LAND AND WATER
www.csiro.au

CSIRO

Hydroclimate projections for Victoria at 2040 and 2065

Nicholas J Potter, Francis HS Chiew, Hongxing Zheng, Marie Ekström and Lu Zhang

Citation

Potter NJ, Chiew FHS, Zheng H, Ekström M and Zhang L (2016) Hydroclimate projections for Victoria at 2040 and 2065. CSIRO, Australia.
<https://publications.csiro.au/rpr/pub?pid=csiro:EP161427>

Contents

Figures

Tables

Acknowledgments

We acknowledge the project funding provided through the Victorian Climate Initiative (VicCI) by the Victorian Department of the Environment, Land, Water and Planning (DELWP).

Input into the scoping study developed for this report was provided by the VicCI Project Management Committee as well as the VicCI Steering Committee. In particular, the following people provided significant input: Rae Moran and Mike Manton (independent experts), Bertrand Timbal and Graham Hawke (Bureau of Meteorology), Jin Teng (CSIRO), and Geoff Steendam, Grace Mitchell and Sharon Davis (DELWP). A number of Victorian water corporations, through the Technical Reference Group convened by DELWP, provided useful feedback and input into the report. Jin Teng and David Post (CSIRO) provided additional reviews of/comments on the report.

The streamflow data were obtained from the Bureau of Meteorology Water Data Online, and are licensed under Creative Commons Attribution 3.0 Australia (CC BY 3.0 AU) License. State-specific attributions are: ACT data © ACT Environment Protection Authority, NSW data © State of NSW (DPI Water), Vic data © State of Victoria (Department of Environment, Land, Water and Planning), SA data © Crown in right of the State of South Australia.

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups (listed in Table 3) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

Key findings

This report presents hydroclimate projections for Victoria for 20 year periods centred around 2040 and 2065, prepared through the Victorian Climate Initiative (VicCI) for the Victorian Department of Environment, Land, Water & Planning (DELWP). The projections are based on the latest generation of global climate models (CMIP5) replacing the CMIP3 models that provided the change information for previous regional runoff projections prepared by the South East Australian Climate Initiative (SEACI) (Post et al., 2012). The large majority of CMIP5 models, like the CMIP3 models, indicate rainfall declines across Victoria, which will be amplified in the runoff.

Compared to the 2060 SEACI results (Post et al., 2012), the median projected change in runoff at 2065 is about 1/3 less dry in most cases, with a slightly larger range of results (in terms of the 10th and 90th percentile changes). This is primarily a direct response to the somewhat less dry regional rainfall projection from CMIP5 models relative to the CMIP3 models (CSIRO and Bureau of Meteorology, 2015, Figures A.2 and 7.2.5; **Figure 9** and **Figure 11**).

The spatial pattern of rainfall changes at 2040 and 2065 (**Figure 9** and **Figure 11**) is similar, with the response enhanced (i.e. more wet or dry) by 2065. The low-impact scenario has increases in rainfall over most of the study region, but with little to no increase in rainfall in the south-western part of the study region and the main runoff producing areas along the Great Dividing Range in Victoria. The high-impact scenario shows decreases over the entire study region, particularly in the western part. The medium-impact scenario shows some decreases in rainfall over most of Victoria, particularly in the second half of the year (i.e. winter and spring).

The projected medium-impact scenario change in regional potential evaporation (**Figure 10** and **Figure 12**) is a 4–6% increase in PET by 2040, and a 6–10% increase by 2065. The PET increase is driven mainly by rising temperatures. Unlike rainfall, the future PET projections are similar across GCMs and with little spatial variability across the region.

The spatial pattern of projected changes to runoff broadly follows the spatial pattern for rainfall changes. The medium-impact scenario shows runoff decreases of 5–15% over most of Victoria by 2040 and 10–30% by 2065, with comparatively larger reductions in the south-west. The low-impact scenario shows runoff increases over most of Victoria of 5–20% by 2040, reducing to little change by 2065. The high-impact scenario shows runoff decreases of greater than 20% over the entire study region by 2040, and greater than 40% in most regions (and over 50% decrease in runoff in the west), by 2065.

1 Introduction

Under the Statement of Obligations issued by the Victorian Water Minister to Victorian Water Corporations on 20 December 2015, Victorian water corporations are required to comply with any guidelines issued for forecasting the impact of climate change on water supplies issued by the Department. A key part of the guidance is expected to be a quantitative estimate of climate and runoff change into the future.

The Victorian Climate Initiative (VicCI) is a three-year regional climate initiative launched in May 2013 by the Victorian Department of Environment and Primary Industries (DEPI) – now the Victorian Department of Environment, Land, Water & Planning (DELWP) – and the research partners Bureau of Meteorology and CSIRO. This report presents projected changes in climate and runoff at 2040 and 2065 for Victoria relative to 1975–2014. These projections use empirical scaling of outputs from global climate models.

1.1 Previous runoff projections for Victoria

Over the past decade, at least three sets of runoff projections have been developed for the State of Victoria. These are: CSIRO/DSE projections in 2005 (Jones and Durack, 2005); SEACI projections in 2012 – described by Post and Moran (2011; 2013), Post et al. (2012) and Moran and Sharples (2011); and the projections for Australia's Natural Resource Management (NRM) regions covering Victoria (CSIRO and Bureau of Meteorology, 2015). The CSIRO/DSE projections were estimated using a sensitivity-based model. The Post et al. (2012) projections were based on empirically downscaled global climate models (GCMs) from the Coupled Model Intercomparison Project Phase 3 (CMIP3; Meehl et al., 2007), and a hydrological model. The NRM projections were based on Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012) model outputs directly forcing an annual Budyko-curve model (Zhang et al., 2004; Teng et al., 2012b), and with associated mean soil-moisture change estimates from a monthly supply-and-demand model (Zhang et al., 2008). The current report is an update of the projected changes previously estimated by Post et al. (2012). The main difference in the production of these projections and those by Post et al. (2012) is the use of the latest and larger set of GCMs of the CMIP5 archive relative to those of the CMIP3 archive.

1.2 Modelling procedure for runoff projections

Plausible impacts on surface runoff due to a warming atmosphere are typically assessed using a top-down modelling approach (Giorgi, 2008), which involves the following steps (Figure 1):

- Selection of emissions pathway(s)

- Modelling the global climate response to changing atmospheric greenhouse and aerosol concentrations
- Downscaling future GCM climate information to catchment scale from full GCM ensemble or a representative subset
- Hydrological modelling using the downscaled climate inputs.

Once projections of future runoff time series are obtained, different metrics can be produced that can inform potential impacts on regional runoff characteristics. Examples of such metrics are: projected change in annual/seasonal runoff, changes in high flows, low-flow spells, drought durations, etc. Further, runoff projections can potentially be used as input to water supply system models to provide estimates on system performance under climate change. It is important to note, however, that limitations of the downscaling method (in particular, empirical scaling as used here) mean that certain metrics cannot be adequately modelled. This is a topic of on-going research.

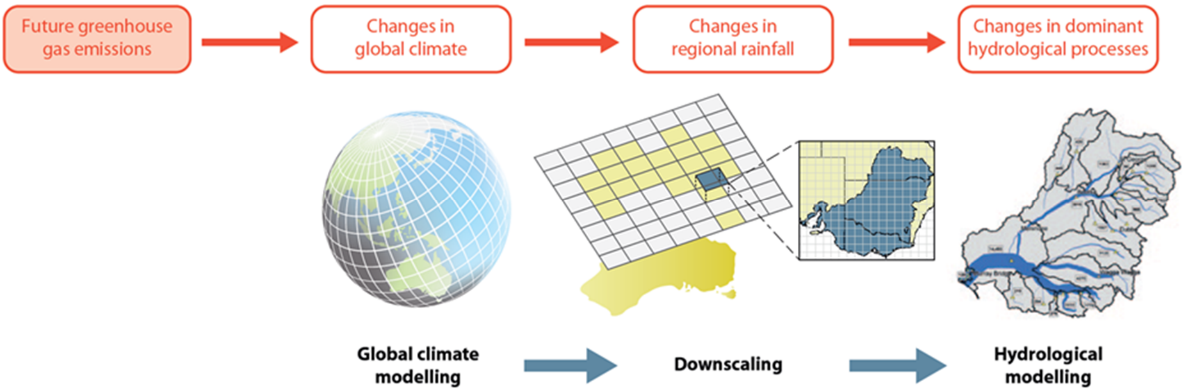


Figure 1 Top-down modelling for runoff projections (adapted from CSIRO, 2012, Figure 11)

2 Methods and data

2.1 Study region

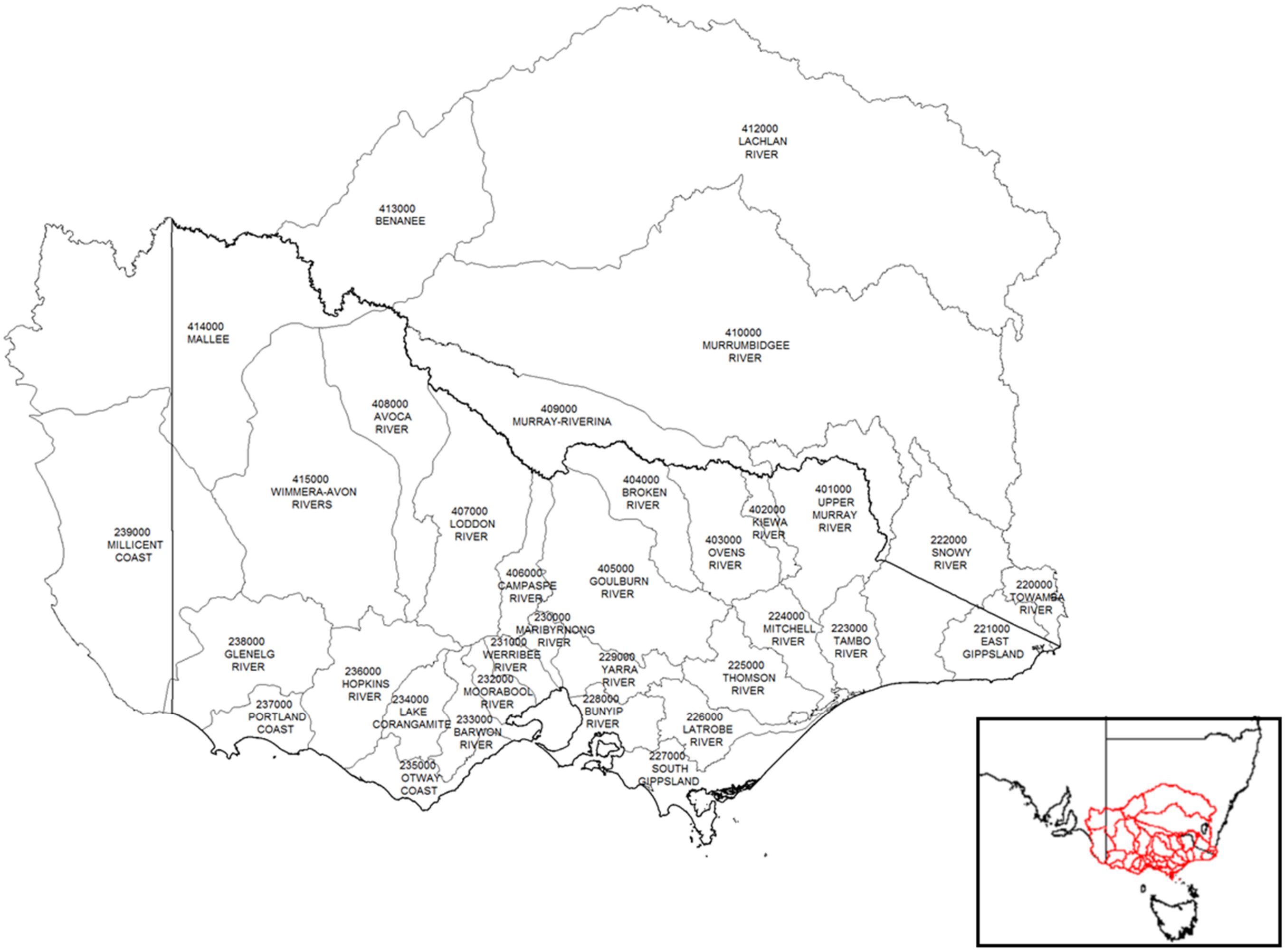


Figure 2 Study region showing reporting regions (Australian river basins)

The study region is shown in Figure 1. The State boundary of Victoria is shown as a darker line with the boundaries of Australian river basins, based on Australia's River Basins 1997 (www.bom.gov.au/water/about/riverBasinAuxNav.shtml), as lighter lines. The inset provides the location of the study region in south-eastern Australia. Any river basin intersecting Victoria was included, as well as the Murrumbidgee, Murray-Riverina, Lachlan and Benanee basins in order to assess some of the contributions to the Murray River flow originating outside Victoria. The basins and their approximate area are listed in Table 1.

Table 1 Drainage basins in the study region

BASIN ID	RIVER BASIN	APPROX. AREA (KM^2)
220000	Towamba River	2200
221000	East Gippsland	5600
222000	Snowy River	15800
223000	Tambo River	4200
224000	Mitchell River (Vic.)	4900
225000	Thomson River	6400
226000	Latrobe River	4700
227000	South Gippsland	6800
228000	Bunyip River	4100
229000	Yarra River	4100
230000	Maribyrnong River	1500
231000	Werribee River	2000
232000	Moorabool River	2200
233000	Barwon River	3800
234000	Lake Corangamite	4100
235000	Otway Coast	3900
236000	Hopkins River	10100
237000	Portland Coast	4000
238000	Glenelg River	12100
239000	Millicent Coast	34300
401000	Upper Murray River	15300
402000	Kiewa River	1900
403000	Ovens River	8000
404000	Broken River	7100
405000	Goulburn River	16900
406000	Campaspe River	4000
407000	Loddon River	15700
408000	Avoca River	14200
409000	Murray-Riverina	15000
410000	Murrumbidgee River	81600

BASIN ID	RIVER BASIN	APPROX. AREA (KM^2)
412000	Lachlan River	90900
413000	Benanee	21300
414000	Mallee	41500
415000	Wimmera-Avon Rivers	30400

2.2 Observed climate data

Gridded daily climate data were sourced from the Bureau of Meteorology at 0.05°×0.05° (approximately 5km×5km) resolution across the study region from the Australian Water Availability Project (AWAP; Jones et al., 2009). The variables that are used here are:

1. point rainfall (raw and recalibrated to monthly totals)
2. incoming solar radiation
3. vapour pressure at 9am and 3pm
4. maximum temperature
5. minimum temperature.

