated AWRA-L model for the Southern Slopes region is good based on having a 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 that AWRA was able to match the trend direction of the majority of the 33 streamflow observation sites. These trends are calculated from gauged data commencing in the 1970s for most sites. Results showed the trend direction was correctly modelled by AWRA-L for 76% of sites for annual streamflow volumes, 64% for summer volumes, and 85% for winter volumes. They found that 29 sites (88%) featured decrease in streamflow during summer, 32 (97%) sites in autumn, 26 (79%) sites in winter and 30 (91%) sites in spring.

In summary, the ability of the National Hydrological Projections ensemble members to simulate the hydroclimate for the Southern Slopes region is satisfactory. The evaluation shows that the bias-correction methods successfully adjusted the climate data, and this replicated the soil moisture, runoff and potential evapotranspiration.

4. Available National Hydrological Projections storylines for the Southern Slopes 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 Southern Slopes 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 Southern Slopes region.

In addition to the Hydrological Projections, previous climate projections for the region are described in the Southern Slopes CCiA report from Grose et al. (2015a). More detailed analysis of the precipitation projections, the seasonality of the responses and links to pressure changes are described in (Hope et al. 2015). The 'seasonal paradox' of precipitation change in Victoria was highlighted, where the strongest observed precipitation decline is in autumn, but the projections agree on a strong precipitation decline in spring. Three state-based efforts further provide projections information in this region.

For Victoria, results from the Victorian Water and Climate Initiative (VicWaCI) (DELWP n.d.) are described in DELWP et al. (2020), Hope et al. (2017) and South Eastern Australian Climate Initiative (SEACI n.d.). VicWaCI focuses on supporting the planning of water resource and flood managers. Victorian water resource managers are supported with guidelines for assessing the impact of climate change on water availability in Victoria (DELWP 2016, 2020). Victorian Climate Projections 2019 (VCP19) was an initiative based on 6 dynamically downscaled projections. Results are presented on the CCiA website (CCiA 2020). The dataset is similar to the projections from the GCMs combined with CCAM that are presented here. However, subsequent analysis procedures differ: VCP19 has a further downscaling step to 5 km whereas the ensemble used here is bias corrected. For Tasmania, projections were available from the Climate Futures program (Climate Futures n.d.). The Tasmanian climate projections are based on an earlier generation of climate models CMIP3 plus dynamical downscaling to provide enhanced information over the mountains and coastlines of Tasmania.

The projected hydroclimate for the region is presented in Chapter 5 as a set of available plausible future changes of key hydrological variables or available storylines.

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

Projections for annual mean precipitation of the 16-member ensemble in the Southern Slopes region project both small increases and decreases in precipitation (Figure 4.1). The projected median changes in annual precipitation differ under the 2 representative concentration pathways. The magnitude of change in mean annual precipitation decreases with time and is lower for RCP4.5 than RCP8.5. The projected variability shown by ACCESS1-0_ISIMIP2b under RCP8.5 in Figure 4.1 shows a large year-to-year variability in annual precipitation totals.

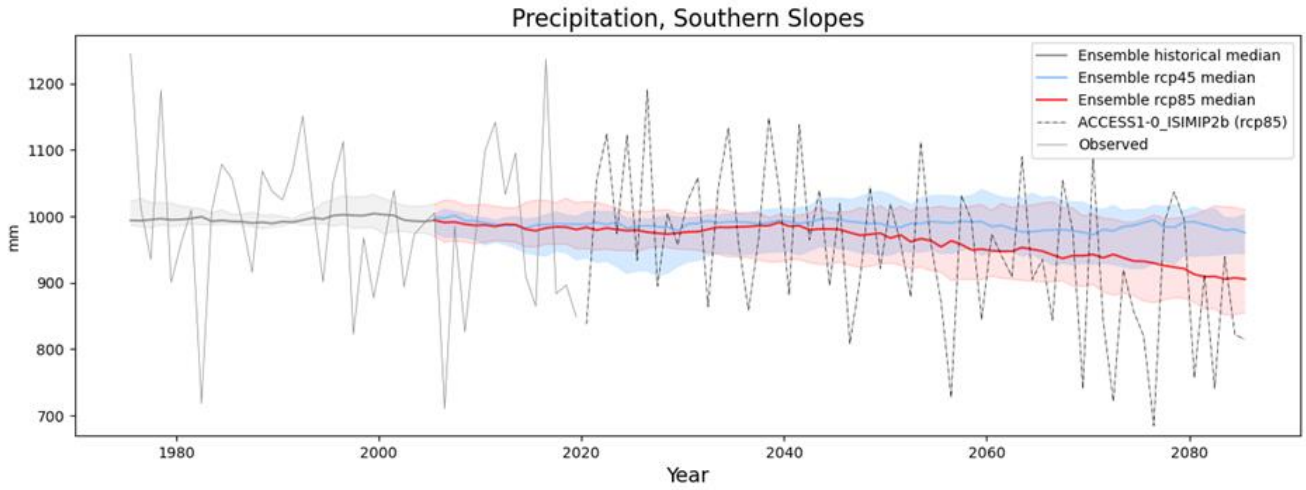

Figure 4.1. Annual modelled precipitation projected to 2099 by the 16-member ensemble for RCP4.5 (blue) and RCP8.5 (red) in the Southern Slopes region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. The time series for 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 large spread in the storylines, which project both increases and decreases in mean annual precipitation under both representative concentration pathways, means that both wetter and drier future changes are plausible (Figure 4.2a). However, the 16-member ensemble median projects a decrease in annual precipitation for all time periods and representative concentration pathways.

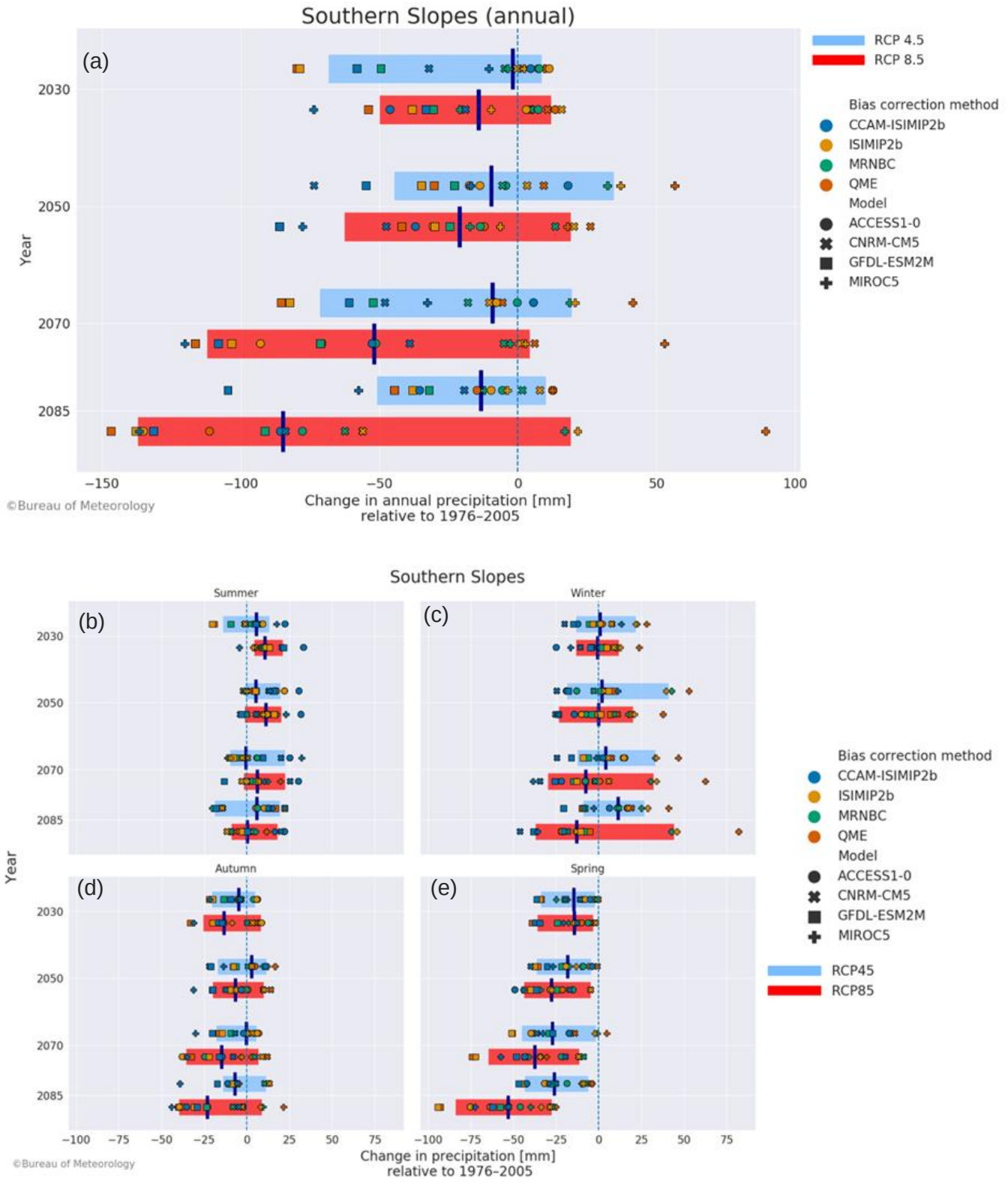

Figure 4.2. Absolute change in modelled (a) annual precipitation (mm) and seasonal precipitation for (b) summer (December–February), (c) winter (June–August), (d) autumn (March–May) and (e) spring (September–November) projected by each ensemble member for 2030, 2050, 2070 and 2085 in the Southern Slopes region. The change is relative to the reference period (1976–2005)

Annual average changes to precipitation for the Southern Slopes region are projected to be small by mid-century (i.e. around less than 2%). By 2050 and continuing to late century under RCP8.5, larger decreases in average

annual precipitation are projected in the Victorian part of the region than the Tasmanian or south-eastern NSW parts (Figure 4.3a). Mean annual precipitation is projected to decrease even more throughout the 21st century for the entire Southern Slopes region under RCP8.5; a 5.3% decrease in the median (range from −11.3% to 0.4%) is projected by 2070 and even greater by 2085 (Figure 4.2a). This pattern is underpinned by a good understanding of associated climate driver changes and processes to produce less precipitation (Pepler et al. 2021); the southerly shift in the westerlies may also be implicated (Perren et al. 2020). While there is strong agreement in direction of change, the 16-member ensemble projects a large spread of values (Figure 4.1). Grose et al. (2015a) also found that almost all CMIP5 models project a reduction of mean annual precipitation across the Southern Slopes region.

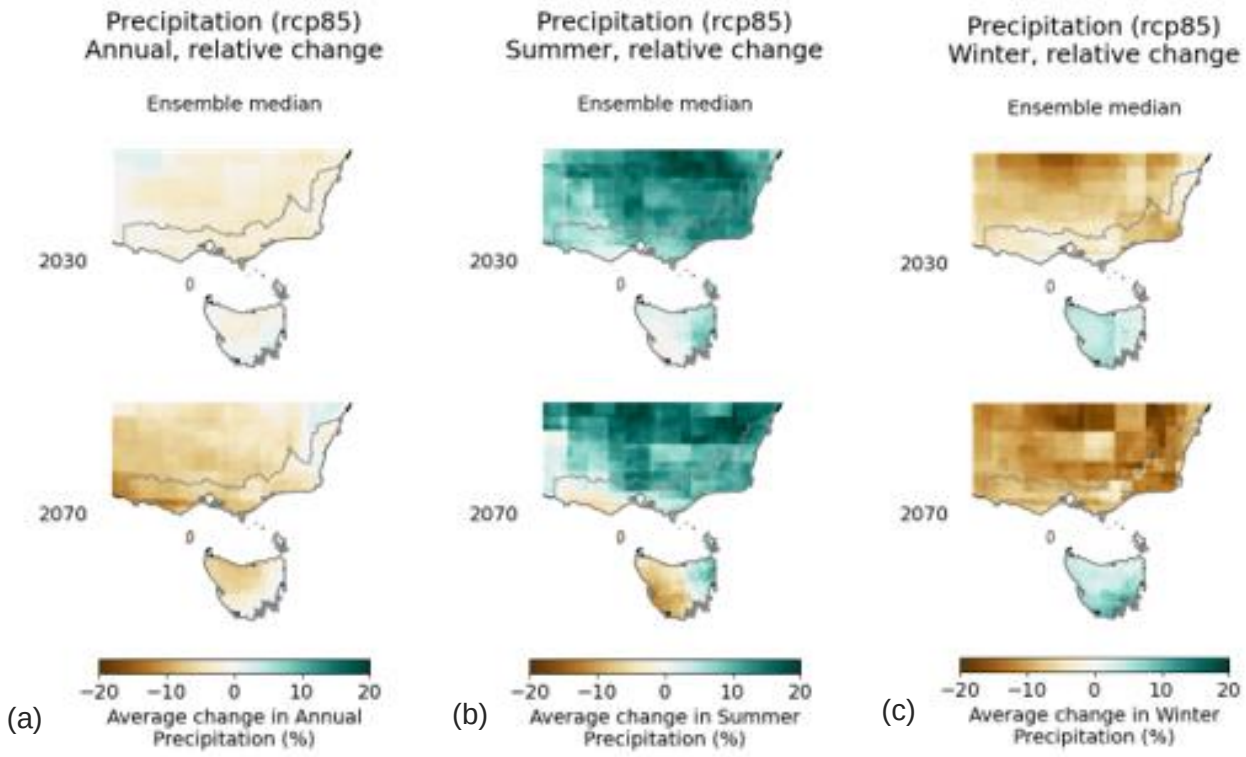

Figure 4.3. Absolute change (mm) (median) in annual, summer and winter precipitation projected across the Southern Slopes region for 2030 and 2070 for RCP8.5. The change is relative to the reference period (1976–2005)

Some projections for seasonal time periods project strong change signals. This is most notable for spring precipitation: almost all storylines project a decrease, which could be up to 100 mm (30%) by late century under RCP8.5 (Figure 4.2e). Under both representative concentration pathways, large decreases in mean springtime precipitation are projected across the entire region by mid-century, and very large springtime decreases are projected across the Victorian portion of the region by late century. The magnitude of possible spring differences from the climate of 1976–2005 ranges from −13% to −1% in the 2030 period and −16% to −2% in the 2085 period under RCP4.5. The comparable figures for RCP8.5 are −13% to −1% in 2030 and −31% to −10% in 2085. Climate Change in Australia found that, by 2090, spring precipitation is projected to change across the Southern Slopes region by around −25% to +5% under RCP4.5 and −45% to +5% under RCP8.5 (Grose et al. 2015a). Those CCiA results are comparable to the National Hydrological Projections result presented in this report.