For this analysis, the recalibrated rainfall time series is used as a representation of observational rainfall. To provide AWAP gridded data, the raw rainfall data is spatially interpolated between rainfall gauges, and this can result in small discrepancies between monthly sums and the reanalysis end-of-month rainfall totals, hence the need for recalibration, in which the raw rainfall amounts are rescaled to equal the monthly total. An examination of the differences between raw and recalibrated rainfall suggests the two rainfall time-series are similar, which is expected in Victoria due to the high density of rainfall gauges.

Solar radiation, vapour pressure, minimum and maximum temperature are combined to produce areal potential evapotranspiration (PET) using Morton's (1983) wet area formulation (for details see, e.g., Van Dijk, 2010). These variables exist from 1950 onwards, with the exception of incoming radiation data, which is only available from 1990 onwards. In order to estimate pre-1990 potential evapotranspiration, monthly climatology values of incoming radiation are used. Figure 3 shows annual average recalibrated rainfall and derived PET for the period 1975–2014. Rainfall predominantly occurs in the uplands of the Great Dividing Range and follows a gradient decreasing towards the north-west of the study region. Potential evapotranspiration is more regular and is larger towards the northern part of the study region.

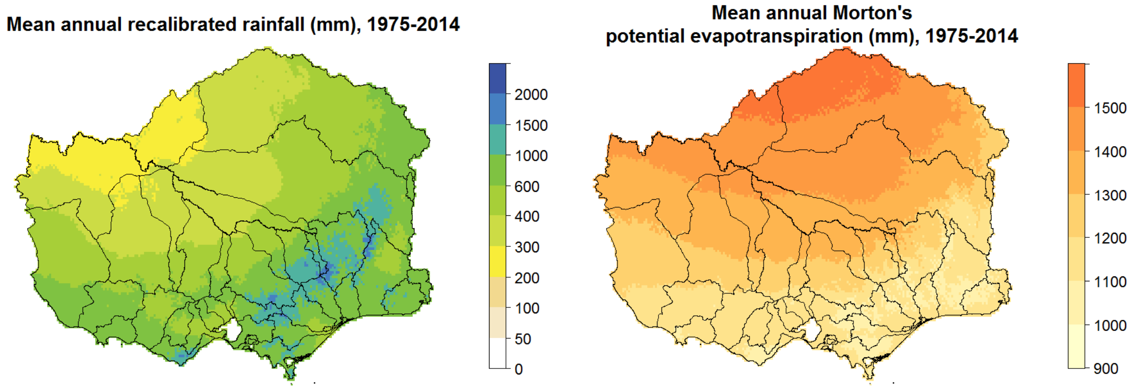


Figure 3 Annual average values of AWAP recalibrated rainfall and derived potential evapotranspiration over 1975–2014

2.3 Climate baseline and future scenarios

2.3.1 Baseline for historical climate observations

For the current projections, the baseline climate period is chosen as January 1975 – December 2014. The IPCC Third Assessment Report (IPCC, 2001) stated that the climate baseline 'should be representative of the present-day or recent average climate in the study region and of a sufficient duration to encompass a range of climatic variations, including several significant weather anomalies (e.g., severe droughts or cool seasons).' The high degree of hydroclimatic variability in south-eastern Australia, and particularly since average rainfall during the Millennium Drought was among the driest multi-year average in the historical record, makes the choice of climate baseline for Victoria somewhat problematic. Especially for drier catchments, the uncertainty arising from different definitions of the climate baseline can be of a similar order of magnitude to the uncertainty arising from GCM selection (Post and Moran, 2013; Moran and Sharples, 2011). The motivation for choosing the baseline climate period of 1975–2014 is discussed below.

Choosing a representative baseline climate is a trade-off between: (1) having the climate baseline representative of the current climate, as informed by historical data and our understanding of climate change impact on rainfall, temperatures and potential evaporation; (2) having a sufficiently long baseline period to average out interannual variability due to, for example, El Niño events. The World Meteorological Organisation (WMO) suggests defining climate baselines of at least 30 years in duration. Timbal et al. (2016) provide a detailed analysis of the last 30-years climate in terms of the historical record. In short, the last 30-years has been unusually warm and with significant dry cool season rainfall.

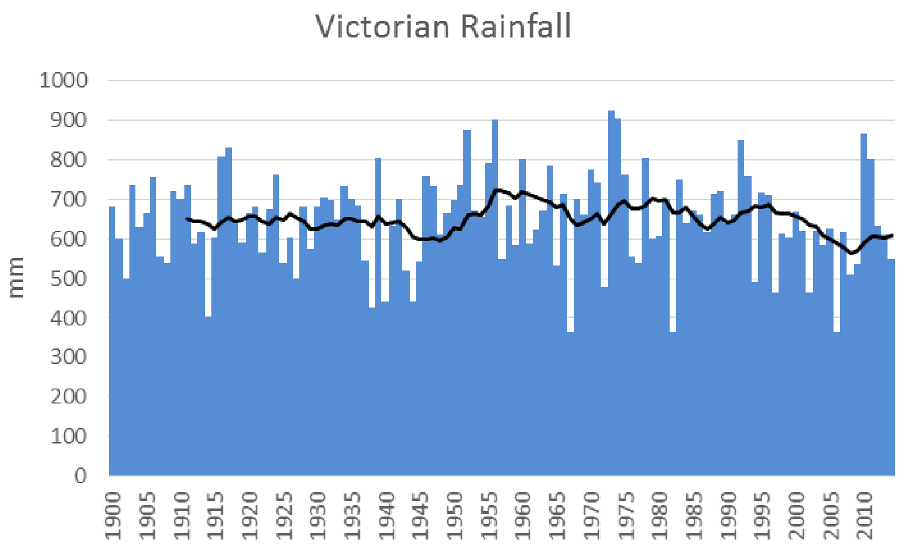


Figure 4 Annual historical rainfall for Victoria. The 12-year moving average is shown as a black line

Figure 4 shows annual rainfall in Victoria, based on data from the Bureau of Meteorology (2015). Two main inter-decadal features are evident: a period of increased inter-decadal variability after the 1940s, and the two severe and prolonged droughts, namely the "World War II Drought" (around the 1940s) and the "Millennium Drought" (1997–2009). Annual rainfall averaged over selected time periods of interest is shown in Table 2.

Table 2 Mean annual rainfall for Victoria for different time periods (taken from Bureau of Meteorology climate data)

DESCRIPTION	TIME PERIOD	MEAN ANNUAL RAINFALL(MM)	RELATIVE DIFFERENCE FROM LONG-TERM MEAN ANNUAL RAINFALL (%)
Millennium drought	1997–2009	561.3	−13%
MDBSY* calibration period	1975–2006	630.4	−3%
IPCC AR5 climate baseline extended	1986–2014	630.9	−3%
MDBSY extended	1975–2014	632.3	−2%
IPCC AR5 climate baseline	1986–2005	640.4	−1%
IPCC AR4 climate baseline extended	1961–2014	643.5	−1%
Entire BoM record	1900–2014	647.9	0%
Post-1950s	1950–2014	656.9	1%
IPCC AR4 climate baseline	1961–1990	660.2	2%
Negative IPO phase	1950–1985	677.9	5%
Post-Millennium drought	2010–2014	691.7	7%

* Murray-Darling Basin Sustainable Yields project (CSIRO, 2008; Chiew et al., 2008, 2009c).

From Table 2, we see that 1950–1985 (which roughly corresponds with a distinct negative IPO phase) is among the wettest periods, with 5% more mean annual rainfall than the long-term average; this period also corresponds to the period of the most growth of major water storages in the MDB (CSIRO, 2008). The Millennium Drought is the driest period of those considered, with a

13% reduction in mean annual rainfall, which was accompanied by large reductions in runoff occurring in the southern MDB (Potter et al., 2010) and southern Victoria as well (Chiew et al., 2014).

The IPCC climate baseline during the fourth assessment report (AR4) was 1961–1990, which corresponds to a relatively wet period in Victoria (Table 2; Chiew et al., 2009a). This climate baseline has subsequently been updated for the fifth assessment report (AR5) to 1986–2005 (IPCC, 2013, p. 1034), which was also used by CSIRO and Bureau of Meteorology (2015). The IPCC AR5 climate baseline is slightly drier than the long-term average, with 1% less mean annual rainfall (Table 2). The time period 1975–2006 was used as a hydrological model calibration period for the Murray-Darling Basin Sustainable Yields project (Chiew et al., 2008; 2009c), mainly as it was considered a long enough time period for hydrological model calibration, but short enough to have a relatively small land-use and infrastructure change component.

Apart from the WMO recommendation, there is a strong argument for choosing a baseline climate period in Australia of at least 30–40 years, rather than the 20 year period chosen by the IPCC for AR5. This is due to the higher interannual variability of rainfall and runoff in Australia (e.g. Peel et al., 2004) compared to similar climate zones around the world. The IPCC's AR5 states that it is 'likely' that anthropogenic influences have altered the global hydrologic cycle (IPCC, 2013). Research in SEACI and VicCI have confirmed the role of climate change in influencing rainfall patterns for Australia, particularly the 'expansion of the tropics' (e.g. CSIRO, 2012). This suggests that a recent baseline is more appropriate than a longer baseline covering the first half of the 20th century. The baseline of 1975–2014 is chosen for the current projections. In terms of annual rainfall, this baseline time period is similar to the baseline from most other relevant studies (Table 2), and captures a greater amount of recent variability including the full extent of the Millennium Drought, ongoing cool-season rainfall declines, as well as the 2010 heavy rainfall events.

2.3.2 Target dates, representative climate periods and emissions scenarios for future climates

Deriving downscaled climate information for hydrological projections involves selecting not just the downscaling method (see section 2.5), but also the target dates for projections, emissions scenarios and representative climate periods for the target dates. To develop the projections for Victoria, it was agreed in discussion with DELWP on their user needs that target dates for projections should be 2040 and 2065. The regional projections for Victoria was developed as follows:

- Scaling factors were derived as distributional differences (see details in section 2.5) between GCM current and projected climate. The GCM current climate is taken as the model simulations for the 20-year period 1986–2005 and the future periods are thus two 20-year periods centred on the target years: 2040 and 2065, namely 2031–2050 and 2056–2075. The years of the current climate and the length of the future periods are chosen to be consistent with projections of the AR5 (IPCC, 2013) and recent national projections (CSIRO and Bureau of Meteorology, 2015).
- To produce regional time series of required climate variables, scaling factors were applied to observed gridded data for the period 1975–2014. Applying the scaling factors to a 40 year-period allows for a better representation of decadal variability in the regional climate.

- Finally, projected changes to streamflow were estimated as differences between streamflow estimates for the observed baseline period 1975–2014 and the two 40-year time series scaled according to the climate change signal for 1986–2005 relative to 2031–2050 and 2056–2075.

The future climate projections in CMIP5 are conducted in three phases. The first phase covers the start of the modern industrial period through to the present day (1850–2005). The second phase covers the 'future' (2006–2100), and is described by a collection of emission pathways, called 'Representative Concentration Pathways' (RCPs) in the IPCC AR5 report (Moss et al., 2010; van Vuuren, 2011; IPCC, 2013). The third phase (covering 2100–2300), which is not used here, is described by a corresponding collection of Extended Concentration Pathways (Meinshausen et al., 2011).

The IPCC AR5 has four emissions pathway scenarios: RCP2.6 (equivalently RCP3-PD); RCP4.5; RCP6.0 and RCP8.5, which are discussed at length in the IPCC (2013) AR5 report, as well as by van Vuuren (2011) and Rogelj (2011). The RCPs are named after their respective radiative forcing by 2100 relative to pre-industrial levels, and are roughly 2.6 Wm^{-2} (RCP2.6/RCP3-PD, strong mitigation, and decline of radiative forcing past 2100), 4.5 Wm^{-2} (RCP4.5, medium-low radiative forcing, stabilisation at 2100), 6.0 Wm^{-2} (RCP6, medium-high radiative forcing, stabilisation at 2100), and 8.5 Wm^{-2} (RCP8.5, high radiative forcing, which reaches 8.5 Wm^{-2} by 2100 and continues increasing afterwards). RCP4.5 and RCP8.5 are often chosen to represent mid- and high level emission scenarios for climate mitigation and adaptation studies.

Earlier research noted by Moran and Sharples (2011) suggested that, at that time, observed global greenhouse gas emissions were tracking either the IPCC AR4 A1FI or A1B scenarios. In terms of global temperature increase by the end of the 21st century, A1FI corresponds roughly to RCP8.5, and A1B corresponds roughly to RCP6 (Rogelj et al., 2012; IPCC, 2013). In turn, the expected median global temperature increase by 2100 relative to 1988–1999 is around 4.4°C for RCP8.5, 2.5°C for RCP6.0 and 1.9°C for RCP4.5 (Rogelj et al., 2012, Table 2). More recent data (Peters et al., 2013; Friedlingstein et al., 2014) also have current and near-future GDP-growth-based projections (2010–2019) tracking at the higher end of the IPCC emissions scenarios (i.e. RCP8.5).