Projected changes to winter precipitation across the region are less clear than spring changes (Figure 4.2c, e). There is a wide range of spread between the models, and projections include both increases and decreases. In addition, storylines dynamically downscaled with CCAM_ISIMIP2b consistently produce much drier projected changes than the other storylines. In addition, MIROC5 storylines project increases in precipitation, but these results may not be reliable as Grose et al. (2019) found MIROC5 does not represent southern Australian precipitation well, and therefore MIROC5 ensemble members may not be as reliable in this region as others.

Generally, all 4 selected GCMs show a weak correlation between the intensity of the sub-tropical ridge and a reduction in precipitation, which means they may underestimate cool-season decreases (Timbal et al. 2017). It is not known why projections of the GFDL-ESM2M model are much warmer and drier than other models, but they could be considered an example of plausible precipitation decreases.

Winter projections show significant variation across the region (Figure 4.3c). Increases in winter precipitation are projected for Tasmania under both representative concentration pathways. By mid-century the emerging increases are proportional to increases in greenhouse gases, and the increases become very large late in the century. This growing increase in precipitation is related to Tasmania being far enough south that it is influenced by an intensification of the westerlies that bring storms to the south of Australia. Conversely, winter precipitation is projected to decrease on the mainland (Figure 4.3c). Under RCP4.5 these decreases are apparent by late century, and under RCP8.5 the late century deceases are projected to be very large. These decreases in winter precipitation align with observed decreases. There is a good understanding of the influence of the sub-tropical ridge (Hope et al. 2015) and how a more intense STR reduces winter precipitation by reducing the number of rain-bearing cool-season storms and precipitation from fronts and lows (Pepler et al. 2021).

Grose et al. (2015a) found that 15 out of 42 CMIP5 climate models adequately represented local circulation features. That study found the resulting projected change in precipitation for 2080 to 2099 (relative to 1986 to 2005) under RCP8.5 showed that the precipitation reductions in winter are even stronger in both the south-west and the south-east of the continent than previously indicated using the full group of CMIP5 climate models. This is consistent with the observed precipitation declines in winter over the last several decades being at the drier end of CMIP5 model projections to 2030. Climate Change in Australia (Grose et al. 2015) found most models project a decrease in winter precipitation in Victoria of up to 15% under RCP4.5 and up to 30% under RCP8.5 relative to 1986 to 2005, which are larger decreases than found in this analysis.

Under both representative concentration pathways, the projected median summer precipitation shows a small increase over the mainland (Figure 4.3b). However, there is a small spread in the 16-member ensemble indicating little change, and small increases and decreases are possible. There is a large spatial difference in summer precipitation, with large increases projected in eastern Victoria and Tasmania, while western Victoria and Tasmania project small increases and no change, respectively, by 2030 followed by decreases in summer precipitation by 2070. These projections are slightly wetter than projections for summer by CCiA (which found small increases in the east mainland, a small decrease in the west and decreases in Tasmania); however, the future changes are broadly the same (drier in the west, wetter in the east and overall little change).

There is less certainty in the warm-season (November–April) climate processes than cool-season processes. Local land–atmosphere processes may become more important, as indicated by increases in the intensity of thunderstorms over recent decades (Pepler et al. 2021). Changes to the sub-tropical ridge are also projected to lead to increases in precipitation (Hope et al. 2017). Projecting localised summer precipitation requires high-resolution climate models, even higher than the resolution provided by the CCAM version used in the National Hydrological Projections. High-resolution models tend to project increases in summer precipitation over the Great Dividing Range (Grose et al. 2015a).

While little change is projected to autumn precipitation (Figure 4.2d), this does not align with observed trends in recent decades. This discrepancy is known as the ‘seasonal paradox’ and is an area of ongoing research. There are known deficiencies in the simulation of the current climate in autumn (Hope et al. 2015), so large decreases in precipitation are also plausible.

The assessment summary of projected precipitation in the Southern Slopes region is presented in Table 4.1.

Table 4.1 Assessment summary for precipitation in the Southern Slopes region

Feature	Largest plausible range of change (across all time periods and ensemble members)	Additional evidence: plausible process	Additional evidence: ability to simulate	Summary statement
Cool-season precipitation (May–October)	RCP4.5 −79 to 34 mm/season (−28% to 12%) RCP8.5 −118 to 39 mm/season (−42% to 15%)	Precipitation decreases have been observed in recent decades during the cool season, mainly autumn and spring. Expanding STR will block winter rain-bearing storms.	Most GCMs do not simulate the position of STR well, introducing uncertainty in projections.	Increases and decreases in precipitation are possible. However, evidence such as observed precipitation decrease and our good understanding of processes suggest that a drier future is more plausible than a wetter future.
Warm-season precipitation (November–April)	RCP4.5 −43 to 24 mm/season (−19.0% to 13.1%) RCP8.5 −41 to 53 mm/season (−18% to 29%)	How warm season weather will respond to a changing climate is not well understood. No increasing trend in summer season precipitation is observed.	Projecting thunderstorms requires high spatial and temporal resolution not achieved in any projection data.	Changes to warm weather precipitation are uncertain due to poor process understanding and low model agreement. Very large increases and decreases are both plausible. Natural inter-annual variability will continue to be important climate feature.

4.3. Runoff

Runoff projections for the Southern Slopes region show that both increases and decreases are plausible; however, a general decreasing trend is projected in the ensemble median that is greater for RCP 8.5 than for RCP 4.5 (Figure 4.4). Under RCP8.5, large decreases are projected late in the century across the entire region in mean annual runoff and for each season, except for winter runoff (Figure 4.5). While most ensemble members project a decrease in runoff for most seasons, winter runoff projects both increases and decreases.

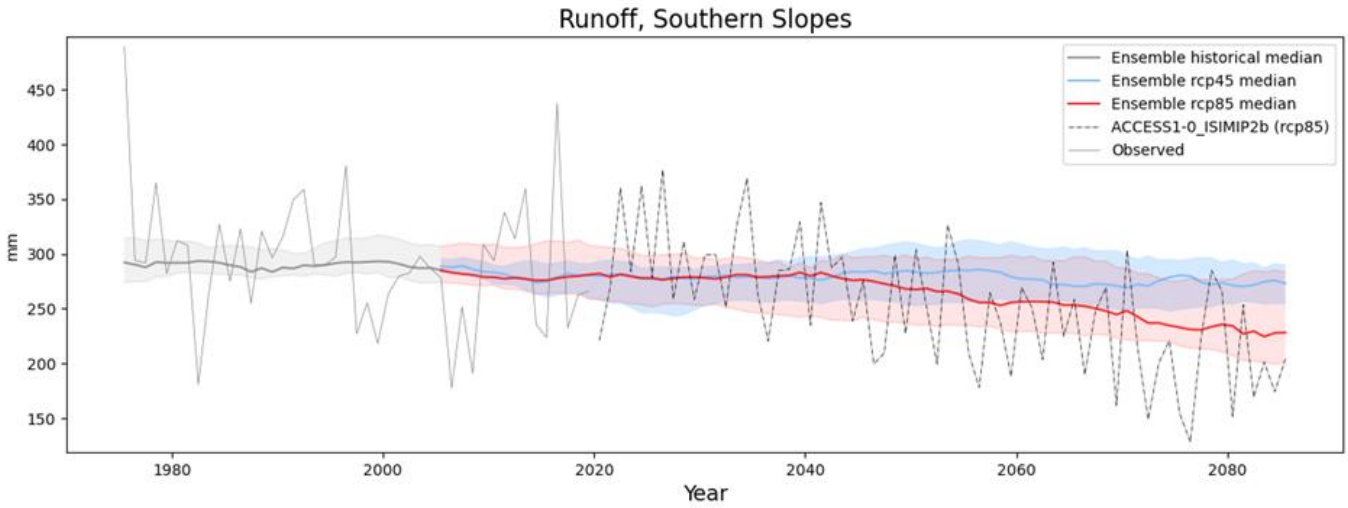

Figure 4.4. Annual modelled runoff (mm) projected to 2099 by ensemble members for RCP4.5 (blue) and RCP8.5 (red) greenhouse gas emission scenarios in the Southern Slopes region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. 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

Western Tasmania and the Victorian Alps have the largest decreases projected under both RCP4.5 and RCP8.5 (Figure 4.6) in absolute terms. However, for Tasmania under RCP4.5, the projected decrease represents a small percentage of the current runoff volumes generated in this subregion. In terms of relative changes,

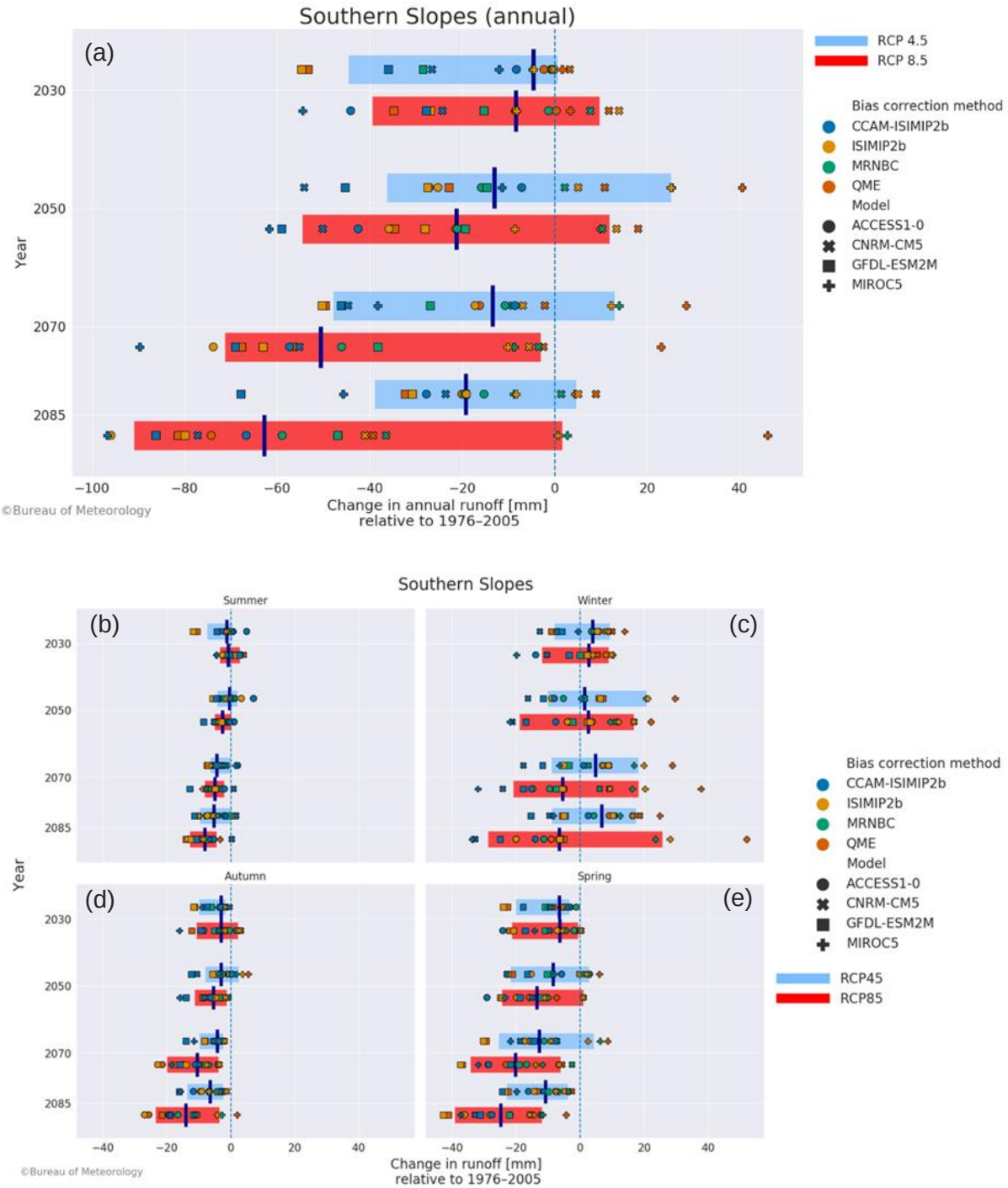

Figure 4.5. Absolute change in modelled (a) annual and seasonal runoff (mm) for (b) summer (December–February), (c) winter (June–August), (d) autumn (March–May) and (e) spring (September–November) projected by each ensemble member for 2030, 2050, 2070 and 2085 in the Southern Slopes region. The red bar 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)

Across the Southern Slopes region, there is little change projected in summer runoff with some decreases indicated by late century (Figure 4.5b). The ensemble members median for winter runoff also indicates little change (Figure 4.5c). However, there is a very large model spread making these results less certain, and both increases and decreases are possible. Changes to winter runoff are clearer at the subregional scale: decreases are projected for the mainland and increases projected for Tasmania by late century under both representative

concentration pathways. Summer runoff is projected to decrease in Tasmania, which will increase the seasonal contrast of runoff (which is largest in winter and lowest in summer).

Most storylines project decreases in spring and autumn runoff across the entire region under both representative concentration pathways (Figure 4.5d, e). The trend is already observed in historical streamflow records across the region in spring and is projected to continue in all future time periods. The magnitude of decrease is projected to strengthen later in the century and is higher for RCP 8.5 than RCP 4.5 (Figure 4.5d, e). These trend projections are significant since water availability in the region relies on the cool-season filling of storages, whose volumes are therefore projected to decrease.

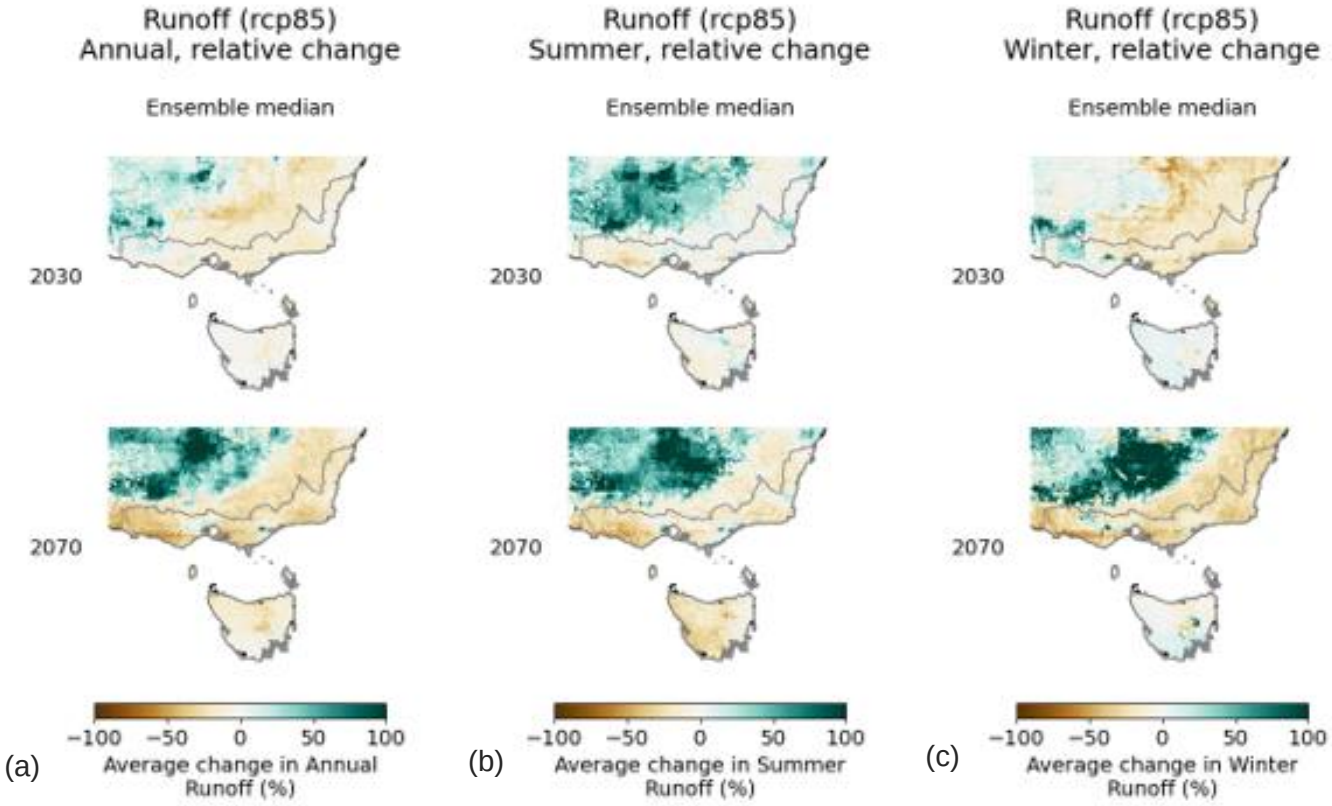

Figure 4.6. Relative change (mm) (median) in modelled (a) annual, (b) summer and (c) winter runoff projected across the Southern Slopes region for 2030 and 2070 for RCP8.5. This change is relative to the reference period (1976–2005)

An important source of uncertainty in projecting runoff is the limited ability of climate models to resolve small-scale (temporally and spatially) weather systems such as thunderstorms, which are likely to be associated with runoff generation in warmer months. This uncertainty means the summer runoff estimates may be underestimated.

Another important source of uncertainty relates to significant changes in precipitation–runoff relationships that have been observed in recent decades in many catchments in this region. Since the Millennium drought, a significant proportion of catchments yield less runoff for the same amount of precipitation (Saft et al. 2015, Peterson et al. 2021). This observation highlights the uncertainties in estimating runoff that arise due to the complex dynamics of catchment conditions and the interplay of hydrological variables that could be subject to change under new climate conditions.

Table 4.2. Assessment summary for runoff in the Southern Slopes region

Feature	Largest plausible range of change (across all time periods and ensemble members)	Additional evidence: plausible process/ model reliability	Observed trends	Summary projection statement
Cool-season runoff (May–October)	RCP4.5 −41 to 42 mm/season (−20% to 21%) RCP8.5 −74 to 51 mm/season (−36% to 26%)	85% of observed streamflow sites matched trend direction in winter. Evaluation shows a bias between −15% and 10%.	Decreases in cool-season runoff have been observed in 26 of 33 flow data sites in winter, 30 in spring, and 33 sites in autumn.	Increases and decreases are projected for cool-season runoff. Decreases are projected across the Victorian portion, which aligns with our understanding of processes and observed trends. The Tasmanian portion is projected to show an increase in the ensemble median.
Warm-season runoff (November–April)	RCP4.5 −25 to 5 mm/season (−30% to 7%) RCP8.5 −37 to 7 mm/season (−45% to 8%)	64% of observed streamflow sites match the trend direction in summer. Evaluation shows a bias between −12% and 12%.	Decreases in warm-season runoff have been observed in 29 of 33 sites in summer.	Increases and decreases are projected for warm-season runoff. Increases are projected more in eastern Victoria, whereas western Victoria and Tasmania have strong signals towards a decrease.

4.4. Soil moisture

Mean annual soil moisture is projected to decrease across the entire region by late in the century under both representative concentration pathways (Figures 4.7 and 4.8). This is consistent with projected increases in temperature and potential evapotranspiration.

Despite the projected trend for large decreases, large year-to-year variability of mean annual soil moisture is still projected, as presented by the ACCESS1-0_ISIMIP2b bias-corrected model for RCP8.5 (Figure 4.7). This reflects a projection for continued periods of above-average wet and dry years to occur over the drying trend. However, due to the strong drying signal, future periods of below-average dry could be more extreme than under current conditions.

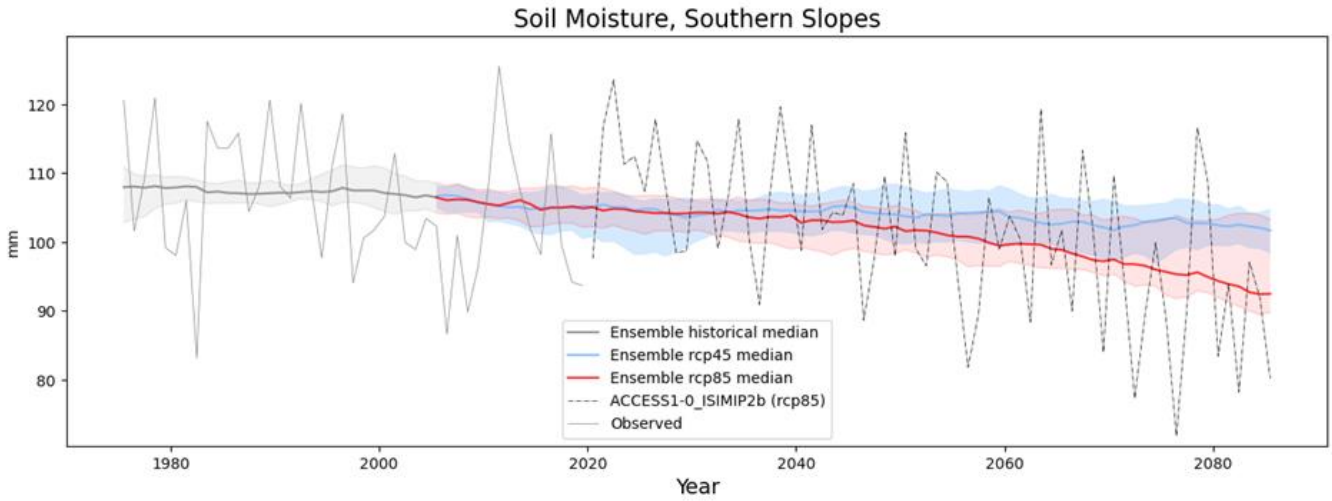

Figure 4.7. Annual modelled root zone soil moisture projected to 2099 by ensemble members for RCP4.5 (blue) and RCP8.5 (red) in the Southern Slopes region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. The time series 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

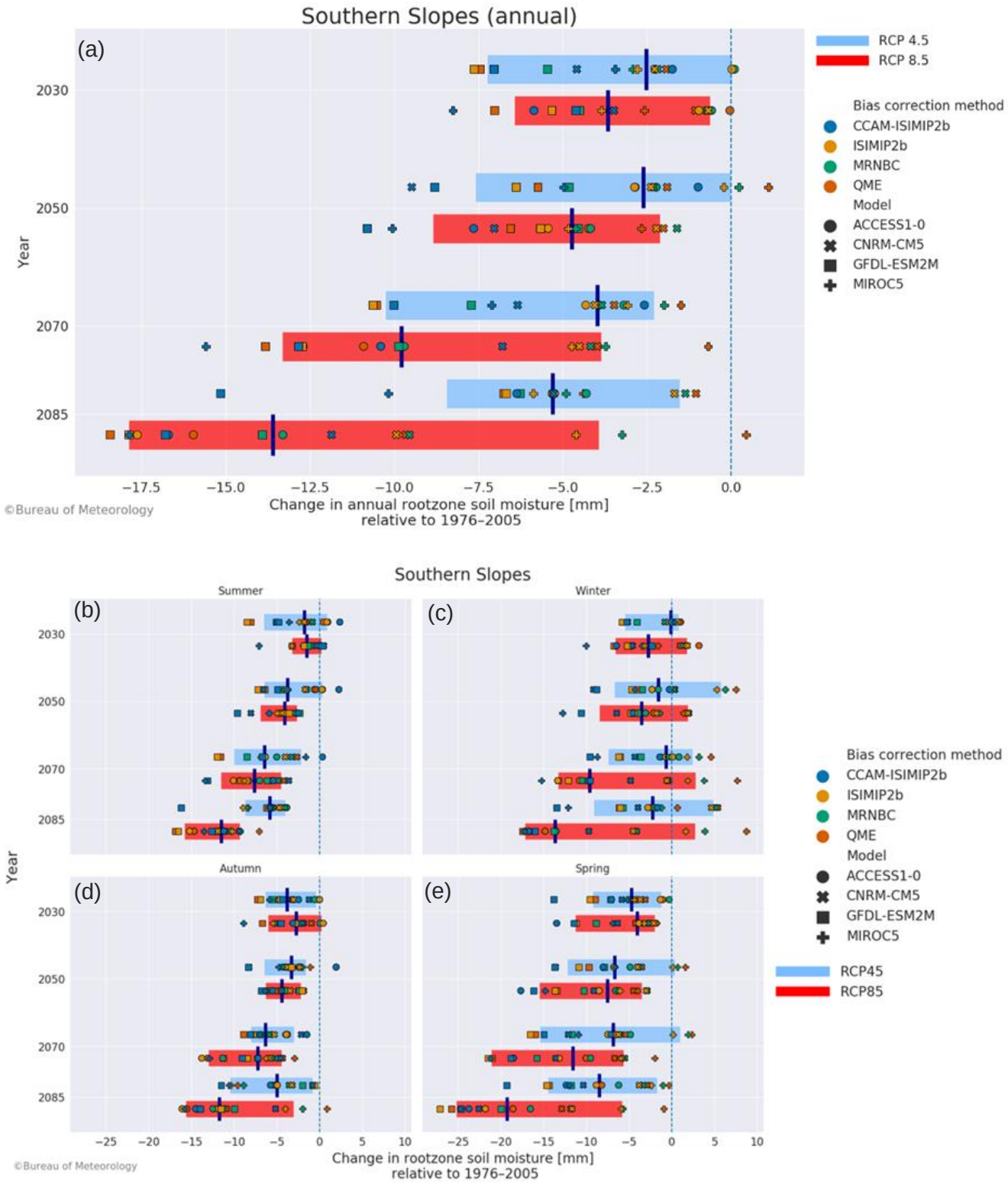

Figure 4.8. Absolute change in modelled (a) annual soil moisture (mm) and seasonal soil moisture for (b) summer (December–February), (c) winter (June–August), (d) autumn (March–May) and (e) spring (September–November) projected by each ensemble member for 2030, 2050, 2070 and 2085 in the Southern Slopes region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentile for RCP4.5. The dark blue line shows the ensemble median. The change is relative to the reference period (1976–2005)

Seasonal soil moisture projections show a strong agreement between models for a decrease from mid-century for spring and autumn under both representative concentration pathways (Figure 4.8d, e). Decreases in the spring average are the largest in magnitude (5 to 25 mm). Winter soil moisture is projected to experience little change under RCP4.5, although the model spread suggests both increases and decreases are plausible (Figure 4.8e). Under RCP8.5, little change is projected in mid-century in winter, but decreases are projected in late century by most storylines.

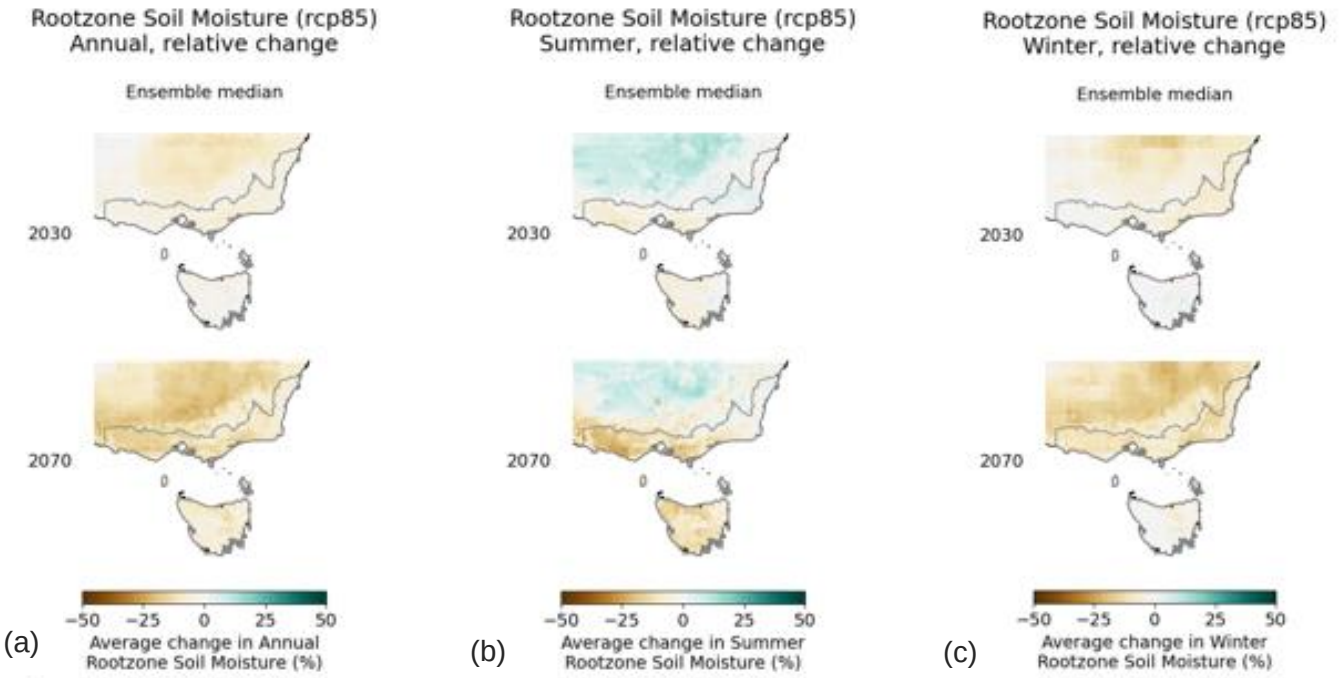

Figure 4.9. Relative change (fraction full) (ensemble median) in (a) annual, (b) summer and (c) winter root zone soil moisture projected for 2030 and 2070 for RCP8.5 across the Southern Slopes region. The change is relative to the reference period (1976–2005). Fraction full (scale 0-1) is equivalent to % full/100 and represented the fraction of available water content in the root zone (0–1 m) soil profile

The spatial distribution of the change in annual root zone moisture is shown in Figure 4.9 for annual averages and also summer and winter. The key spatial trend is for larger decreases on the mainland than on Tasmania. The mainland decreases are most pronounced in winter and spring. There is no significant difference between the mainland and Tasmania in terms of projected decreases in summer.