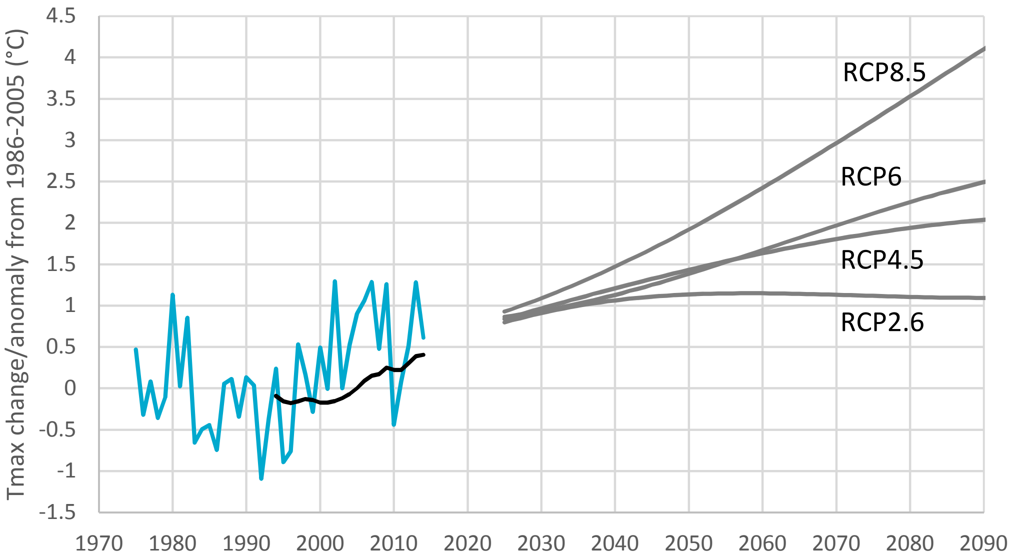


Figure 5 Projected mean warming in the Murray Basin throughout the 21st century based on CMIP5 multi-model ensemble

Figure 5 shows the maximum temperature anomaly (relative to 1986–2005) historically for the Murray Basin based on the AWAP historical climate data (blue line), a 20-year moving average (black line) and average anomalies from the CMIP5 multi-model ensemble for the four RCPs (data from the Climate Futures Tool, CSIRO and Bureau of Meteorology, 2016; grey lines). Figure 5 shows that by 2040, there is little difference in terms of global temperature increase between the three lowest emissions scenarios, with warming around 1.1–1.2°C above 1986–2005, whereas RCP8.5 has an expected temperature increase of around 1.5°C. By 2065, there is a larger difference between scenarios, reflecting the climate response to the different concentration rates of greenhouse gas and aerosol forcing as time progresses. However, both RCP4.5 and RCP6 converge around this time with an expected increase of 1.7°C. RCP8.5 at 2065 has an expected increase of around 2.7°C.

The choice of emissions scenario is related to the presentation of the range of model outcomes. Moran and Sharples (2011) note that there are two ways of defining the range of model outcomes, namely the 'warming-weighted' and the 'impact-weighted' approaches. The warming-weighted approach selects the lowest impact, typically as the 10th percentile (i.e. wet response), model outcome from the scenario with the least warming, and the highest impact as the 90th percentile (i.e. dry response) model outcome from the scenario with the most warming. In contrast, the impact-weighted approach chooses the wettest and driest impacts from amongst all different scenario/model combinations.

Previous experience (Post and Moran, 2011; 2012) suggests that under the impact-weighted method, the driest and wettest impacts both occur from the emissions scenario with the greatest amount of warming (i.e. RCP8.5), since more warming typically results in an intensification of the hydrological cycle.

In light of the fact that the extreme (i.e. 10th and 90th percentile) impacts are likely to occur under the RCP8.5 scenario, and also since current emissions are currently tracking very close to RCP8.5, this scenario is selected for the current projections. The low-impact scenario is then taken

as the 10th percentile of model results, the medium-impact scenario as the median and the high-impact scenario as the 90th percentile. As suggested by Moran and Sharples (2011), alternative 'weaker' scenarios (e.g. RCP4.5 and RCP6) can be considered using the impact-weighted approach by recasting the impact under RCP8.5 at an earlier or later date. This depends on the validity of the 'pattern-scaling hypothesis', which assumes that there is no qualitative difference in the RCP scenarios, and the eventual hydroclimate impact of climate change is related primarily to global temperature increase. As a hypothetical example, for future emissions following RCP6, the projected impact at 2040 under RCP8.5 is simply delayed by 10–15 years, and this information can inform the timing of adaptation responses. The pattern-scaling hypothesis, and uncertainty from the choice of emissions scenario, is examined in more detail in Appendix B .

2.4 CMIP5 global climate models (GCMs)

The range of future climate scenarios in this report is derived from the CMIP5 database (http://cmip-pcmdi.llnl.gov/cmip5/) used for reporting in the IPCC AR5. CMIP5 (the fifth phase of the Coupled Model Inter-comparison Project) is sponsored by WCRP's Working Group on Coupled Modelling (WGCM) with input from the IGBP AIMES project (Taylor et al., 2012). It involves global climate model experiments from more than 20 climate modelling groups around the world. CMIP5 provides an ensemble of model simulations that can be used to assess the models' ability in simulating the recent past, to provide projections of future climate change, and to understand factors responsible for differences in model projections. Table 3 summarises the 42 CMIP5 GCMs. The range of future climate scenarios presented in this report are derived from the 42 CMIP5 GCMs available on 15 March 2013, i.e. the same as that adopted by IPCC AR5.

Table 3 The 42 CMIP5 models used to derived the range of future climate projections

ID	MODEL	APPROXIMATE RESOLUTION (LONG. × LAT.)	MODELLING CENTRE (OR GROUP)
G01	ACCESS1-0	1.875×1.25	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia
G02	ACCESS1-3	1.875×1.25	
G03	BCC-CSM1-1-M	2.8125×2.7906	Beijing Climate Center, China Meteorological Administration
G04	BCC-CSM1-1	2.8125×2.7906	
G05	BNU-ESM	2.8125×2.7906	College of Global Change and Earth System Science, Beijing Normal University
G06	CANESM2	2.8125×2.7906	Canadian Centre for Climate Modelling and Analysis
G07	CCSM4	1.25×0.9424	National Center for Atmospheric Research
G08	CESM1-BGC	1.25×0.9424	Community Earth System Model Contributors
G09	CESM1-CAM5	1.25×0.9424	
G10	CESM1-WACCM	2.5×1.8848	
G11	CMCC-CESM	3.75×3.4431	Centro Euro-Mediterraneo per I Cambiamenti Climatici
G12	CMCC-CMS	3.75×3.7111	
G13	CMCC-CM	0.75×0.7484	

ID	MODEL	APPROXIMATE RESOLUTION (LONG.× LAT.)	MODELLING CENTRE (OR GROUP)
G14	CNRM-CM5	1.40625×1.4008	Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique
G15	CSIRO-MK3-6-0	1.875×1.8653	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence
G16	EC-EARTH	1.125×1.125	EC-EARTH consortium
G17	FGOALS-G2	2.8125×2.7906	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS,Tsinghua University
G18	FGOALS-S2	2.8×1.659	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences
G19	FIO-ESM	2.81×2.76	The First Institute of Oceanography, SOA, China
G20	GFDL-CM3	2.5×2.0	NOAA Geophysical Fluid Dynamics Laboratory
G21	GFDL-ESM2G	2.0×2.0225	
G22	GFDL-ESM2M	2.5×2.0225	
G23	GISS-E2-H-CC	2.5×2.0	NASA Goddard Institute for Space Studies
G24	GISS-E2-H	2.5×2.0	
G25	GISS-E2-R-CC	2.5×2.0	
G26	GISS-E2-R	2.5×2.0	
G27	HADGEM2-AO	1.875×1.25	National Institute of Meteorological Research/Korea Meteorological Administration
G28	HADGEM2-CC	1.875×1.25	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)
G29	HADGEM2-ES	1.875×1.25	
G30	INMCM4	2.0×1.5	Institute for Numerical Mathematics
G31	IPSL-CM5A-LR	3.75×1.8947	Institut Pierre-Simon Laplace
G32	IPSL-CM5A-MR	2.5×2.5352	
G33	IPSL-CM5B-LR	3.75×1.8947	
G34	MIROC-ESM-CHEM	2.8125×2.7906	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
G35	MIROC-ESM	2.8125×2.7906	
G36	MIROC5	1.40625×1.4008	
G37	MPI-ESM-LR	1.875×1.8653	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)
G38	MPI-ESM-MR	1.875×1.8653	
G39	MRI-ESM1	1.125×1.12148	Meteorological Research Institute
G40	MRI-CGCM3	1.125×1.12148	
G41	NORESM1-ME	2.5×1.8947	Norwegian Climate Centre
G42	NORESM1-M	2.5×1.8947	

Multi-model ensembles of climate models typically perform better than any one particular model (IPCC, 2013). Nevertheless, for applications, GCMs are often screened for their ability to represent the regional climate. Knutti et al. (2010b) suggest that eliminating models in this way can be beneficial for regional assessments, however they note that there are ‘no simple rules or criteria to define this’. Much research has been undertaken in rating the CMIP3 GCMs for their ability to represent historical climate (e.g. Smith and Chandler, 2009; Vaze et al., 2010; Kirono and Kent,

2011; CSIRO, 2012; McMahon et al., 2015a). In general, different selection criteria result in different model subsets, and no particular model has been found to be consistently better at modelling relevant climate variability in south-eastern Australia. Previous research has suggested that the changes in projected hydroclimatic variables tend not to be very different if weightings are applied to GCMs, or subsets of GCMs are used, although sometimes the range of results is reduced (e.g. Smith and Chandler, 2009; McMahon et al., 2015a). Other studies (e.g. Chiew et al., 2009b; Teng et al., 2012a; Westra et al., 2014a; 2014b) found that using GCMs that perform better in reproducing the historical climate does not actually reduce the range of results, particularly when the climate projections are subsequently downscaled. This is perhaps due to the fact that a GCM skilful in reproducing historical climate does not necessarily result in more skilful simulations of future climates (Knutti et al., 2010a).

CSIRO and Bureau of Meteorology (2015) outline a comprehensive assessment of a subset of the CMIP5 models' ability to simulate temperature, precipitation and climate features (e.g. ENSO, IOD) across Australia (see also Timbal et al., 2016). CMIP5 models generally underpredict winter rainfall in Southern Australia, although it is noted that this effect is mostly confined to Tasmania. The report outlines a number of deficiencies in certain models (CSIRO and Bureau of Meteorology, 2015, Table 5.6.1), although this is assessed over Australia as a whole, rather than Victoria and south-east Australia explicitly. Recently, however, Grose et al. (2015), and related work in Project 5 of VicCI, examined CMIP5 climate models performance from the perspective of modelling the subtropical ridge (STR), an important controlling influence in winter storm-tracks in southern Australia. Generally, CMIP5 models project an increase and shift in the STR, which would tend to decrease cool-season rainfall, although the observed relationships between the STR and Victorian rainfall are not modelled well by the CMIP5 GCMs (Grose et al., 2015). However, eliminating the six poorest models in terms of STR does not appreciably change rainfall projections (Grose et al., 2015).

The ability of CMIP5 models to simulate prolonged long-term droughts (as characterised by the length of runs of no wet months) comparable to the Millennium Drought was examined in Project 5 of VicCI (Hope et al., 2015). While projected long-term droughts are present in the 21st century model runs, the duration of these droughts are all shorter than the Millennium Drought. Further, there was no significant difference between the modelled length of dry periods in the 20th and 21st centuries. These findings suggest that CMIP5 modelling runs may underestimate cool season rainfall reductions and prolonged drought occurrences.

In their final analysis, CSIRO and Bureau of Meteorology (2015) do not exclude or weight GCMs due to 'possible detrimental effects' to the multi-model ensemble. The GCM evaluation can however assist in individual climate model selection for impact studies, and particularly when selecting model representative of a particular change signal via the climate future web tool (CSIRO and Bureau of Meteorology, 2016). In light of these observations, we chose to use all available GCMs in the multi-model ensemble in preparing the current hydroclimate projections. The low impact scenario (i.e. 10th percentile of model results), medium (50th percentile), and high impact scenarios (90th percentile) are presented below to represent the range of response, and the most likely outcome.

2.5 Empirical downscaling of climate variables

Downscaling refers to the process of disaggregating climate data from GCMs to a finer spatial resolution in order to provide regionalised climate information (Ekström et al., 2015). Due to their finer resolution, downscaled projections are considered more usable for hydrological models, which simulate processes on much finer scales than GCMs.

Downscaling involves many fundamentally different approaches to achieve a finer resolved climate projection (e.g. Fowler et al., 2007; Chen et al., 2011; Ekström et al., 2015). Briefly, downscaling methods can be categorised as: (1) 'empirical' downscaling, or 'change-factor methods', which relate changes in the distribution of historical GCM climate variables to future GCM climate variables, and then apply these changes to observed climate; (2) statistical downscaling methods, which develop a statistical relationship between GCM atmospheric variables and observed climate variables, and then apply that relationship to derive future climate variables from future GCM variables; and (3) dynamical downscaling methods, where regional climate models (RCMs) are used, which model the physical climatic processes at smaller spatial scale informed by a larger-scale GCM. Sometimes empirical scaling methods are classified as statistical downscaling approaches, but it is useful to separate these methods as they are really based on different conceptual approaches. Empirical scaling methods vary in the nature of the change factors used (i.e. from a simple linear factor to probability distribution transformations).

A fundamental assumption for all statistical downscaling methods is that any derived relationships remain constant into the future. Of course, without, or even with the benefit of, additional knowledge (such as may be derived from physically based climate models), this assumption is difficult to verify (Giorgi, 2008). Dynamical downscaling provides localised climate information using a physically based method (Torma et al., 2015; Rummukainen, 2016). However, bias can be high using these methods (e.g. Wilby et al., 2000; Piani et al., 2010; Teng et al., 2015) owing to model assumptions and the fact that such methods are not explicitly calibrated to rainfall station data. However, dynamical downscaling methods may be better suited to explore the effect of changes in hydroclimatic processes than scaling or statistical methods. It is also recognised that success in downscaling is dependent on the skill of GCMs in reproducing relevant climate characteristics (Ekström et al, 2015).

Many downscaling comparisons exists (e.g. Fowler et al., 2007; Chen et al., 2011). In European studies, winter rainfall is generally more successfully downscaled than summer rainfall, and rainfall in wetter climates is more easily downscaled than in drier climates (Fowler et al., 2007; Haylock et al. 2006). Although there is a range of results, most studies generally conclude that no single downscaling method is best, and this is largely because, like with GCMs, different downscaling methods are developed with particular purposes in mind and by researchers with different disciplinary backgrounds. Fundamentally, the choice of downscaling method needs to be principally determined by the end use of the climate information, and uncertainty resulting from this choice needs to be communicated (Fowler et al., 2007; Chen et al., 2011).

In an Australian context, Frost et al. (2011) recommends using empirical scaling methods for regional water resource planning applications, due principally to the method's robustness. Chiew et al. (2010) found that projected rainfall and runoff characteristics from daily empirical scaling typically lie within the range of other regionally available downscaling methods (i.e. statistical and

dynamical downscaling). For this reason and because the method is easily applied to the entire CMIP5 ensemble range, the empirical scaling method is employed here.

Timbal et al. (2016) show that an alternative downscaling method, the analogue statistical downscaling method (SDM), gives a somewhat different projected rainfall decline for south-eastern Australia compared to the raw CMIP5 model ensemble. The findings from Teng et al. (2012c) also suggested that SDM tends to provide a narrower range of change in rainfall than the raw GCMs but introduces more uncertainty. Using the SDM downscaled data to derive runoff projections is thus expected to produce drier runoff projections compared to empirical downscaling as is used in this report. However, as other downscaling methods for this region suggest somewhat different ranges of rainfall change in this region we note that further regional assessment of the change signal of rainfall is warranted (Ekström et al., 2016).