Table 4.3. Assessment summary for root zone soil moisture in the Southern Slopes region

Feature	Largest plausible range of change (across all time periods and ensemble members)	Additional evidence: process understanding	Additional evidence: plausible process/ model reliability	Summary statement with confidence
Cool-season soil moisture (May–October)	RCP4.5 −6 to 2 mm/season (−13% to 4%) RCP8.5: −8 to 2 mm/season (−16% to 4%)	Changes to soil moisture are driven by seasonal average potential evapotranspiration and precipitation changes.	Bias low but generally 2% to 3%; both positive and negative bias.	Projections to 2050 are for little change and also decreases. By late century, soil moisture is projected to decrease in summer, autumn and spring under both representative concentration pathways. For winter the upper range of projections include little change.
Warm-season soil moisture (November–April)	RCP4.5 −6 to 0.3 mm/season (−16% to 1%) RCP8.5 −7 to 0.36 mm/season (−20% to −1%)			

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 is projected to increase in both mid-century and late century for the entire region and under both representative concentration pathways (Figures 4.10 to 4.12). This projected increase in evapotranspiration is a key driver for projected decreases in soil moisture and the drying trend projected for many catchments within the region.

Increases in evaporation could impact the region through reducing water security as more water is lost to evaporation in storages. Also, increases in transpiration from forests can compete with recharge of groundwater sources that sustain baseflow in streams during dry periods.

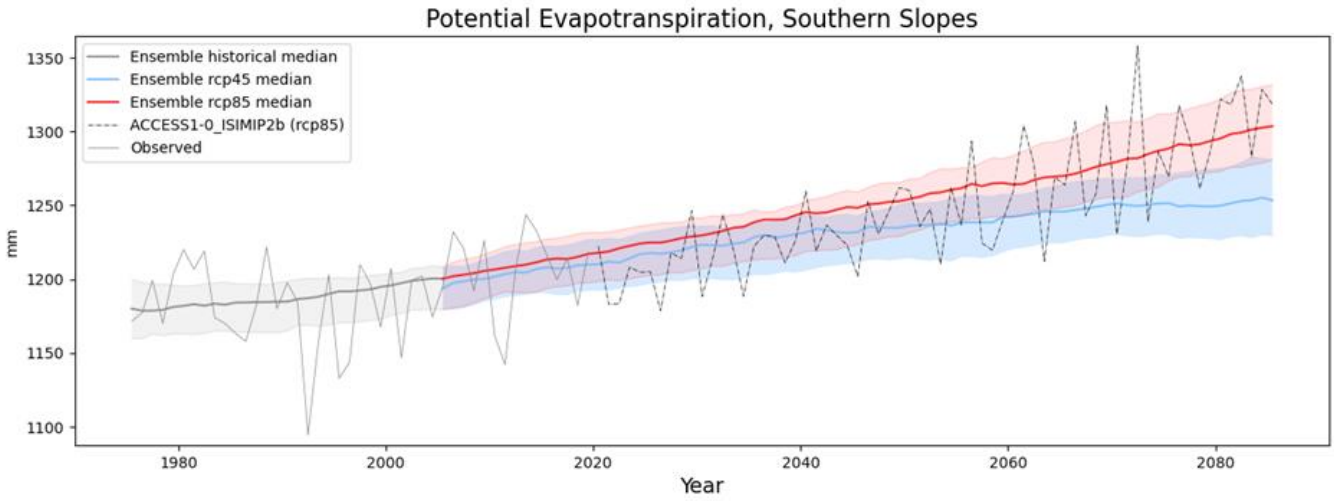

Figure 4.10. Annual modelled potential evapotranspiration (mm) projected to 2099 by ensemble members for RCP4.5 (blue) and RCP8.5 (red) in the Southern Slopes region. The shaded areas represent the 10th to 90th percentile range for all ensemble members in the historical and future time periods. The time 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

While either larger or much larger increases in potential evapotranspiration are projected for all seasons under both representative concentration pathways (Figure 4.11b–e), spring and summer are the seasons projecting the most increases. Projected changes of potential evapotranspiration changes in these seasons range from about 10 to 70 mm for spring and 5 to 45 mm for summer, while changes are smaller for the autumn and winter months (2 to 35 mm and 5 to 30 mm, respectively) (Figure 4.11b–e).

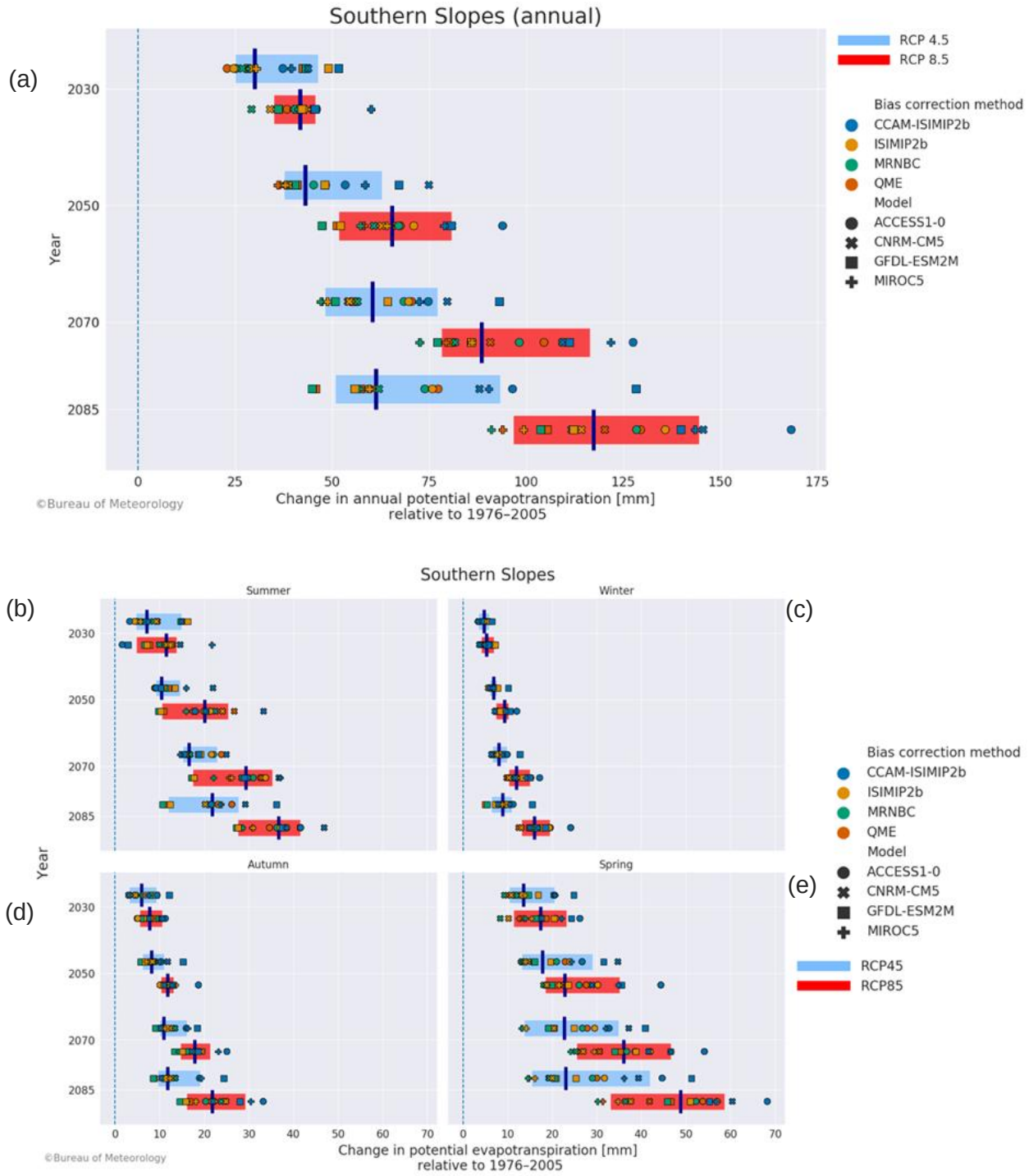

Figure 4.11. Absolute change in modelled (a) annual evapotranspiration (mm) and seasonal evapotranspiration for (b) summer (December–February), (c) winter (June–August), (d) autumn (March–May) and (e) spring (September–November) projected by each ensemble member for 2030, 2050, 2070 and 2085 in the Southern Slopes region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentile 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 change in potential evapotranspiration for both representative concentration pathways and 4 time periods are shown in Figure 4.12. This shows a steady increase in the change in potential evapotranspiration in the future across the entire region, with the magnitude proportionate to the representative concentration pathway.

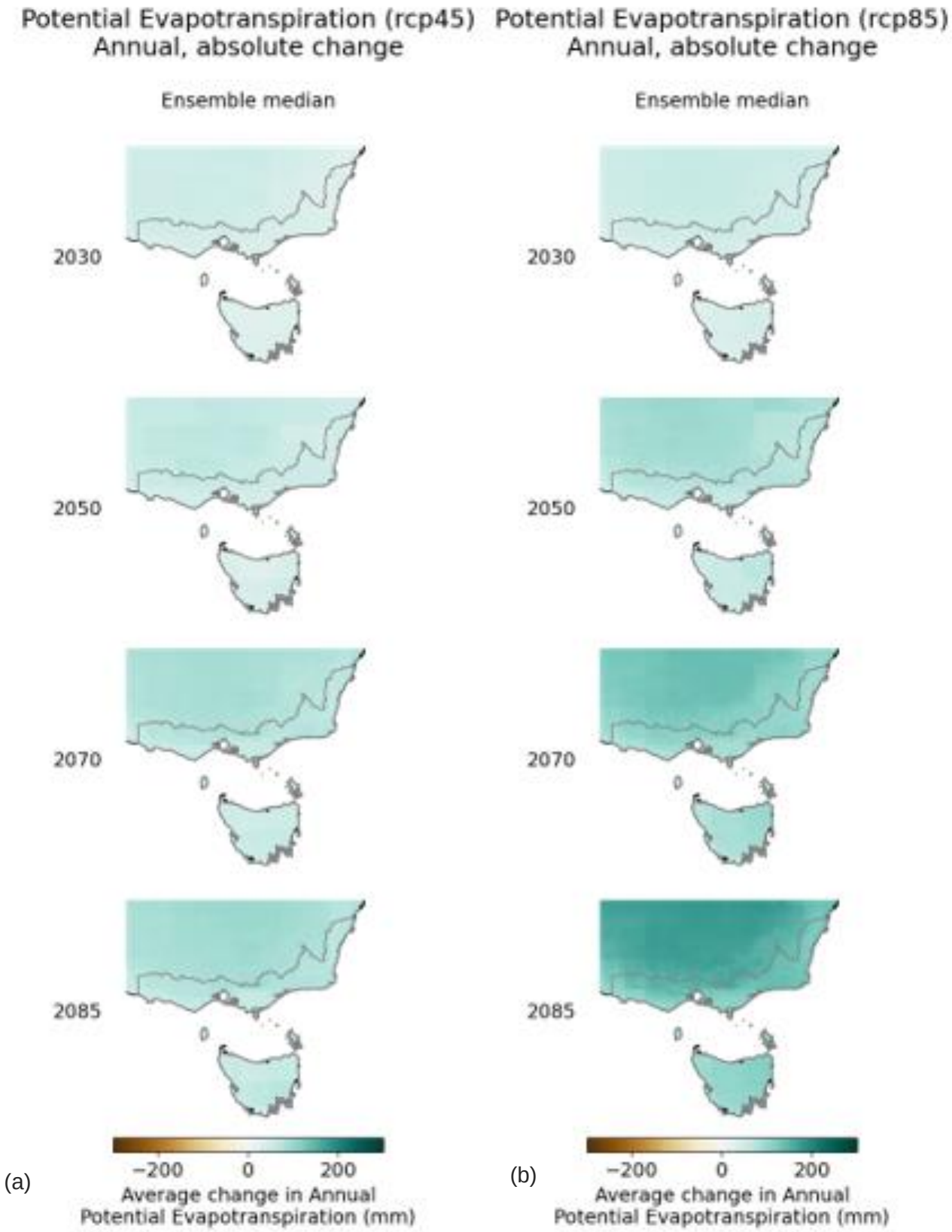

Figure 4.12. Absolute change (mm) (ensemble median) in annual modelled potential evapotranspiration for (a) RCP4.5 and (b) RCP8.5 for 2030, 2050, 2070 and 2085 across the Southern Slopes region. The change is relative to the reference period (1976–2005)

The assessment summary for potential evapotranspiration in the Southern Slopes region is presented in Table 4.4.

Table 4.4. Assessment summary for potential evapotranspiration in the Southern Slopes region

Feature	Largest plausible range of change (across all time periods and ensemble members)	Additional evidence: process understanding	Additional evidence: plausible process/ model reliability	Summary statement with confidence
Annual potential evapotranspiration	RCP4.5 23 to 128 mm/year (2% to 11%) RCP8.5 3 to 2 mm/season (30 to 168%)	Small increase observed in the recent past. This aligns with the understanding that a warmer climate results in higher potential evapotranspiration.	Low bias in potential evapotranspiration simulation.	Increase in annual and seasonal potential evapotranspiration for both representative concentration pathways and in all seasons. Magnitude is proportionate to greenhouse gas emission concentration.

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). 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), which are indicative of floods.

Both precipitation (Figure 4.13) and runoff (Figure 4.14) analyses project an increase in the maximum 1-day and 20-year return period for two 30-year periods (2030 and 2070) and both representative concentration pathways (RCP4.5 and RCP8.5). In comparison, the trends in annual mean precipitation and runoff project that the 16-member ensemble medians for mean precipitation and runoff tend towards little change or a decrease. This pattern (little change or decrease in annual mean relative to increase in extremes) is found in almost all other National Hydrological Projections regions and is supported by the results from other studies (Abbs & Rafter 2009; Alexander & Arblaster 2009; IPCC 2013; Rafter & Abbs 2009; Wasko & Sharma 2017) and reflects a shift towards a larger proportion of precipitation occurring in the form of high-intensity events. 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 Southern Slopes region, by 2070 the spread in the storylines is larger than the near future (2030). In addition, the spread of the runoff indicators is slightly larger than the spread in the precipitation indicators.

In summary, the results suggest that the intensity of extreme events is going to increase in the Southern Slopes region, possibly via an increase in intensity of east coast lows (Pepler et al. 2019). 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.

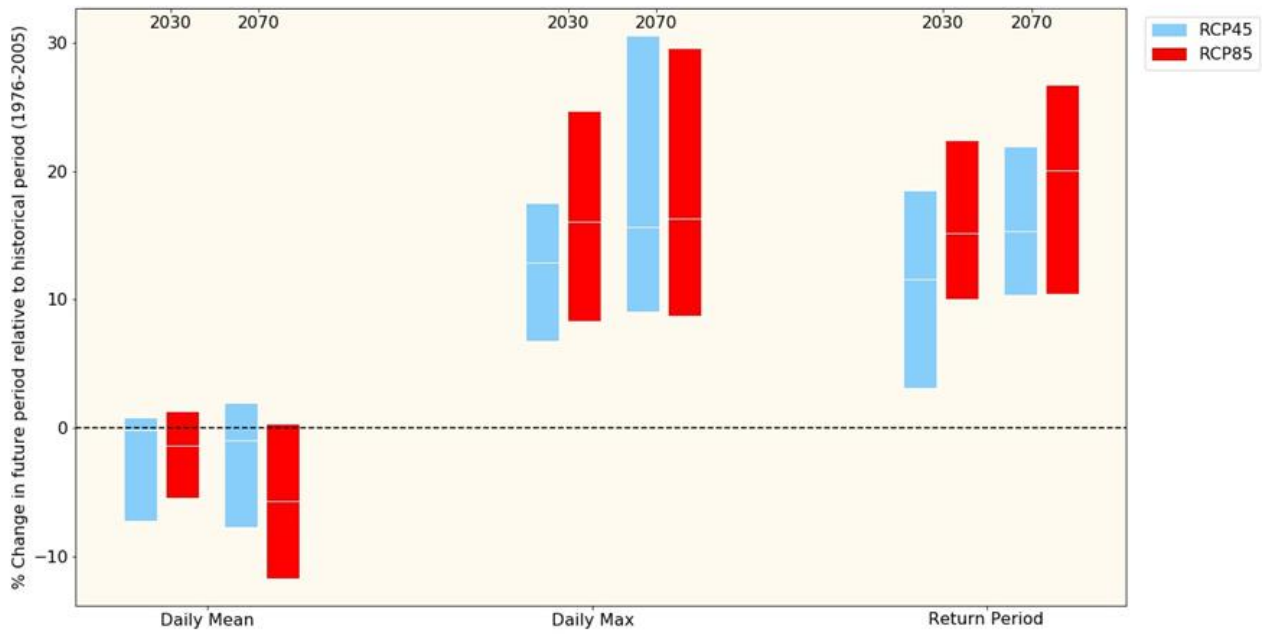

Figure 4.13. Future extreme wet analysis based on modelled precipitation shown by changes (%) in mean daily precipitation, maximum daily precipitation and 20-year return period of the annual maximum precipitation for 2030 and 2070 in the Southern Slopes region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentiles for RCP4.5. The white lines show the ensemble median. The change is relative to the reference period (1976–2005)

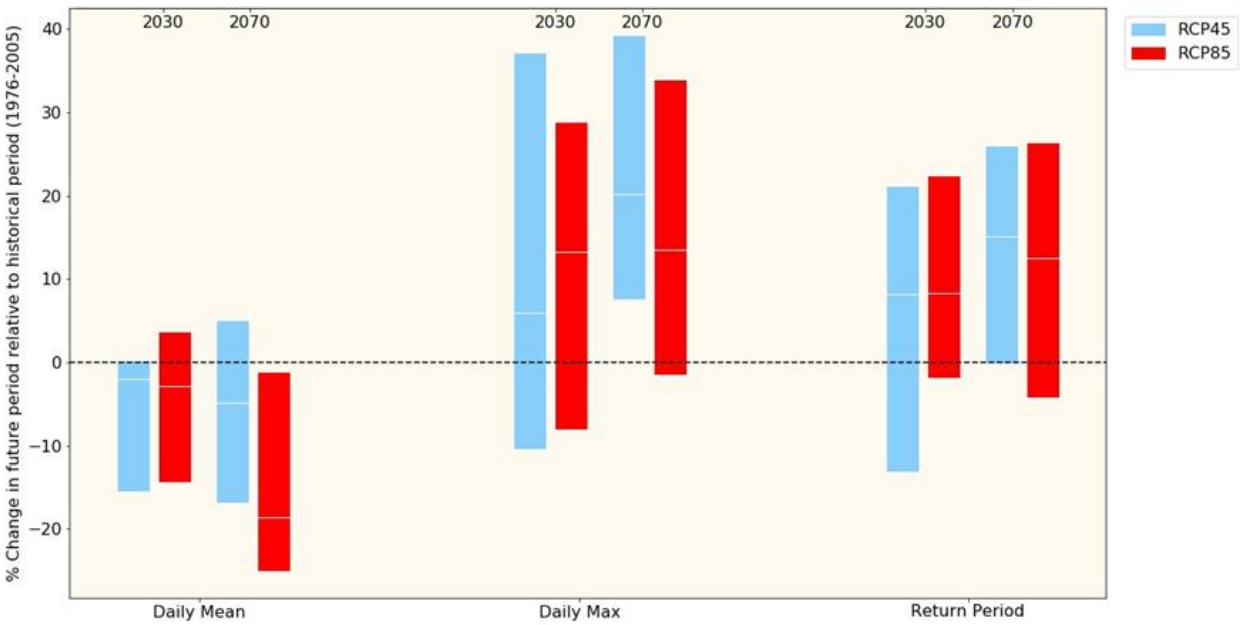

Figure 4.14. Future extreme wet analysis based on modelled runoff shown by changes (%) in mean daily runoff, maximum daily runoff and 20-year return period of the annual maximum runoff for 2030 and 2070 in the Southern Slopes region. The red bar shows the 10th to 90th percentiles for RCP8.5. The blue bar shows the 10th to 90th percentiles for RCP4.5. The 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.

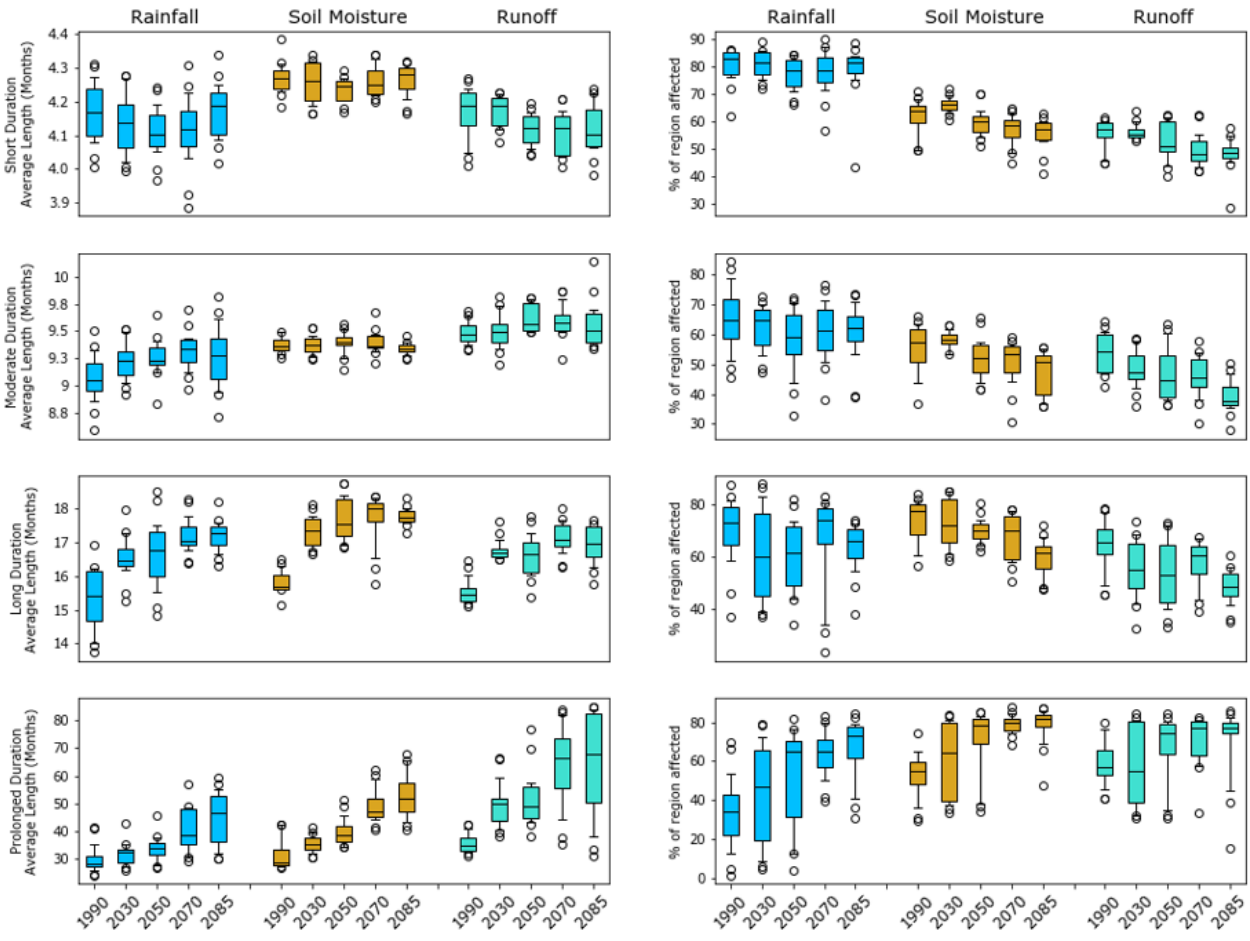

Figure 4.15. Change in projected median drought lengths (left) and percentage of total area affected by extreme dry conditions (right) for modelled precipitation (meteorological drought indicator), modelled soil moisture (agricultural drought indicator) and modelled runoff (hydrological drought indicator) in the Southern Slopes 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 4.15

Duration	Drought type	Projected result	Impact
Short (3–6 months)	All types	Little change on average projected for all short drought types in terms of duration but agriculture drought is projected to increase slightly.	Projected flash droughts remain similar on average compared to the historical reference period. Higher variability is plausible for the drought-affected regions, tending towards a decrease in area affected.
Moderate (7–11 months)	All types	Little change on average projected for all drought types but up to a 10% decrease in the spatial extent of drought, where a wider ensemble spread is shown in the area affected.	Projected moderate droughts remain similar to the historical reference period with higher variability plausible for the drought-affected regions, tending towards a decrease in area affected.
Long-term (12–23 months)	All types	Increases projected to varying degrees across the future time periods, where the maximum increase is seen in agricultural long-term drought conditions (>15%). Areas under drought are projected to decrease by as much as 20%, varying over the future time periods for all droughts.	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 dry conditions	Projected about 5% to 25% increase in time in drought across the future time periods. Projected increase in area under meteorological drought across the future time periods overall, ranging from –5% to 35%.	Projected increases in prolonged periods of low precipitation are plausible with an intensification of precipitation-deficient areas in the future.
	Hydrological dry conditions	Projected about 15% to 50% increase in time in drought across the future time periods. Projected increase in area under hydrological drought by up to about 15%.	Projected increase in prolonged periods of low-runoff states, which can lead to water supply shortages and insufficient environmental flows in the future (see Chapter 5).
	Agricultural dry conditions	Projected increase of between 15% and 50% in time in drought across the future time periods. Projected increase in area under agricultural drought by up to 25%.	Projected increase in prolonged soil moisture deficits and states are plausible, with an increase in drought-affected areas towards the end of the century. This can lead to impacts on crop and pasture growth as well as natural vegetation growth in the future.

In summary, the Southern Slopes region is projected to have an increase in multi-year, prolonged extreme dry conditions, proportional with time. However, the spatial extent of future extreme dry condition is uncertain due to the spread of results across the 16-member ensemble (Table 4.5). The socioeconomic implications of these results mean that water-sensitive industries, agriculture, and water management in this region need to prepare for drier conditions and an unreliable year-to-year water supply, which is brought about by an increase in long-term to prolonged dry spells. In particular, the increase in the area under agricultural prolonged drought means that this drier landscape could have implications for bushfire fuel, worsening bushfires in the future. The environmental implications for ecosystems and river health could be significant as these results project reduced availability of water for plants and less surface water, meaning more variable environmental flows.

5. Exploring future water resource impacts: applying selected storylines to the Southern Slopes 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 Southern Slopes region.

5.1. Representing water-sensitive impacts to hydrological variables on hydro-electricity security of Lake Gordon

These storylines explore examples of changes in the seasonality of runoff into Lake Gordon, a large surface water storage in western Tasmania that is used to generate hydro-electricity. The amount of water stored in hydro-electricity storages is known as total energy in storage (TEIS). TEIS water storage levels hardly ever go above 50% or below about 25%. It generally peaks between 40% and 49% during the wettest part of winter and spring each year and bottoms out between 20% and 29% in the driest part of autumn and summer, representing different extremes in the seasonal cycle.

Most storage inflows occur in the cool season in this region. The west coast of Tasmania has some of the most reliable precipitation in Australia in terms of a very low year-to-year variability. Water managers can expect the storages to fill reliably each cool season, and there is relatively little risk that the following year will not meet average conditions. Changes to seasonality of precipitation could make seasonal precipitation less reliable. This could see greater or smaller differences between seasons, which could change the management dynamics of the system.

Changes to cool-season (May–October) runoff and changes to warm-season (November–April) runoff are used as indicators of changes to seasonal inflows to Lake Gordon and represent supply (cool-season runoff) and demand (warm-season runoff).

5.1.1. Establishing representative storylines

To determine plausible storylines reflecting range of changes to water availability, changes to cool-season (May–October) runoff for each ensemble member are plotted against the warm-season (November–April) runoff over the 30 years centred on 2050 (Figure 5.1). This plot shows that most storylines project decreases for the warm months, but in the cooler months both increases and decreases are projected. Projected cool-season changes in runoff range between ±10%. Projected cool-season changes have a much large spread, ranging from 10% to −35%.