2.6 Deriving empirical downscaling factors

The empirical downscaling method used here is known as 'daily scaling', and the scaling occurs in three steps (two for potential evapotranspiration). The first step is scaling the daily distribution of historical rainfall to match the future GCM changes in daily distribution as described below. The second step is scaling the daily scaled rainfall (and the historical PET) to match seasonal changes (seasonal scaling). The third and final step is scaling both time-series so that the change in annual totals matches the future GCM changes in annual totals of both rainfall and PET. The PET for each GCM grid is estimated from the solar radiation, maximum and minimum temperatures, and actual vapour pressure data using Morton's wet environment or equilibrium evaporation formulation (see section 2.2).

The empirical scaling factor is defined as the change in future climate condition relative to current (or historical) climatology. Once derived, the scaling factors are applied to a historical time series of climate data (in this case the baseline historical climate data of 1975–2014) to produce sequences of future climate at each AWAP grid cell. As noted in section 2.3.2, the historical climate is represented by the GCM simulations for the period 1986–2005, while the future climate is represented by two periods: 2031–2050 and 2056–2075 respectively. The empirical scaling factors for the rainfall and potential evapotranspiration are expressed as the ratio of change,

$$SF = X_f / X_h \tag{1}$$

where X_f and X_h are the GCM simulation for the future and historical periods. The scaling factors for each of the GCMs are re-gridded (from Table 3 the GCMs have different horizontal spatial resolutions) so that the scaling factors for each GCM correspond to the common 5 km x 5 km AWAP climate data grid.

In order to capture future changes to the distribution of rainfall amounts (not just the annual and seasonal means), 53 daily scaling factors are firstly calculated for each season. The first 50 daily scaling factors represent the change in the maximum daily rainfall amount, through to the 50th highest daily rainfall amount. The 51st factor represents the change in rank 51–100 rainfall, the 52nd factor is for change in rank 101–200 rainfall and the 53rd is for the remainder of the rainfall

amounts. In applying these daily factors to historical data, the factors are applied to the nearest whole percentiles of the historical data.

Seasonal and annual scaling factors are calculated for both rainfall and potential evapotranspiration. In order to assume that total annual change is the same to that when only an annual scaling factor is used, the seasonal scaling factors for each season are 'rescaled' as:

$$SF_i' = SF_i \frac{SF_a X_h}{\sum SF_i X_{hi}} \qquad (2)$$

Where SF_i and SF_i' are original and rescaled seasonal scaling factors respectively; SF_a is the annual scaling factor. X_{hi} is the total rainfall or potential evapotranspiration for each season. This seasonal and annual scaling is applied to both the daily scaled rainfall (as described above) and PET. In this way, the changes in seasonal and daily characteristics (for rainfall) are scaled as informed by the projected GCM changes while ensuring that the projected annual changes are also maintained.

2.7 Hydrological modelling

There are several lumped conceptual hydrological models commonly used to model runoff for Australia (e.g. Vaze et al., 2011). These include SIMHYD, AWBM, Sacramento, GR4J, SMARG, and IHACRES, each varying in conceptual design. The number of parameters to calibrate also varies, ranging from four for GR4J through to 14 for Sacramento. Testing these models across south-eastern Australia found GR4J and Sacramento performed best, although there is little difference in performance among the rainfall-runoff models studied (Vaze et al., 2011). The uncertainty from choice of hydrological model is relatively small compared to the uncertainty in the future rainfall projections from GCMs. For this reason, a simple hydrological modelling approach is sufficient. Since projections are required mainly at selected catchments/basins, it is best to use one of the more commonly-used models (such as SIMHYD) calibrated against observed streamflow in these catchments.

The change in future runoff is influenced by the change in climate inputs as well as any possible change in the climate-runoff relationship (i.e. hydroclimate or hydrologic non-stationarity, see for example Chiew et al. (2014)). For these projections we model changes in runoff due to changes in climate inputs and do not account for hydrologic non-stationarity. In modelling runoff change resulting from change in climate inputs, the largest uncertainty tends to come from the uncertainty in future rainfall projections, rather than the uncertainty from choice of hydrological model. Westra et al. (2014c), Teng et al. (2012a) and others show that the uncertainty in modelled future runoff resulting from the uncertainty in GCM rainfall projection is four to five times larger than the uncertainty from rainfall-runoff model selection and hydrological non-stationarity. Nevertheless, uncertainty of hydrological response increases in the more distant future when hydrological models developed and calibrated using past observations further are extrapolated into the future under significantly warmer and higher CO_2 conditions (Chiew et al., 2015). The effect of hydrological non-stationarity is an important ongoing research project, and further research is required.

For the current projections, runoff is modelled using the SIMHYD rainfall-runoff model (Chiew et al., 2002), with Muskingum routing. Ninety catchments in and around Victoria were chosen as

calibration catchments (Table 4). These were selected from a list of suitable calibration catchments for the AWRA project (Zhang et al., 2013). The AWRA calibration catchments were selected to be unregulated (i.e. no large upstream dams or reservoirs), have at least 10 years data between 1975 and 2011, and are of at least 50 km^2 in size, with no major irrigation or land use impacts. These catchments are listed in Table 4. Parameters were calibrated to 1975–2014 streamflow data using the Shuffled Complex Evolution method (Duan et al., 1992), a widely used hydrological parameter calibration routine, with the bias-penalised Nash-Sutcliffe Efficiency objective function following Viney et al. (2009). Two of the catchments, which are not shown in Table 4, initially selected from the AWRA calibration catchments were deemed to have unsuitable parameter calibration in terms of reproducing the observed streamflow and were excluded. Figure 6 shows the distribution of calibration Nash-Sutcliffe Efficiency. Half of the catchments have calibration NSE greater than 0.73, and 80% of the catchments have calibration NSE greater than 0.63. For runoff simulation in ungauged areas, parameters are taken from the closest calibration catchment, as determined by Voronoi polygons around the catchment centroids (Figure 7).

Table 4 Calibration catchment details
Rainfall, PET and streamflow means are calculated over the baseline of 1975–2014. Number of donor cells refers to the number of grid-cells of the study area that receive parameter values from the given catchment for regional runoff simulation (see Figure 7).

CATCHMENT ID	CATCHMENT NAME	BASELINE OBSERVED STREAMFLOW (MM)	BASELINE MODELLED STREAMFLOW (MM)	PROPORTION NON-MISSING STREAMFLOW	MEAN ANNUAL RAINFALL (MM)	MEAN ANNUAL PET (M)	CALIBRATION NASH-SUTCLIFFE EFFICIENCY	AREA (KM^2)	NO. DONOR CELLS
212040	Kialla Ck @ Pomeroy	84.6	91.0	86	742	1240	0.32	93	239
218001	Tuross R. @ Tuross Vale	282.2	279.4	100	829	1085	0.70	90	19
219022	Tantawangalo Ck @ Candelo Dam Site	190.9	202.9	99	854	1086	0.63	200	33
220003	Pambula R. @ Lochiel	203.8	204.0	99	887	1121	0.72	106	65
220004	Towamba R. @ Towamba	156.4	165.4	99	869	1099	0.75	766	68
221208	Wingan R. @ Wingan Inlet National Park	159.1	168.4	89	949	1111	0.75	423	134
221211	Combienbar R. @ Combienbar	173.6	183.0	100	985	1065	0.68	182	78
222004	Little Plains R. @ Wellesley (Rowes)	116.4	114.7	97	836	1082	0.69	610	117
222015	Jacobs R. @ Jacobs Ladder	235.7	242.0	69	1082	1105	0.63	184	195
222202	Brodribb Riber R. @ Sardine Creek	165.4	159.4	100	933	1075	0.67	648	125
222216	Murrindal R. @ Basin Rd (Buchan)	144.8	164.5	28	851	1081	0.79	293	205
224207	Wongungarra River R. @ Guys	244.3	258.8	35	1182	1120	0.73	732	63
224209	Cobbannah Ck near Bairnsdale	103.3	97.9	31	774	1092	0.64	103	188

CATCHMENT ID	CATCHMENT NAME	BASELINE OBSERVED STREAMFLOW (MM)	BASELINE MODELLED STREAMFLOW (MM)	PROPORTION NON-MISSING STREAMFLOW	MEAN ANNUAL RAINFALL (MM)	MEAN ANNUAL PET (M)	CALIBRATION NASH-SUTCLIFFE EFFICIENCY	AREA (KM^2)	NO. DONOR CELLS
224214	Wentworth R. @ Tabberabbera	89.0	99.6	100	870	1091	0.61	440	140
225219	Macalister R. @ Glencairn	370.5	374.8	100	1110	1103	0.71	570	101
226222	Latrobe R. near Noojee (U/S Ada R Junct.)	429.7	437.2	88	1394	1045	0.73	65	107
226226	Tanjil R. @ Tanjil Junction	440.0	433.8	100	1281	1059	0.76	299	114
227200	Tarra R. @ Yarram	142.6	150.2	99	912	1070	0.69	223	90
227226	Tarwineast Branc R. @ Dumbalk North	267.8	279.7	100	1009	1067	0.75	130	156
227231	Bass R. @ Glen Forbes South	226.6	232.8	100	953	1105	0.78	240	178
227236	Powlett R. D/S Foster Ck Junction	208.1	219.1	89	980	1102	0.84	225	64
227240	Merriman Ck @ Prospect Rd- Seaspray	60.5	52.4	59	737	1094	0.36	511	154
230219	Boyd Ck @ Darraweit Guim	92.1	96.9	38	688	1169	0.63	136	112
231225	Werribee R. @ Ballan (U/S Old Western Hwy)	203.2	205.8	100	872	1111	0.69	108	112
233223	Warrambine Ck @ Warrambine	24.1	23.5	100	599	1125	0.67	58	172
234201	Woady Yaloak R. @ Cressy (Yarima)	28.2	27.8	99	606	1134	0.64	1167	146
235210	Lardner Ck @ Gellibrand	419.4	427.3	100	1313	1049	0.80	54	34
235229	Ford R. @ Glenaire	554.1	572.6	31	1287	1044	0.78	54	59
235234	Love Ck @ Gellibrand	114.7	131.5	89	957	1088	0.64	77	127
236212	Brucknell Ck @ Cudgee	117.7	124.9	100	797	1113	0.71	225	287
237202	Fitzroy R. @ Heywood	109.2	115.6	100	758	1099	0.71	268	29
237207	Surry R. @ Heathmere	89.6	110.4	98	783	1099	0.76	312	80
238220	Dundas R. @ Cavendish	40.5	56.4	61	631	1171	0.75	214	359
238223	Wando R. @ Wando Vale	75.5	77.0	100	675	1168	0.67	180	238
238230	Stokes R. @ Teakettle	80.8	92.0	100	708	1125	0.70	197	65
238233	Moleside Ck @ Kentbruck	131.9	110.4	27	791	1103	0.75	70	186
238238	Henty Ck @ Henty	58.0	63.5	35	661	1146	0.72	244	84

CATCHMENT ID	CATCHMENT NAME	BASELINE OBSERVED STREAMFLOW (MM)	BASELINE MODELLED STREAMFLOW (MM)	PROPORTION NON-MISSING STREAMFLOW	MEAN ANNUAL RAINFALL (MM)	MEAN ANNUAL PET (M)	CALIBRATION NASH-SUTCLIFFE EFFICIENCY	AREA (KM^2)	NO. DONOR CELLS
239531	Morambro Ck @ Naracoorte-Bordertown Rd Bridge	7.6	14.8	96	515	1238	0.42	411	2168
401008	Mannus Ck @ Tooma	126.5	143.4	59	957	1242	0.78	512	156
401012	Murray R. @ Biggara	267.7	268.2	19	1121	1125	0.49	1257	54
401015	Bowna Ck @ Yambla	31.7	40.7	99	660	1331	0.61	290	1152
401208	Cudgewa Ck @ Berringama	217.0	213.6	100	1094	1226	0.74	351	123
401217	Gibbo R. @ Gibbo Park	269.7	261.6	100	1152	1133	0.80	390	110
401230	Corryong Ck @ Towong	236.5	243.9	53	1063	1199	0.89	978	75
402206	Running Ck @ Running Ck	236.9	265.2	98	1274	1210	0.70	128	56
402213	Kinchington Creek R. @ Osborne Flat	164.9	183.4	99	1023	1258	0.68	124	75
403214	Happy Valley Ck @ Rosewhite	165.4	196.5	100	1132	1238	0.74	138	18
403224	Hurdle Ck @ Bobinawarrah	163.5	173.0	99	979	1258	0.80	154	121
403232	Morses Ck @ Wandiligong	332.1	378.1	98	1380	1183	0.77	124	40
403236	Barwidgee Ck @ Myrtleford	153.3	205.5	34	1154	1229	0.62	174	19
403244	Ovens R. @ Harrietville	646.4	638.0	65	1524	1121	0.81	122	61
404207	Holland Ck @ Kelfeera	166.1	159.0	100	928	1237	0.86	448	226
405205	Murrindindi R. @ Murrindindi above Colwells	461.6	466.5	99	1270	1110	0.76	106	113
405212	Sunday Ck @ Tallarook	95.3	93.0	99	722	1184	0.77	337	62
405215	Howqua R. @ Glen Esk	437.8	423.4	100	1120	1136	0.80	362	57
405218	Jamieson River R. @ Gerrang Bridge	529.0	538.6	100	1116	1134	0.69	364	41
405227	Big R. @ Jamieson	456.1	452.6	100	1342	1113	0.85	627	50
405228	Hughes Ck @ Tarcombe Rd	140.5	135.3	99	755	1225	0.80	475	29
405230	Cornella Ck @ Colbinabbin	29.5	40.2	100	540	1282	0.55	259	1654
405240	Sugarloaf Ck @ Ash Br	90.0	83.7	98	663	1212	0.79	609	28
405241	Rubicon R. @ Rubicon	821.9	809.0	100	1410	1118	0.77	128	45
405251	Brankeet Ck @ Ancona	117.3	122.8	100	857	1220	0.67	123	68
405261	Spring Ck (Colonial Ck) @ Fawcett	137.2	150.7	31	743	1229	0.75	65	35