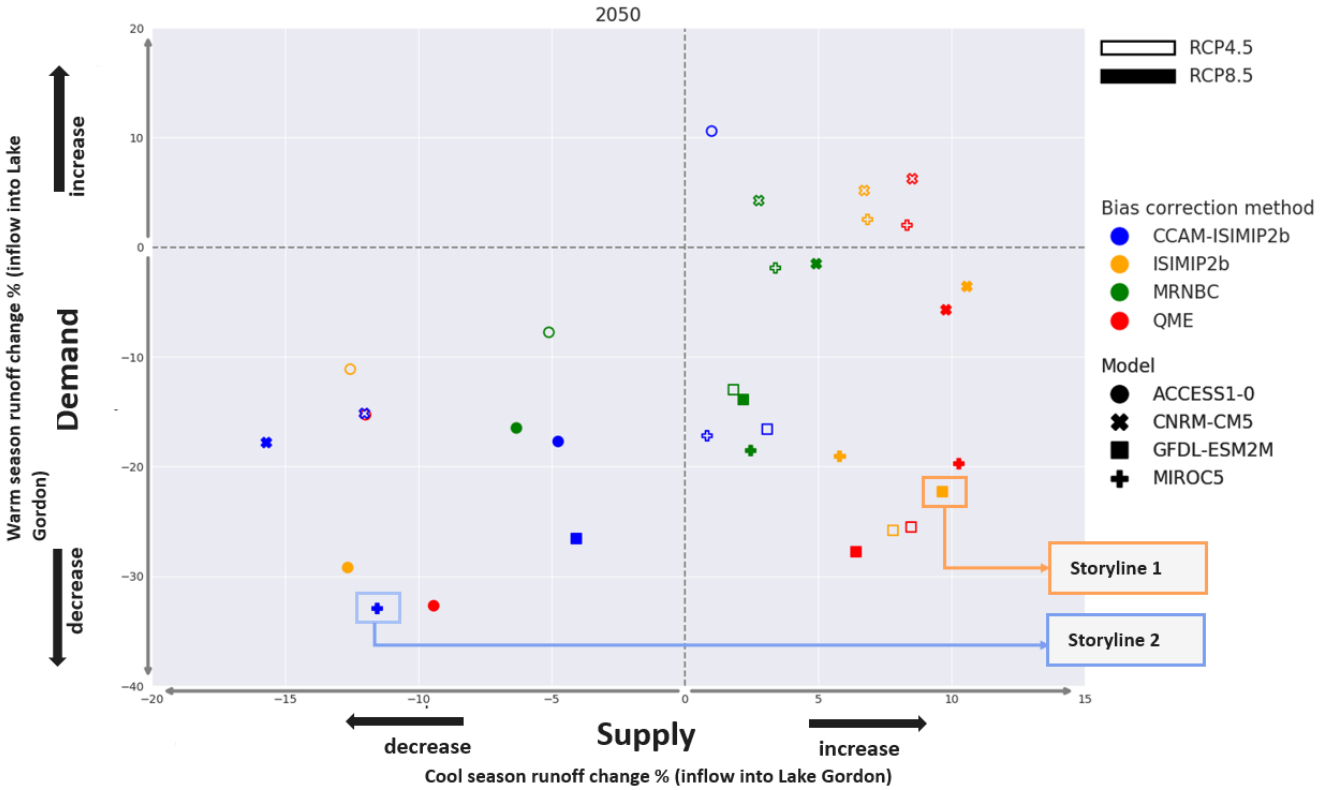

Figure 5.1. Projected changes to cool-season runoff vs projected changes to warm-season runoff. Cool-season runoff is used as a proxy for changes to water supply and warm-season runoff for changes to demand

A number of storylines can be established that represent the range of conditions from the perspective to changes in water supply seasonality (Table 5.1).

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

Storyline	Impacts to be explored
Year-round decreases in runoff (MIROC5_CCAM_ISIMIP2b RCP 8.5)	What happens when runoff is projected to decrease in both cool and warm seasons?
Changes to seasonality of water availability (GFDL-ESM2M_ISIMIP2b RCP 8.5)	What happens when runoff increases are projected in the cool season, but decreases are projected in the warm season?
Year-round increase in runoff (CNRM-CM5_QME RCP4.5)	What happens when runoff is projected to increase in both cool and warm seasons?

5.1.2. Storyline 1: Changes to seasonality of water availability (GFDL ESM2M_ISIMIP2b RCP8.5)

This storyline features increases in cool-season runoff (9%) but decreases in warm-season runoff (−22%). The increases in cool-season runoff are driven by increases in precipitation in the same season. The decreases in warm-season runoff are driven by decreases in precipitation and also increases in potential evapotranspiration and the associated drying of catchments.

In this storyline, more water could be available to fill the storages in the cool season, but that additional water would need to compensate for lower inflows during the warm season. Managing inter-annual and seasonal variability could become increasingly important to optimise water availability all year round for generating hydro-electricity.

5.1.3. Storyline 2: Year-round decreases in runoff (MIROC5–CCAM-ISIMIP2b RCP8.5)

This storyline describes decreases in both average cool-season runoff (−12%) and warm-season runoff (−35%). These decreases in both seasons are associated with decreases in precipitation and increases in potential evapotranspiration (and associated decreases in soil moisture), especially in the warmer months. Increases in potential evapotranspiration are projected in association with increases in temperature. Changes to precipitation are less certain.

Most storage inflows occur during the cool season in Lake Gordon catchment; however, inflows do also occur in the warm months. This storyline describes a situation where the decreases to cool-season inflows would mean that the storages may not fill as reliably as under current conditions. A key management challenge of the hydro-electric dams in western Tasmania is to ensure water is available during the warm months to meet increases in energy demand. With even less reliable filling in the warmer months than currently, management of water to meet demand would become more challenging.

5.2. 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

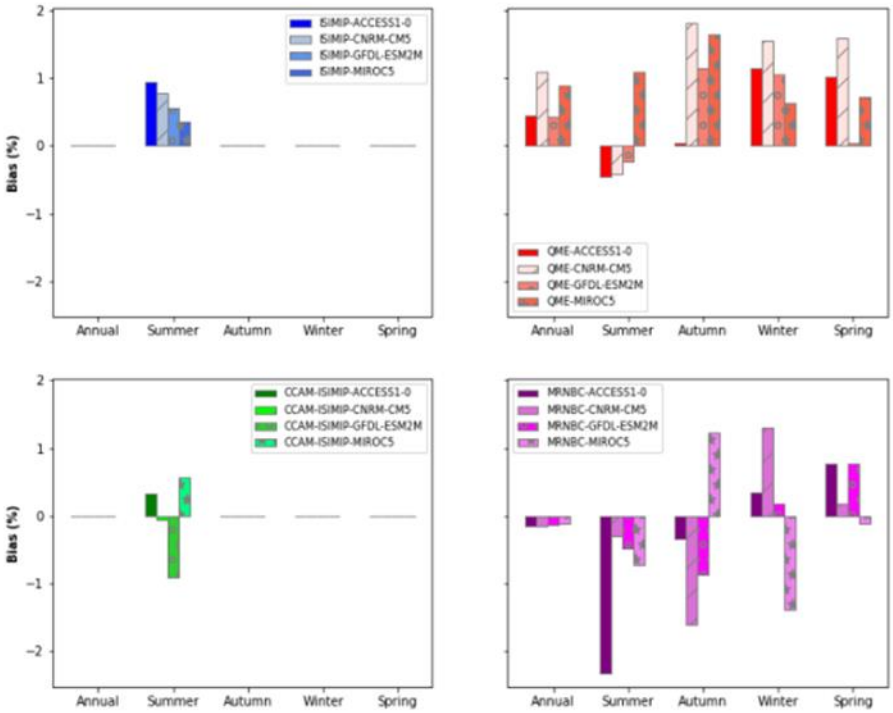

Figure 8.1. Bias (%) in mean annual and seasonal precipitation for the Southern Slopes region

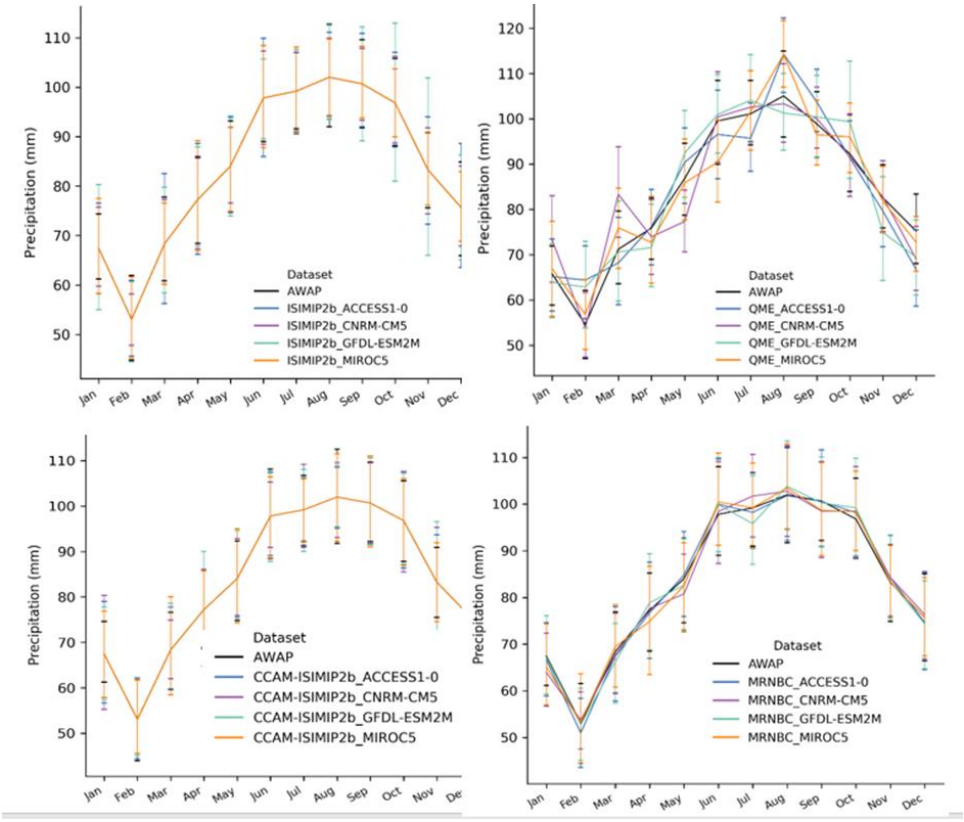

Figure 8.2. Comparison of the mean monthly precipitation (mm) for the 16-member ensemble and observed (AWAP) data for the Southern Slopes region (1976–2005)

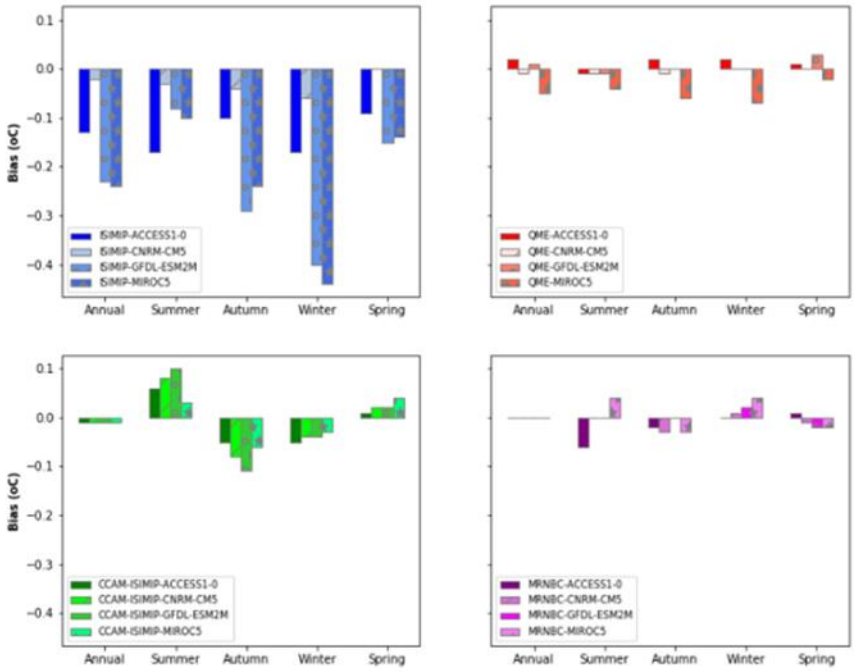

Figure 8.3. Bias (°C) in mean annual and seasonal maximum temperature for the Southern Slopes region

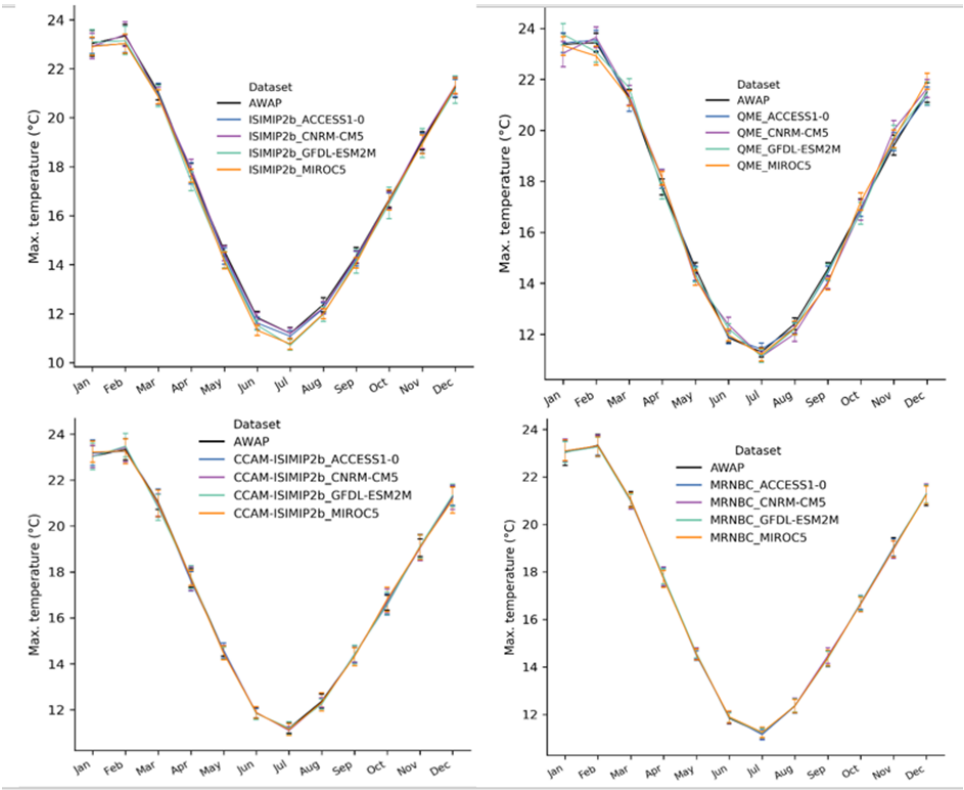

Figure 8.4. Comparison of the mean monthly maximum temperature (°C) for the 16-member ensemble and observed (AWAP) data for the Southern Slopes region (1976–2005)

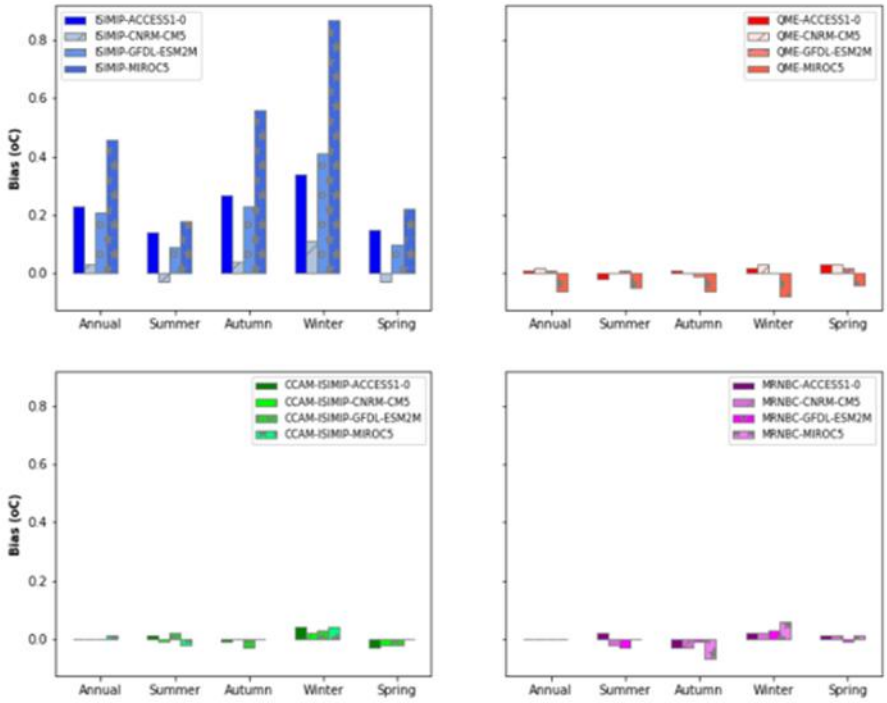

Figure 8.5. Bias (°C) in mean annual and seasonal minimum temperature for the Southern Slopes region

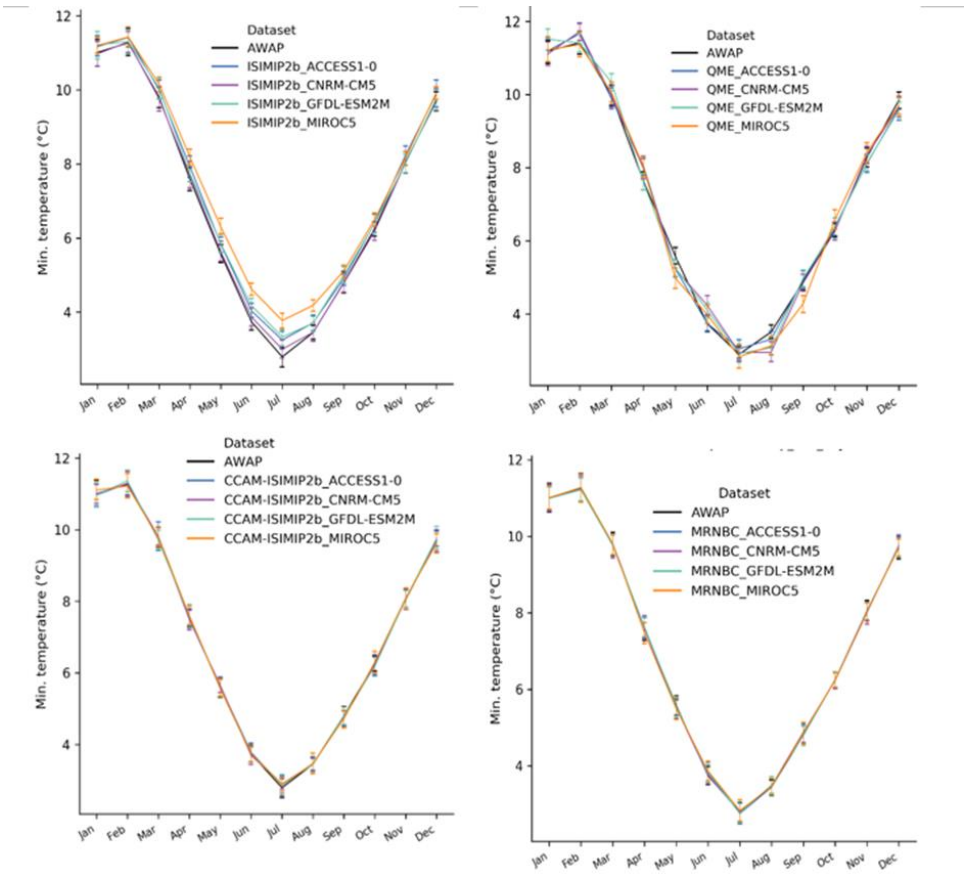

Figure 8.6. Comparison of the mean monthly minimum temperature (°C) for the 16-member ensemble and observed (AWAP) data for the Southern Slopes region (1976–2005)

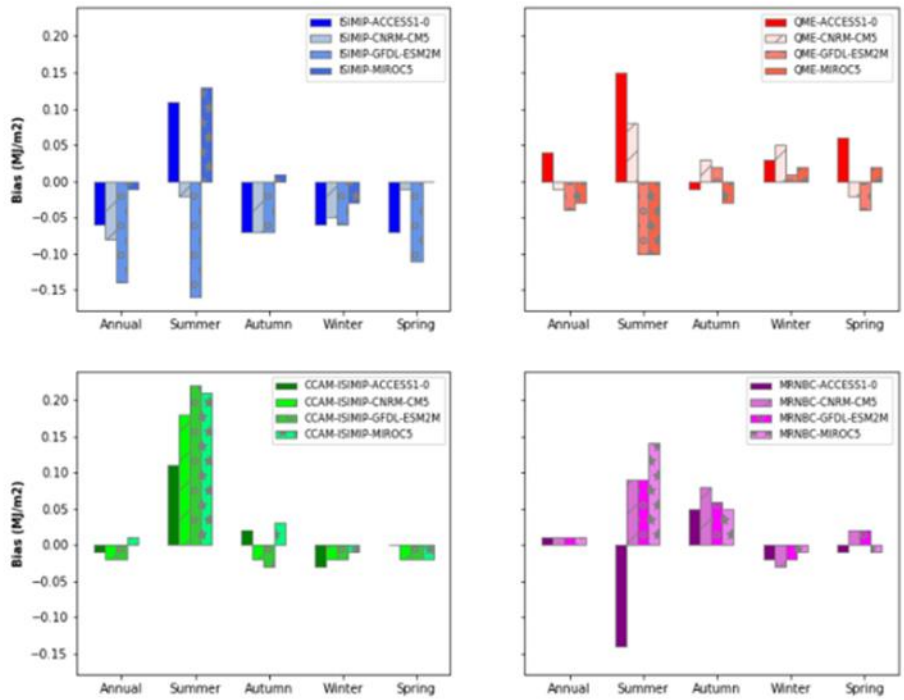

Figure 8.7. Bias (megajoules per square metre, MJ/m^2) in mean annual and seasonal solar radiation for the Southern Slopes region

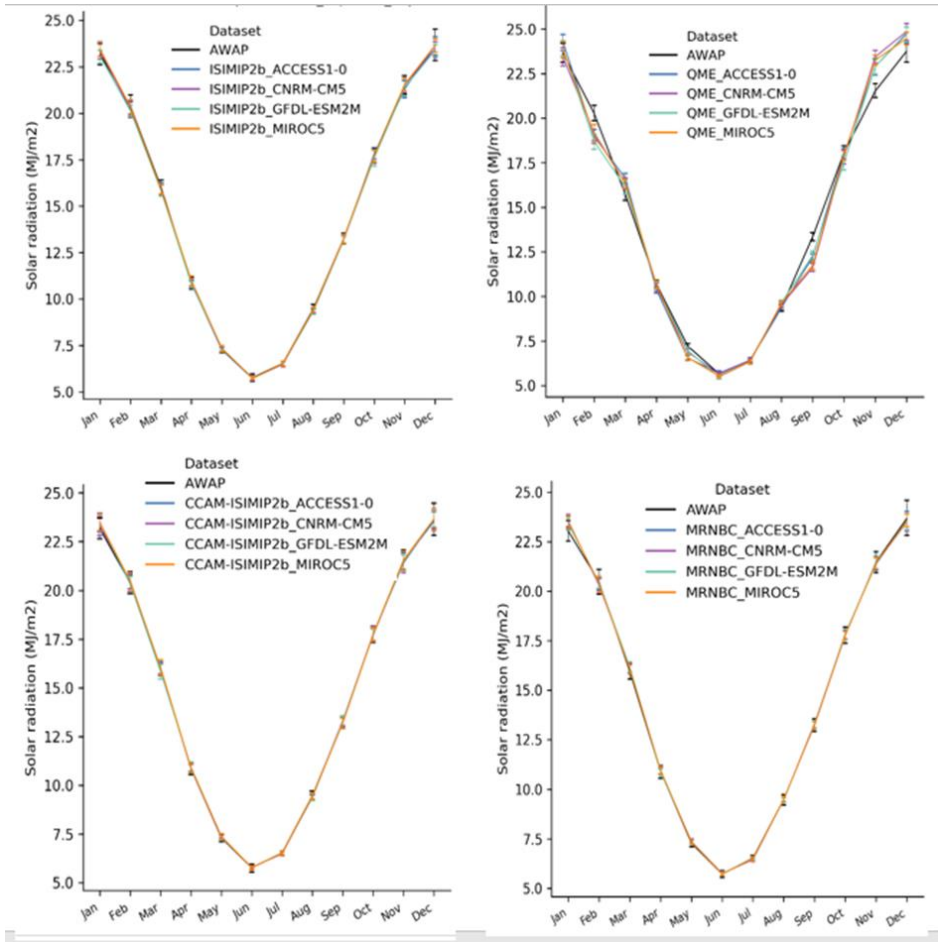

Figure 8.8. Comparison of the mean monthly solar radiation (MJ/m^2) for the 16-member ensemble and observed (AWAP) data for the Southern Slopes region (1976–2005)

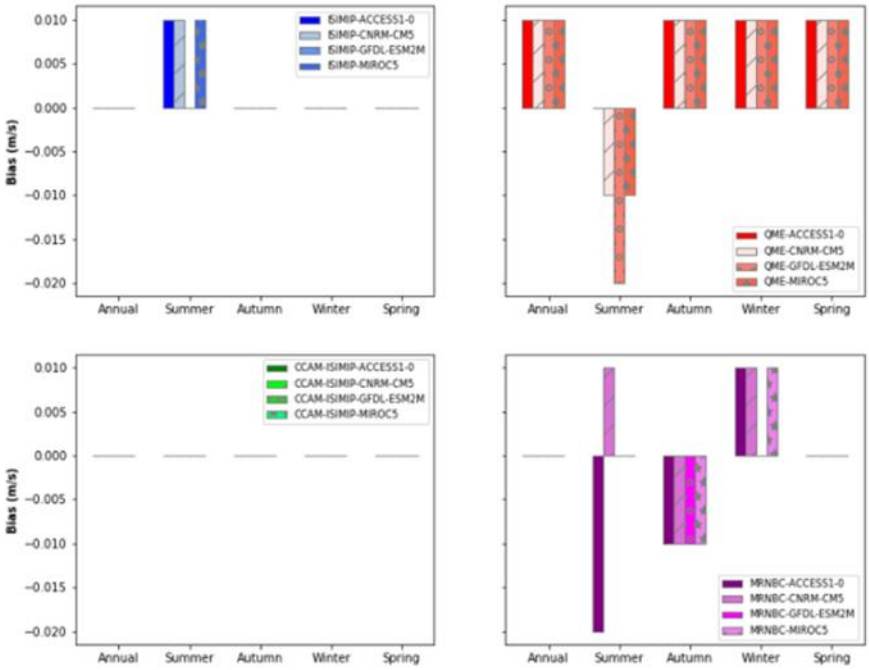

Figure 8.9. Bias (m/s) in mean annual and seasonal wind speed for the Southern Slopes region

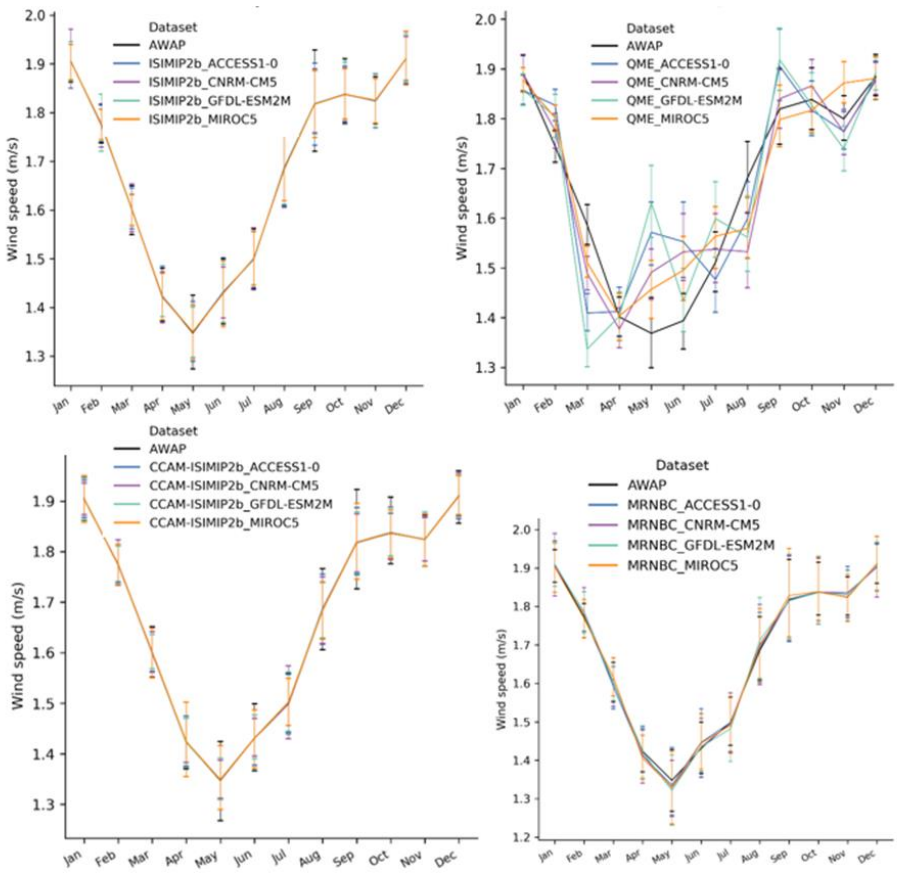

Figure 8.10. Comparison of the mean monthly wind speed (m/s) for the 16-member ensemble and observed (AWAP) data for the Southern Slopes region (1976–2005)