CATCHMENT ID	CATCHMENT NAME	BASELINE OBSERVED STREAMFLOW (MM)	BASELINE MODELLED STREAMFLOW (MM)	PROPORTION NON-MISSING STREAMFLOW	MEAN ANNUAL RAINFALL (MM)	MEAN ANNUAL PET (M)	CALIBRATION NASH-SUTCLIFFE EFFICIENCY	AREA (KM²)	NO. DONOR CELLS
405262	Creightons Ck @ Creighton	151.9	146.4	32	737	1245	0.85	89	247
405291	Whiteheads Ck @ Whiteheads Ck	54.7	76.8	65	660	1239	0.62	54	56
406213	Campaspe R. @ Redesdale	103.2	106.0	98	761	1187	0.81	634	46
406214	Axe Ck @ Longlea	48.5	56.1	100	592	1262	0.75	235	621
406226	Mount Ida Ck @ Derrinal	63.1	68.0	91	631	1240	0.76	172	37
406250	Coliban R. @ Springhill-Tylden Rd	232.8	258.9	78	947	1135	0.77	77	41
407215	Loddon R. @ Newstead	68.6	69.8	98	680	1207	0.84	1028	42
407230	Joyces Ck @ Strathlea	55.1	60.2	100	652	1200	0.84	156	87
408202	Avoca R. @ Amphitheatre	51.2	52.6	100	593	1205	0.69	83	94
408204	Glenlogie Ck @ Amphitheatre	83.1	78.0	30	583	1210	0.49	54	27
410038	Adjungbilly Ck @ Darbalara	182.6	167.9	98	1019	1283	0.75	391	234
410047	Tarcutta Ck @ Old Borambola	90.0	79.7	97	779	1306	0.74	1653	114
410048	Kyeamba Ck @ Ladysmith	47.2	55.8	63	633	1350	0.74	548	1774
410062	Numeralla R. @ Numeralla School	112.1	114.6	99	673	1130	0.60	670	132
410107	Mountain Ck @ Mountain Ck	169.5	165.8	81	902	1270	0.75	185	117
410713	Paddy's R. @ Riverlea	142.6	155.0	99	958	1189	0.58	224	70
410730	Cotter R. @ Gingera	308.5	308.7	100	1135	1124	0.74	130	172
410734	Queanbeyan R. @ Tinderry	108.7	122.3	99	795	1141	0.64	516	87
411003	Butmaroo Ck @ Butmaroo	81.6	88.8	83	758	1192	0.59	61	85
412029	Boorowa R. @ Prossers Crossing	50.7	48.7	94	636	1326	0.75	1552	569
412080	Flyers Ck @ Beneree	104.8	98.4	82	833	1299	0.68	89	598
415207	Wimmera R. @ Eversley	51.7	47.3	100	622	1203	0.76	303	110
415226	Richardson R. @ Carrs Plains	23.2	38.7	100	479	1276	0.72	124	2154
415238	Wattle Ck @ Navarre	31.6	42.5	95	539	1250	0.75	140	224
421055	Coolbaggie Ck @ Rawsonville	32.5	39.4	82	538	1487	0.64	674	685

CATCHMENT ID	CATCHMENT NAME	BASELINE OBSERVED STREAMFLOW (MM)	BASELINE MODELLED STREAMFLOW (MM)	PROPORTION NON-MISSING STREAMFLOW	MEAN ANNUAL RAINFALL (MM)	MEAN ANNUAL PET (M)	CALIBRATION NASH-SUTCLIFFE EFFICIENCY	AREA (KM^2)	NO. DONOR CELLS
426503	Angas R. @ Angas Weir	60.3	71.4	99	781	1261	0.63	61	707
507503	Broughton R. @ Mooroola	10.0	8.0	96	483	1376	0.55	2464	80

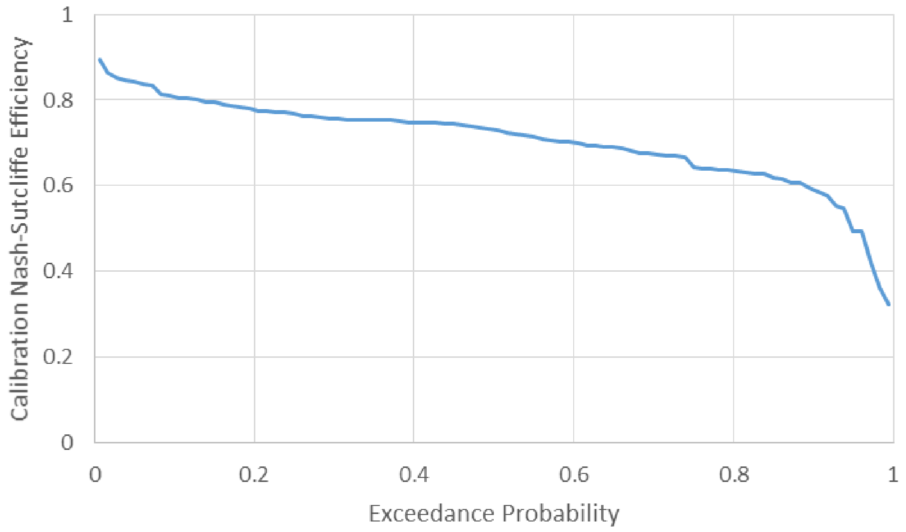


Figure 6 Calibration Nash-Sutcliffe Efficiency (NSE) for the 90 calibration catchments

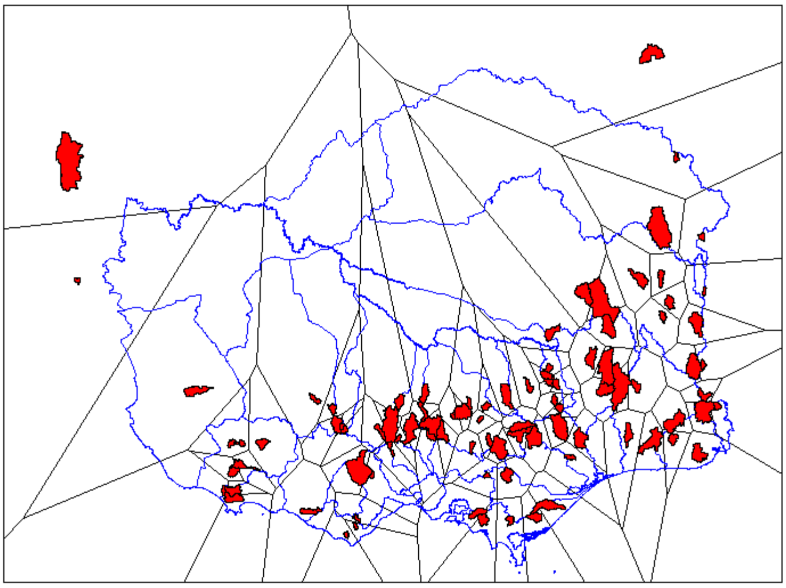


Figure 7 Identification of nearest calibration catchment for runoff simulation
The red areas are the 90 calibration catchments. Voronoi polygons (outlined in black) are calculated around the 90 catchment centroids. Each AWAP grid centre lies in one polygon, and this determines the nearest-neighbour calibration catchment for rainfall-runoff model parameters

3 Results

3.1 Historical runoff

Figure 8 shows the baseline (1975–2014) historical runoff in mm/year modelled with SIMHYD, as described in section 2.7. The modelled runoff shows a clear spatial distribution of runoff amounts, with most of runoff occurring in the upland catchments along the Great Dividing Range north-east of Melbourne. This historical runoff is used as the reference point for calculating the future changes in runoff (both in mm and percentage changes) in section 3.4. Where runoff is greater than about 100 mm, the spatial variability of runoff is principally determined by the spatial distribution of rainfall (see Figure 3). In low rainfall and runoff areas, the influence of parameters from the nearest neighbour catchments (Figure 7) is greater, and runoff is necessarily more uncertain here.

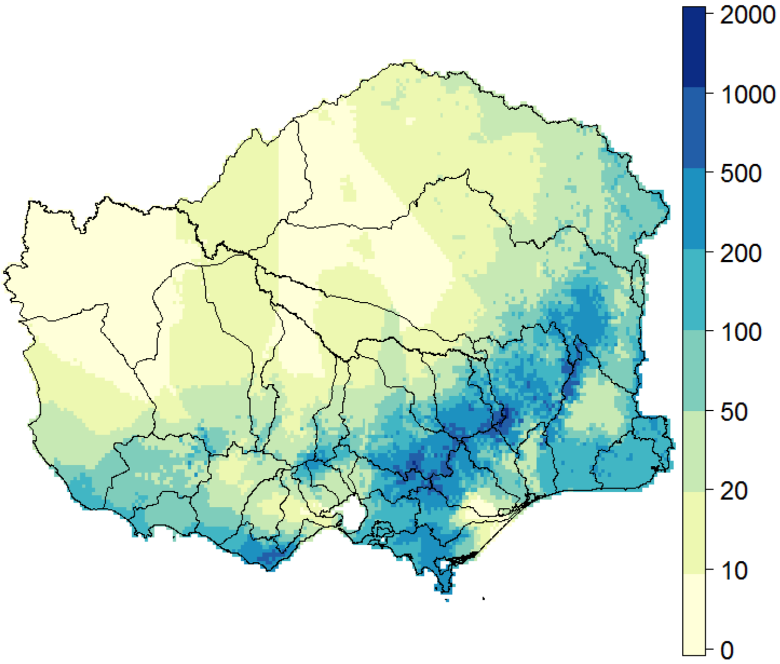


Figure 8 Baseline (1975–2014) runoff (mm) simulated by SIMHYD with Muskingum routing

3.2 Projected changes to rainfall and PET by 2040

Figure 9 and Figure 10 show projected percentage changes to rainfall and PET respectively by 2040 under RCP8.5 relative to 1975–2015. The low-impact scenario (i.e. wet response) has increases in rainfall in all seasons, although little to no increase in rainfall in the south-western part of the

study region annually and in spring (SON). The high-impact scenario (i.e. dry response) for rainfall shows decreases in all seasons and annually. The medium-impact scenario has moderate decreases of mean rainfall over most of Victoria, particularly in the second half of the year (JJA and SON). There are small to moderate increases in rainfall north of the Murray, particularly in summer (DJF). The medium-impact scenario has increases in mean PET of around 5%, and this shows no particular seasonal or spatial patterns.

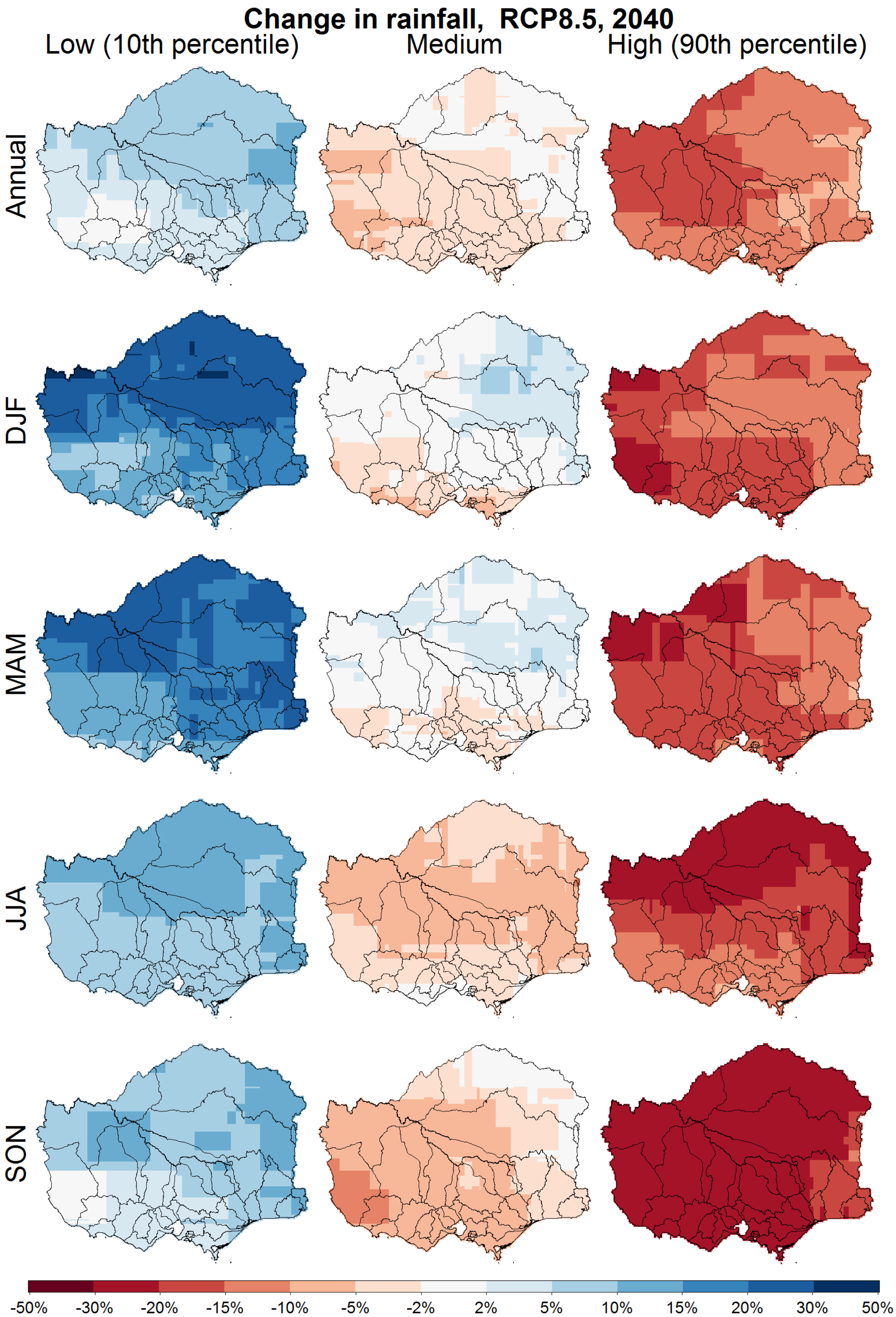


Figure 9 Projected CMIP5 model ensemble changes to annual and seasonal rainfall by 2040 under emissions pathway RCP8.5 relative to 1975–2014

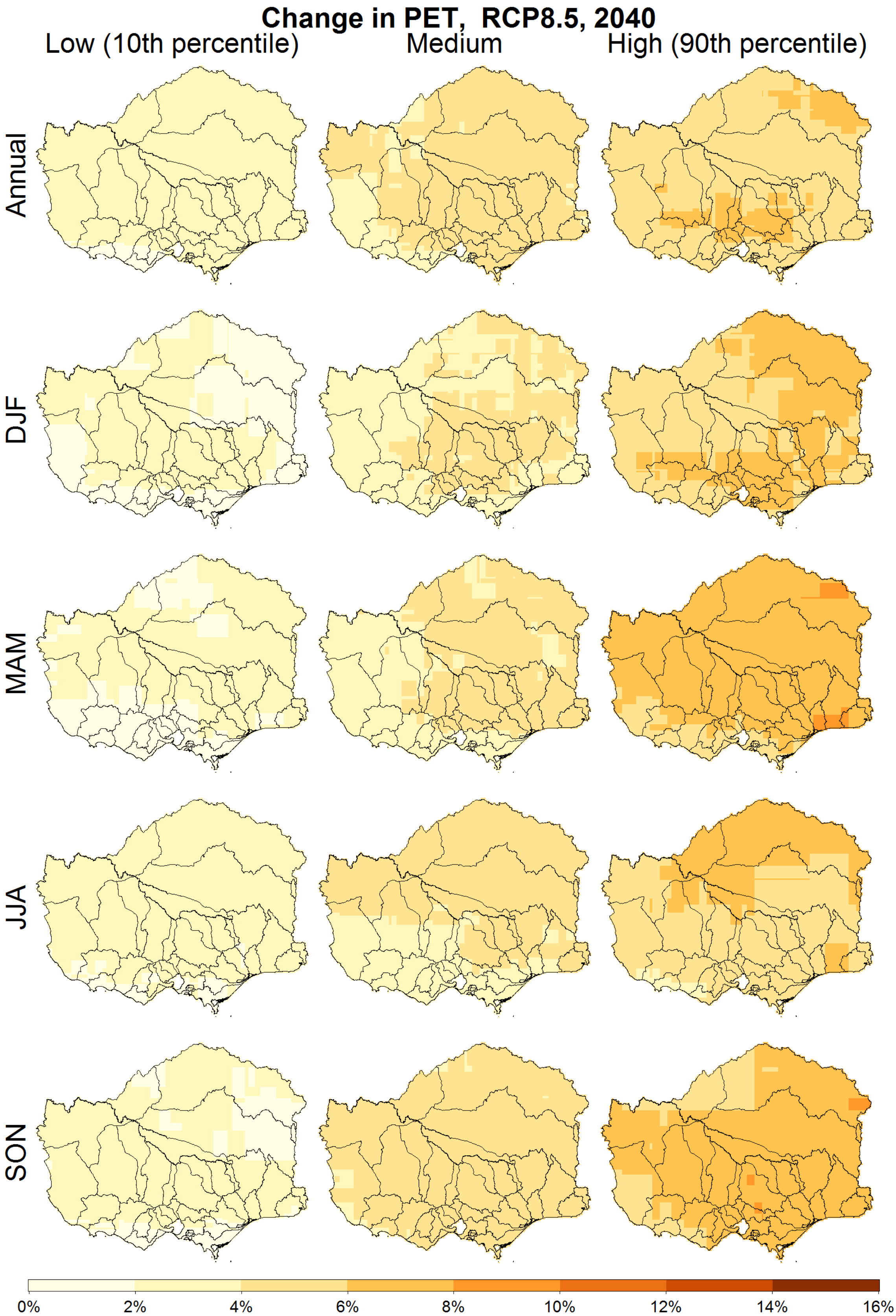


Figure 10 Projected CMIP5 model ensemble changes to annual and seasonal potential evapotranspiration by 2040 under emissions pathway RCP8.5 relative to 1975–2014

3.3 Projected changes to rainfall and PET by 2065

Figure 11 and Figure 12 show projected percentage changes to rainfall and PET respectively by 2065 under RCP8.5. The spatial and seasonal patterns of projected changes to rainfall and PET for 2065 are similar to the projected changes by 2040, although the magnitudes of change are generally higher. Small to moderate increases in rainfall are projected for the NSW part of the study region, and also northern and eastern Victoria. This is consistent with the findings of CSIRO and Bureau of Meteorology (2015, Figure 7.2.5), which show a small to moderate increase in CMIP5 model ensemble median DJF rainfall in far south-eastern Australia by 2090 for RCP8.5. Similarly to the results for 2040 (Figure 9), the medium-impact scenario shows little to no increase in mean annual rainfall for the south-western part of the region. The projection for PET under the medium-impact scenario is for an increase of around 6–10%.

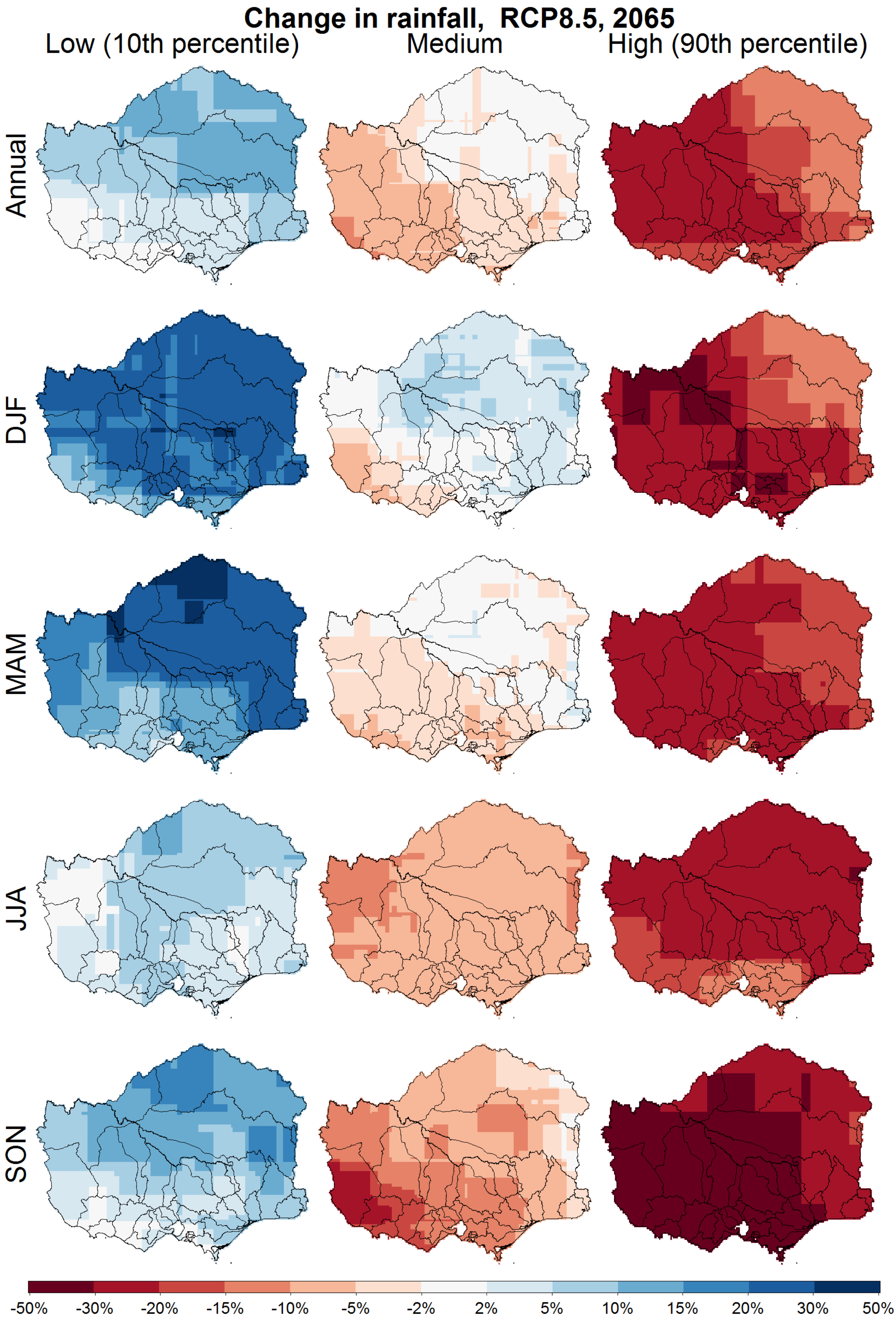


Figure 11 Projected CMIP5 model ensemble changes to annual and seasonal rainfall by 2065 under emissions pathway RCP8.5 relative to 1975–2014

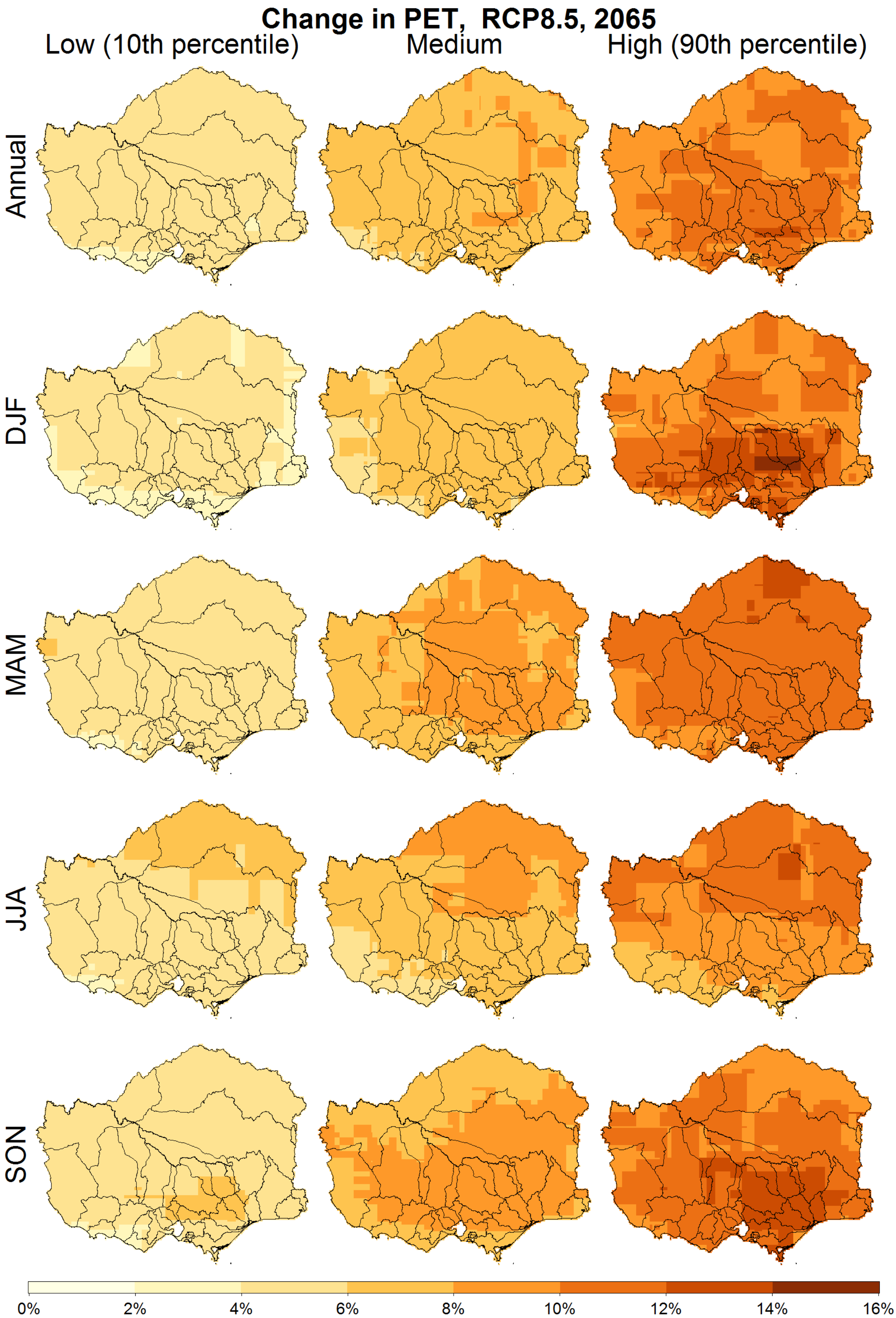


Figure 12 Projected CMIP5 model ensemble changes to annual and seasonal potential evapotranspiration by 2065 under emissions pathway RCP8.5 relative to 1975–2014

3.4 Projected changes to runoff

Figure 13 shows the projected change in runoff at 2065 for each of the 42 GCMs described in Table 3. They are ordered from left to right by decreasing mean regional runoff. The range of results ranges from increased runoff over most of the region to extreme drying (greater than 50% reduction) of the entire study region. Note however that many of the GCMs that produce increased runoff over the study region as a whole have reductions in the south-western part of the region.