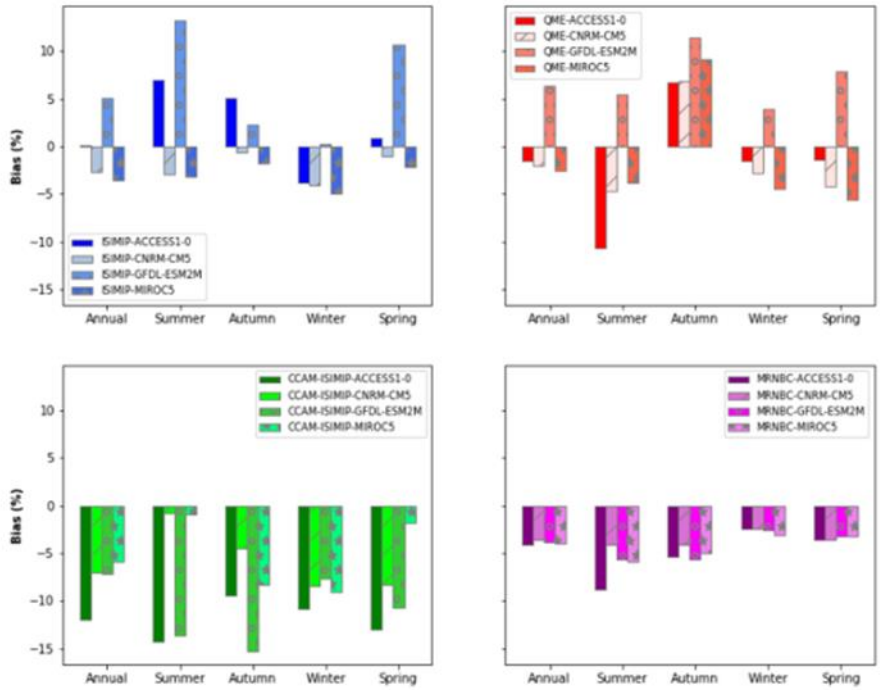

Figure 8.11. Bias (%) in mean annual and seasonal runoff for the Southern Slopes region

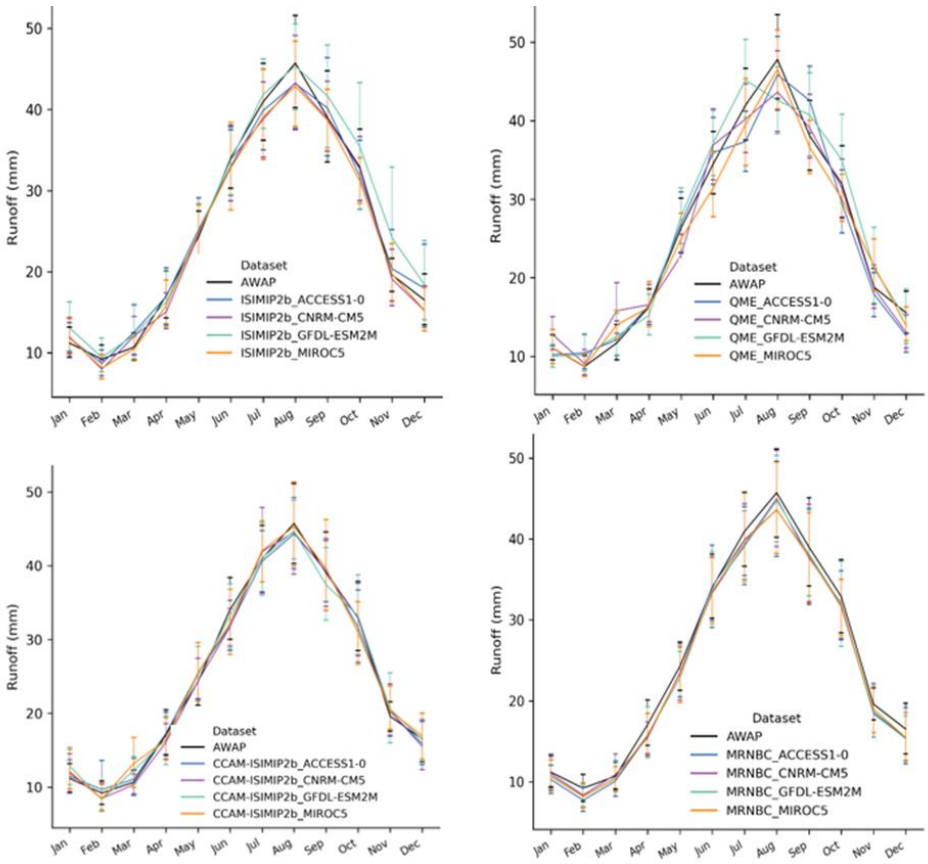

Figure 8.12. Comparison of the mean monthly runoff (mm) for the 16-member ensemble and observed (AWAP) data for the Southern Slopes region (1976–2005)

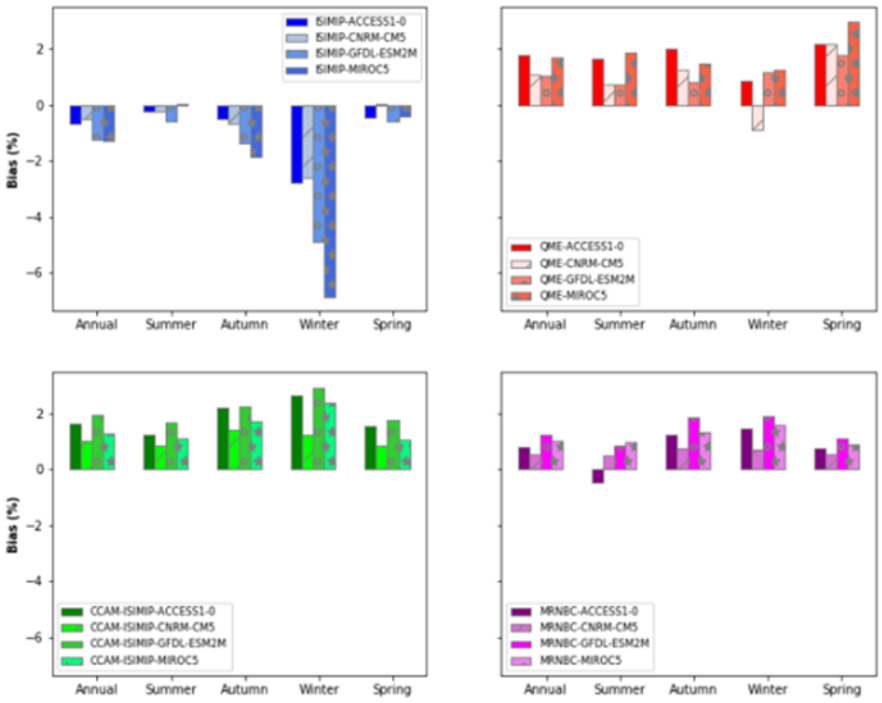

Figure 8.13. Bias (%) in mean annual and seasonal potential evapotranspiration for the Southern Slopes region

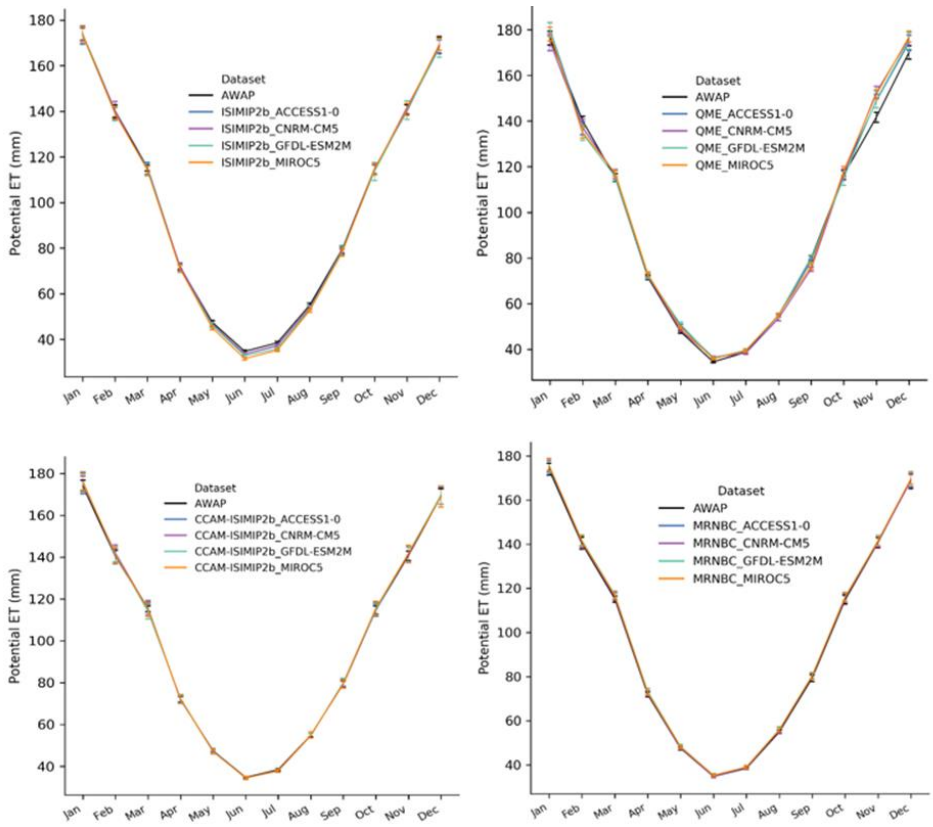

Figure 8.14. Comparison of the mean monthly potential evapotranspiration (mm) for the 16-member ensemble and observed (AWAP) data for the Southern Slopes region (1976–2005)

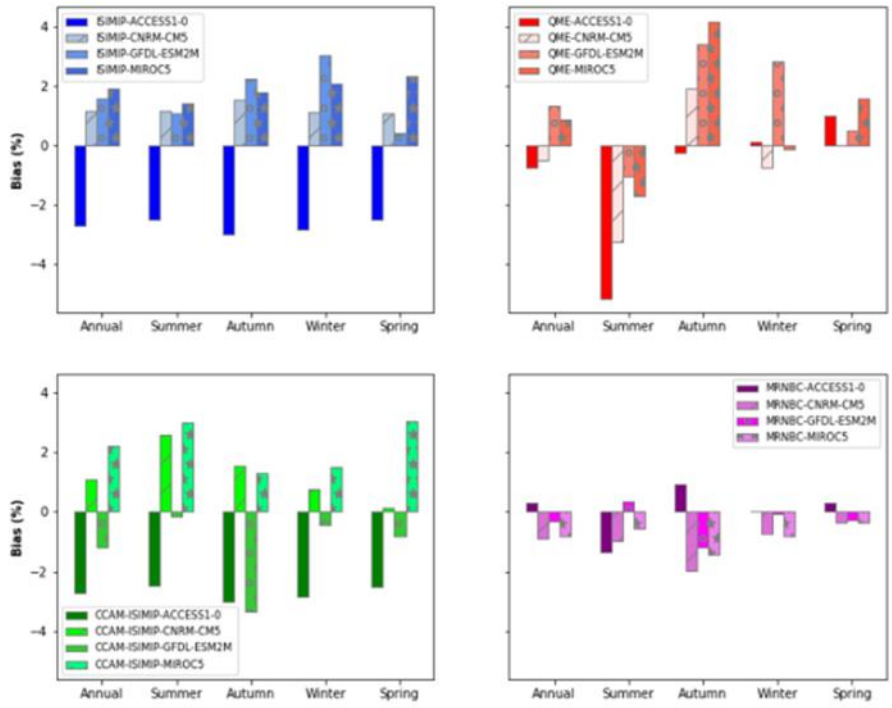

Figure 8.15. Bias (%) in mean annual and seasonal soil moisture for the Southern Slopes region

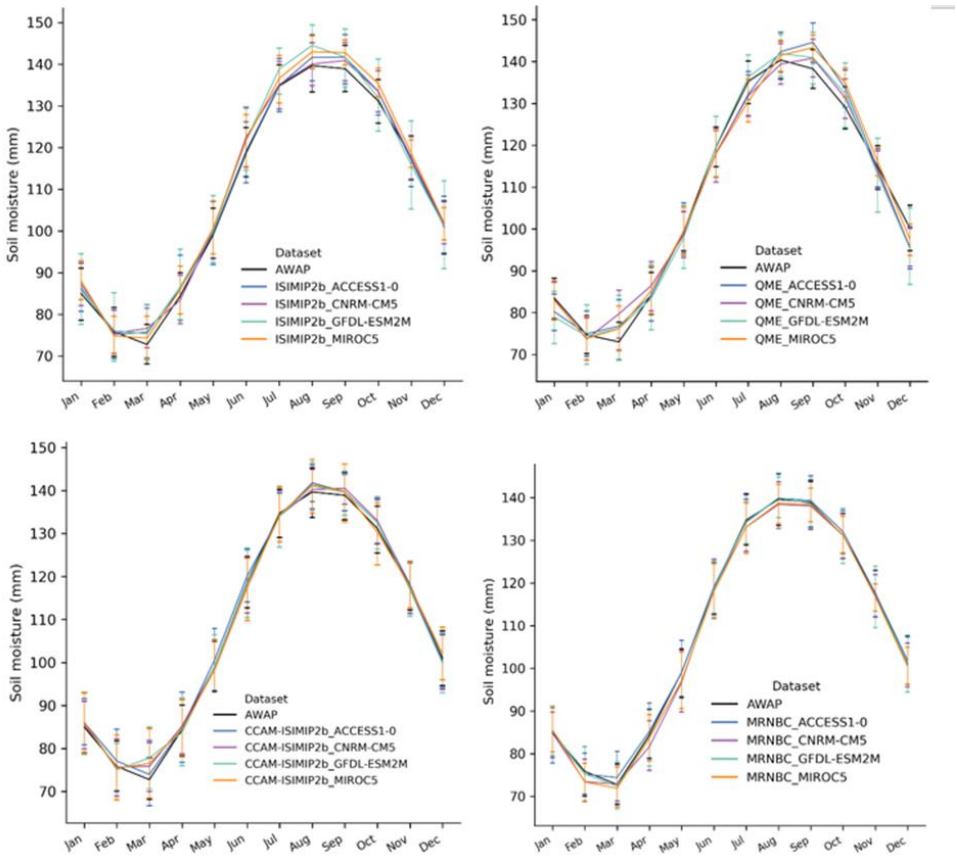

Figure 8.16. Comparison of the mean monthly soil moisture (mm) for the 16-member ensemble and observed (AWAP) data for the Southern Slopes region (1976–2005)