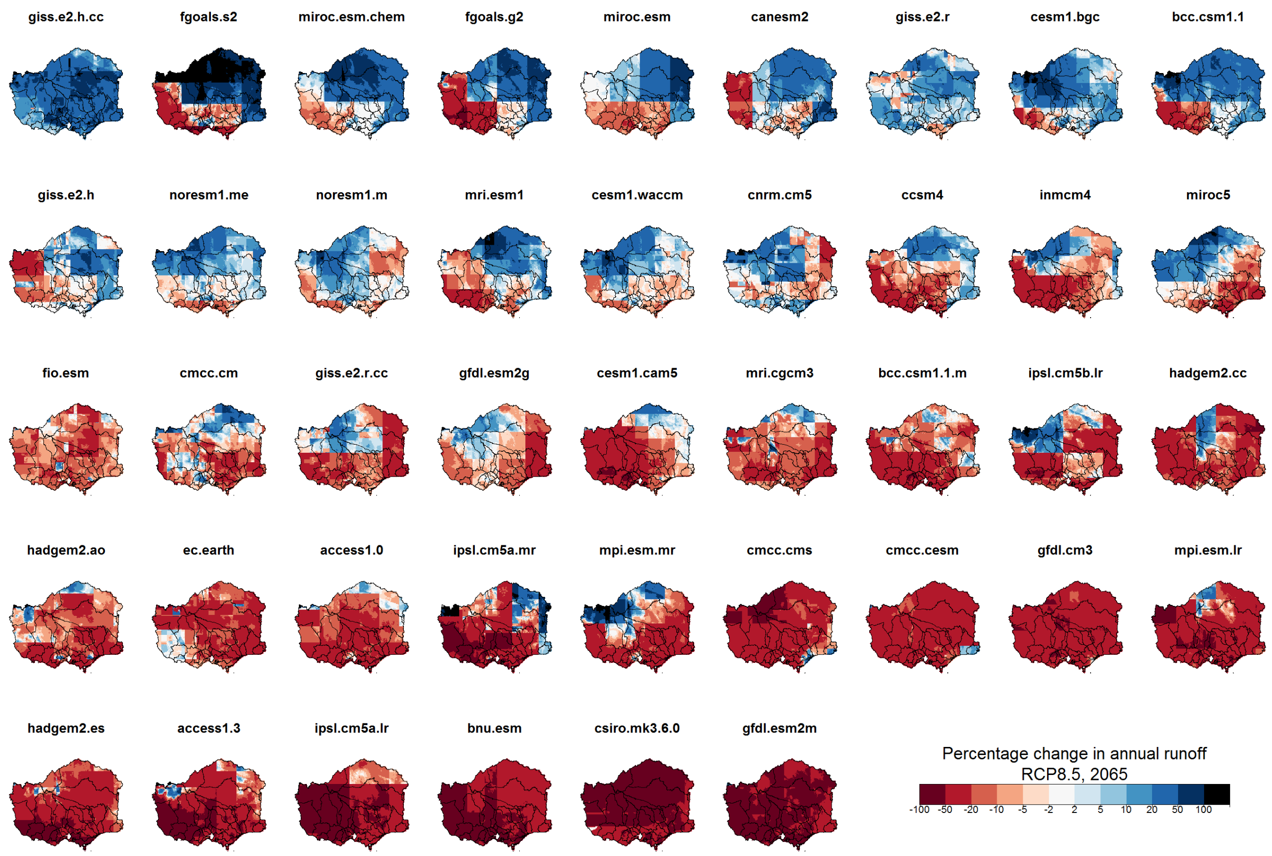


Figure 13 GCM runoff results at 2065

The GCM results are aggregated individually at each grid cell to produce a low-impact response (10th percentile of results), medium impact, and high-impact response (90th percentile of results) for runoff by 2040 and 2065 under RCP8.5 (Figure 14). The low-impact response shows increases of runoff of around 5–20% by 2040 over most of Victoria, and slightly larger than this in the northern part of the region. By 2065 under the low-impact scenario, most of southern Victoria shows little to no increase in runoff, with decreases in runoff in the south-western part of the region. The high-impact scenario is for a 20–40% decrease in runoff over the entire study region by 2040, which is enhanced, particularly in the west, by 2065. The medium-impact scenario has moderate runoff decreases of 5–20% over most of Victoria by 2040, which is enhanced by 2065, particularly in the south-west. There are small to moderate increases (2–10%) in runoff projected for the north of the study region by 2040 and particularly by 2065, but this lies mostly in NSW and in low runoff producing areas (compare Figure 8).

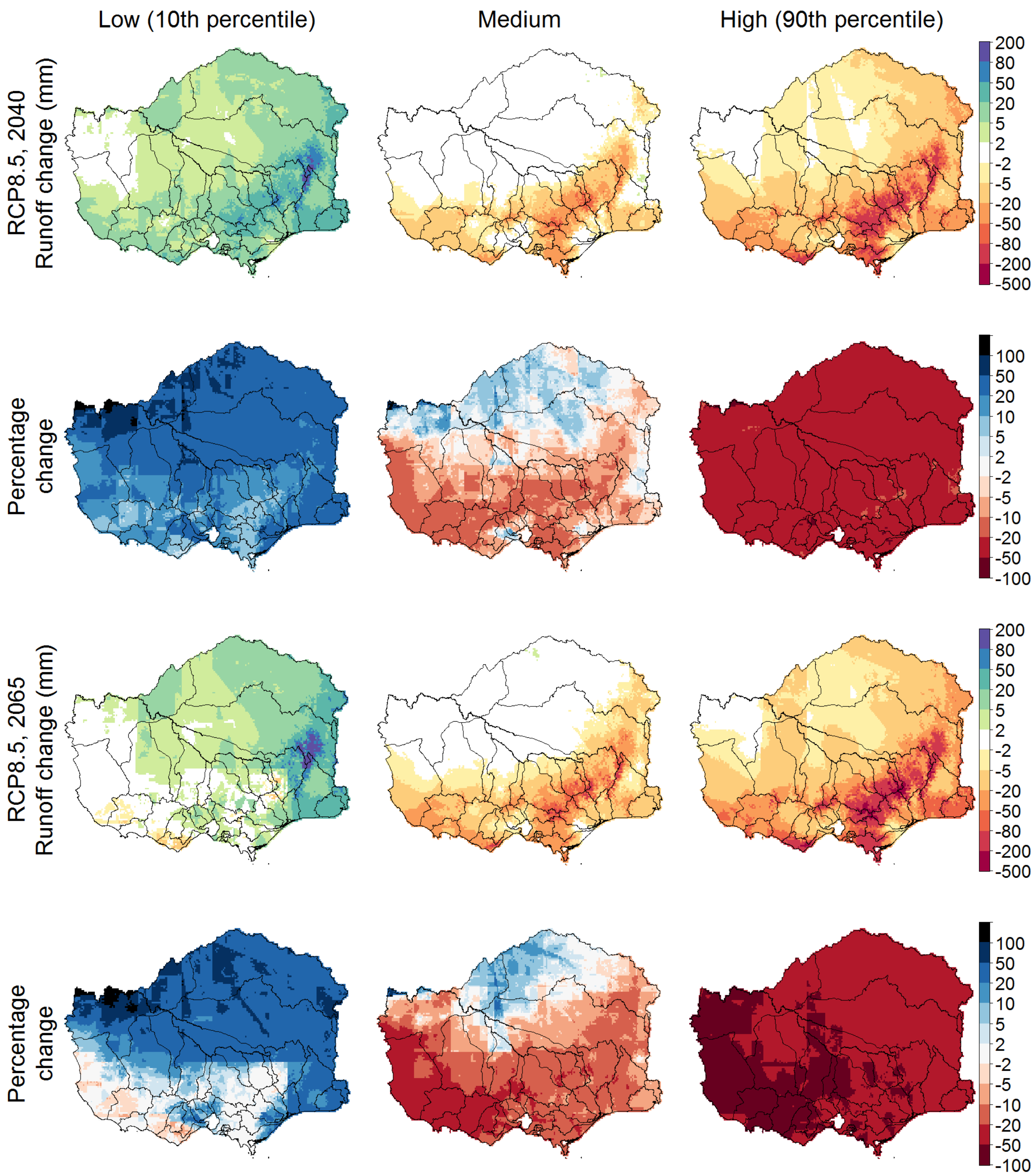


Figure 14 Changes in runoff under emissions pathway RCP8.5 relative to 1975–2014

Table 5 shows the projected percentage change in runoff for each river basin. To derive these values, the projected runoff for each GCM is first aggregated to each region. Then the 10th percentile, median and 90th percentile of aggregated GCM responses are calculated for each region to generate the low, medium and high-impact scenarios. This is to ensure consistency of runoff response, especially at the 10th and 90th percentiles. The changes to runoff under the medium-impact scenario in Table 5 for each river basin in Victoria are shown in Figure 15.

Table 5 Percentage changes to river-basin aggregated annual runoff under emissions pathway RCP8.5 relative to 1975–2014

BASIN ID	BASIN NAME	BASELINE MEAN ANNUAL RUNOFF (MM)	2040, LOW	2040, MEDIUM	2040, HIGH	2065, LOW	2065, MEDIUM	2065, HIGH
220000	Towamba River	172	23%	-3%	-20%	25%	-7%	-35%
221000	East Gippsland	166	23%	-5%	-26%	21%	-8%	-39%
222000	Snowy River	136	23%	-7%	-25%	21%	-18%	-36%
223000	Tambo River	107	23%	-6%	-27%	21%	-13%	-40%
224000	Mitchell River (Vic.)	183	10%	-11%	-26%	2%	-16%	-45%
225000	Thomson River	186	10%	-9%	-28%	2%	-14%	-42%
226000	Latrobe River	186	9%	-11%	-31%	0%	-16%	-42%
227000	South Gippsland	170	9%	-12%	-34%	2%	-17%	-45%
228000	Bunyip River	147	11%	-14%	-33%	2%	-19%	-47%
229000	Yarra River	227	10%	-11%	-29%	1%	-16%	-44%
230000	Maribyrnong River	81	15%	-13%	-33%	5%	-20%	-55%
231000	Werribee River	77	12%	-8%	-29%	7%	-18%	-45%
232000	Moorabool River	58	13%	-8%	-30%	5%	-17%	-46%
233000	Barwon River	47	16%	-6%	-33%	-1%	-22%	-48%
234000	Lake Corangamite	34	18%	-10%	-37%	-2%	-26%	-53%
235000	Otway Coast	241	7%	-7%	-25%	-5%	-16%	-42%
236000	Hopkins River	51	15%	-13%	-36%	-5%	-28%	-60%
237000	Portland Coast	85	15%	-11%	-36%	-3%	-30%	-55%
238000	Glenelg River	67	8%	-14%	-37%	-3%	-31%	-61%
239000	Millicent Coast	26	13%	-10%	-35%	0%	-28%	-57%
401000	Upper Murray River	219	17%	-8%	-23%	13%	-17%	-39%
402000	Kiewa River	280	11%	-9%	-22%	2%	-12%	-39%
403000	Ovens River	205	12%	-11%	-23%	1%	-16%	-44%
404000	Broken River	51	19%	-10%	-36%	8%	-17%	-50%
405000	Goulburn River	182	10%	-10%	-29%	1%	-14%	-42%
406000	Campaspe River	64	10%	-12%	-37%	1%	-21%	-57%
407000	Loddon River	24	12%	-7%	-37%	7%	-18%	-58%
408000	Avoca River	17	23%	0%	-29%	26%	-9%	-44%
409000	Murray-Riverina	13	33%	-5%	-37%	27%	-11%	-47%
410000	Murrumbidgee River	49	22%	-5%	-28%	35%	-10%	-36%
412000	Lachlan River	25	29%	1%	-25%	39%	-4%	-37%
413000	Benanee	11	46%	7%	-28%	45%	7%	-44%
414000	Mallee	4	40%	5%	-25%	42%	-6%	-49%
415000	Wimmera-Avon Rivers	21	12%	-7%	-32%	12%	-14%	-53%

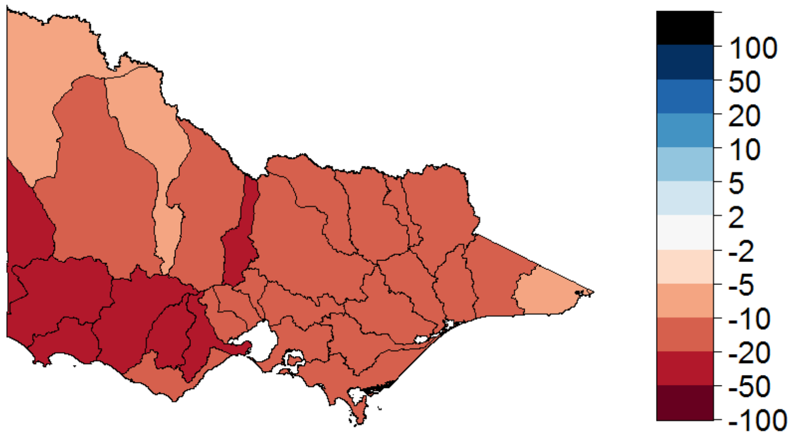


Figure 15 Percentage changes to basin-aggregated mean annual runoff under the medium-impact scenario by 2065 (see Table 5)

Uncertainties in the runoff projections can arise from: choice of emissions scenario (addressed in Appendix B), GCM selection, hydrological non-stationarity, and different downscaling methods. These last three have been assessed as separate projects in VicCI (Hope et al., 2016). Consideration of the uncertainty due to GCM selection and hydrological non-stationarity tends to increase the drying trend across Victoria. The use of different downscaling approaches can either increase the drying signal, or alternatively lead to increases in median rainfall. However, on balance, recent research (Hope et al., 2016) on projections uncertainty suggests most uncertainty points to a drier future, particularly in the drier, Western part of Victoria.

3.4.1 Comparison with SEACI (Post et al., 2012) projections

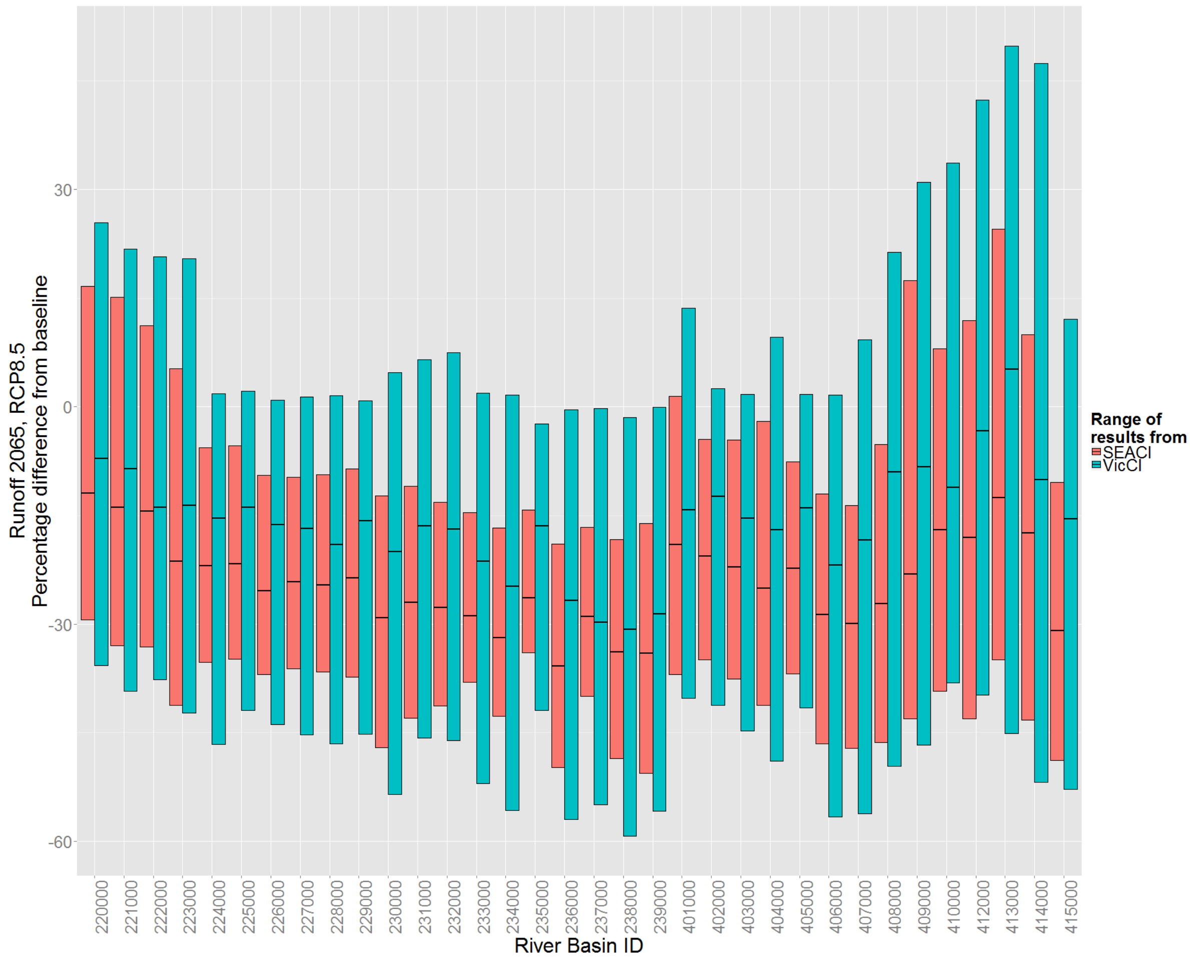


Figure 16 Range of results of runoff projections for 2°C global temperature increase (using the SEACI methodology) and at 2065 using the current methods (VicCI)
The top of each bar represents the 10th percentile of the model ensemble (low-impact scenario), the bottom of each bar represents the 90th percentile (high-impact scenario), and the crossbar represents the median (medium-impact scenario)

The earlier runoff projections developed by SEACI (Post et al., 2012) are available as a gridded data product (http://www.seaci.org/research/futureProjections.html). These data are mean annual runoff, 10th percentile, median and 90th percentile percentage changes in runoff for a 2°C global temperature increase (approximately 2060). These were aggregated to the river basins used in this report (Table 1), and compared to the current basin projections (Figure 16). Note that, in contrast to the changes presented in Table 5, the VicCI projection ranges shown in Figure 16 were summarised at each grid-cell before aggregation to basin (with little overall difference in results), in order to be consistent with the available SEACI data.

In all basins, the runoff change under the medium-impact scenario is smaller (less dry) under the current projections compared to the SEACI results. The range of the current projections is larger too – specifically runoff under the high-impact scenario is drier than the SEACI dry response and the low-impact scenario is wetter compared to the SEACI wet response. Note however that there are several methodological differences, not limited to differences between:

- amounts of global warming (approximately 2.7° for VicCI versus 2°C for SEACI), and corresponding target dates (2065 versus 2060)
- GCM model ensemble (CMIP5 versus CMIP3) with more GCMs available now
- baseline climates.

Nevertheless, the wetter response under the current projections is principally due to the wetter rainfall projections from CMIP5 compared to CMIP3 (sections 3.2 and 3.3; CSIRO and Bureau of Meteorology, 2015, section A.3). The increased range of results partly reflects the slightly higher amount of projected warming, but may also be due to the larger model ensemble.

Appendix A Projected basin-wide independently calculated hydroclimate changes

This appendix contains seasonal runoff changes (annual runoff changes are in Table 5), annual rainfall changes, annual PET changes and annual average temperature changes. Note that the projected temperature changes are in °C, in contrast to the other tables which are percentage change from observed baseline mean values. Similarly to Table 5, these changes are calculated for RCP8.5 at 2040 and 2065. These changes are calculated independently, which means that the low-impact, medium-impact and high-impact scenarios are calculated for each variable separately, i.e. the percentage changes for each variable are taken from the 10th, 50th and 90th percentile of each basin aggregated variable independently. As such, the low-impact, medium-impact and high-impact tabulated changes can and do occur from different GCMs between tables. This means that the changes from different tables cannot be combined together to produce a meaningful scenario of future changes. DELWP (2016, Appendix A) provide further information on these issues, as well as advice on using these climate change factors for applications.

Basin aggregated seasonal changes for rainfall, PET, and average temperature as well as internally consistent (i.e. taken from the same GCM throughout) annual and seasonal changes for runoff, rainfall, PET and average temperature can be found on the CSIRO Data Access Portal (Potter et al., 2016).

Apx Table A.1 Percentage changes to river-basin aggregated summer (DJF) runoff under emissions pathway RCP8.5 relative to 1975–2014

BASIN ID	BASIN NAME	BASELINE MEAN DJF RUNOFF (MM)	2040, LOW	2040, MEDIUM	2040, HIGH	2065, LOW	2065, MEDIUM	2065, HIGH
220000	Towamba River	29.0	54%	1%	-29%	46%	-2%	-36%
221000	East Gippsland	20.1	37%	-5%	-32%	26%	-5%	-48%
222000	Snowy River	23.7	27%	-2%	-29%	30%	-1%	-46%
223000	Tambo River	17.4	38%	-1%	-33%	46%	0%	-46%
224000	Mitchell River (vic)	21.2	19%	-5%	-29%	22%	-7%	-46%
225000	Thomson River	22.8	17%	-8%	-32%	20%	-5%	-46%
226000	Latrobe River	27.7	6%	-10%	-31%	13%	-14%	-47%
227000	South Gippsland	8.2	23%	-10%	-41%	40%	-9%	-61%
228000	Bunyip River	21.7	8%	-12%	-30%	18%	-15%	-49%
229000	Yarra River	45.0	6%	-9%	-28%	6%	-17%	-45%
230000	Maribyrnong River	8.9	46%	-1%	-33%	63%	-13%	-61%
231000	Werribee River	13.1	34%	-1%	-32%	45%	-12%	-54%
232000	Moorabool River	11.7	32%	2%	-35%	42%	-12%	-53%
233000	Barwon River	5.0	31%	-7%	-44%	37%	-21%	-62%
234000	Lake Corangamite	3.8	42%	-6%	-42%	37%	-15%	-53%
235000	Otway Coast	18.3	6%	-15%	-34%	4%	-21%	-49%
236000	Hopkins River	4.6	37%	-3%	-40%	45%	-12%	-50%
237000	Portland Coast	3.1	9%	-17%	-40%	11%	-28%	-57%
238000	Glenelg River	2.7	43%	-2%	-42%	59%	-11%	-63%
239000	Millicent Coast	1.2	47%	-9%	-41%	26%	-15%	-64%
401000	Upper Murray River	27.8	24%	-3%	-30%	22%	-3%	-43%
402000	Kiewa River	32.3	17%	-7%	-29%	22%	-11%	-45%
403000	Ovens River	20.9	17%	-6%	-23%	30%	-8%	-45%
404000	Broken River	5.5	33%	-1%	-25%	42%	-3%	-46%
405000	Goulburn River	21.6	13%	-3%	-24%	19%	-8%	-38%
406000	Campaspe River	4.6	37%	-5%	-35%	60%	-13%	-63%
407000	Loddon River	2.9	59%	10%	-41%	103%	-3%	-61%
408000	Avoca River	3.9	60%	8%	-37%	79%	4%	-53%
409000	Murray-Riverina	2.5	63%	5%	-31%	72%	13%	-46%
410000	Murrumbidgee River	7.9	44%	7%	-23%	56%	6%	-35%
412000	Lachlan River	5.4	61%	17%	-32%	77%	11%	-31%
413000	Benanee	4.8	71%	12%	-27%	80%	11%	-55%
414000	Mallee	0.9	151%	23%	-38%	161%	15%	-55%
415000	Wimmera-Avon Rivers	3.4	43%	5%	-33%	75%	-2%	-56%

Apx Table A.2 Percentage changes to river-basin aggregated autumn (MAM) runoff under emissions pathway RCP8.5 relative to 1975–2014

BASIN ID	BASIN NAME	BASELINE MEAN MAM RUNOFF (MM)	2040, LOW	2040, MEDIUM	2040, HIGH	2065, LOW	2065, MEDIUM	2065, HIGH
220000	Towamba River	47.4	50%	6%	-25%	69%	5%	-45%
221000	East Gippsland	29.0	60%	6%	-28%	71%	3%	-45%
222000	Snowy River	22.5	42%	1%	-26%	64%	-6%	-39%
223000	Tambo River	17.3	48%	0%	-30%	71%	-3%	-43%
224000	Mitchell River (Vic.)	21.0	36%	-5%	-30%	37%	-9%	-43%
225000	Thomson River	23.0	40%	-7%	-30%	37%	-13%	-44%
226000	Latrobe River	23.9	26%	-10%	-30%	18%	-13%	-46%
227000	South Gippsland	18.9	36%	-9%	-37%	30%	-14%	-50%
228000	Bunyip River	21.4	20%	-13%	-32%	11%	-17%	-47%
229000	Yarra River	33.6	16%	-8%	-28%	10%	-15%	-46%
230000	Maribyrnong River	6.4	44%	-3%	-36%	36%	-5%	-55%
231000	Werribee River	7.4	30%	-3%	-31%	29%	-7%	-45%
232000	Moorabool River	6.1	38%	2%	-29%	16%	-2%	-39%
233000	Barwon River	3.8	38%	4%	-33%	16%	-10%	-45%
234000	Lake Corangamite	2.4	41%	2%	-29%	19%	-12%	-45%
235000	Otway Coast	17.5	22%	-1%	-27%	1%	-12%	-44%
236000	Hopkins River	3.0	37%	0%	-26%	24%	-8%	-45%
237000	Portland Coast	4.5	46%	7%	-26%	23%	-10%	-45%
238000	Glenelg River	3.6	42%	5%	-29%	37%	-9%	-47%
239000	Millicent Coast	1.6	30%	-2%	-34%	34%	-13%	-49%
401000	Upper Murray River	21.3	40%	2%	-27%	61%	-3%	-39%
402000	Kiewa River	22.0	37%	1%	-25%	45%	-4%	-34%
403000	Ovens River	17.0	34%	-3%	-28%	32%	-9%	-39%
404000	Broken River	5.3	49%	6%	-32%	56%	-3%	-42%
405000	Goulburn River	19.1	30%	-2%	-27%	24%	-11%	-39%
406000	Campaspe River	4.2	39%	-4%	-38%	34%	-11%	-53%
407000	Loddon River	2.1	43%	0%	-36%	31%	-10%	-53%
408000	Avoca River	2.2	49%	2%	-31%	49%	-8%	-48%
409000	Murray-Riverina	2.0	52%	7%	-32%	89%	-3%	-47%
410000	Murrumbidgee River	7.5	50%	14%	-23%	90%	11%	-30%
412000	Lachlan River	4.7	59%	23%	-31%	115%	8%	-42%
413000	Benanee	1.9	61%	16%	-35%	75%	12%	-41%
414000	Mallee	0.5	61%	16%	-27%	64%	-5%	-44%
415000	Wimmera-Avon Rivers	2.0	32%	1%	-29%	29%	-6%	-50%

Apx Table A.3 Percentage changes to river-basin aggregated winter (JJA) runoff under emissions pathway RCP8.5 relative to 1975–2014

BASIN ID	BASIN NAME	BASELINE MEAN JJA RUNOFF (MM)	2040, LOW	2040, MEDIUM	2040, HIGH	2065, LOW	2065, MEDIUM	2065, HIGH
220000	Towamba River	61.2	22%	-9%	-35%	10%	-16%	-40%
221000	East Gippsland	72.1	25%	-6%	-30%	19%	-15%	-41%
222000	Snowy River	47.9	24%	-7%	-29%	14%	-20%	-42%
223000	Tambo River	43.0	23%	-8%	-32%	14%	-20%	-47%
224000	Mitchell River (vic)	78.1	14%	-9%	-33%	5%	-16%	-39%
225000	Thomson River	75.5	16%	-6%	-28%	9%	-13%	-33%
226000	Latrobe River	66.4	16%	-8%	-28%	5%	-15%	-40%
227000	South Gippsland	87.2	17%	-8%	-28%	5%	-15%	-42%
228000	Bunyip River	54.5	17%	-9%	-32%	6%	-16%	-44%
229000	Yarra River	70.9	14%	-8%	-29%	6%	-13%	-41%
230000	Maribyrnong River	35.5	17%	-8%	-36%	13%	-19%	-53%
231000	Werribee River	27.5	13%	-8%	-30%	12%	-15%	-46%
232000	Moorabool River	17.3	15%	-7%	-32%	16%	-16%	-48%
233000	Barwon River	19.3	24%	-4%	-33%	10%	-19%	-44%
234000	Lake Corangamite	14.0	22%	-6%	-30%	13%	-21%	-52%
235000	Otway Coast	115.4	14%	-4%	-26%	5%	-14%	-37%
236000	Hopkins River	22.2	19%	-6%	-32%	10%	-22%	-56%
237000	Portland Coast	43.3	26%	-5%	-32%	9%	-22%	-54%
238000	Glenelg River	35.3	18%	-9%	-35%	-1%	-23%	-52%
239000	Millicent Coast	14.3	15%	-10%	-33%	1%	-23%	-52%
401000	Upper Murray River	86.2	26%	-9%	-32%	18%	-20%	-45%
402000	Kiewa River	113.6	20%	-8%	-30%	9%	-15%	-42%
403000	Ovens River	89.1	17%	-8%	-32%	9%	-16%	-43%
404000	Broken River	23.4	26%	-12%	-38%	14%	-19%	-50%
405000	Goulburn River	79.3	13%	-7%	-29%	8%	-14%	-39%
406000	Campaspe River	32.6	15%	-12%	-38%	11%	-20%	-51%
407000	Loddon River	10.8	19%	-17%	-41%	13%	-23%	-54%
408000	Avoca River	6.1	22%	-15%	-38%	13%	-22%	-51%
409000	Murray-Riverina	5.5	37%	-17%	-46%	16%	-24%	-59%
410000	Murrumbidgee River	19.2	31%	-13%	-33%	19%	-19%	-47%
412000	Lachlan River	9.5	32%	-14%	-42%	10%	-22%	-53%
413000	Benanee	2.0	34%	-11%	-52%	17%	-21%	-50%
414000	Mallee	1.3	21%	-15%	-41%	7%	-23%	-52%
415000	Wimmera-Avon Rivers	8.8	15%	-14%	-35%	6%	-19%	-52%

Apx Table A.4 Percentage changes to river-basin aggregated spring (SON) runoff under emissions pathway RCP8.5 relative to 1975–2014

BASIN ID	BASIN NAME	BASELINE MEAN SON RUNOFF (MM)	2040, LOW	2040, MEDIUM	2040, HIGH	2065, LOW	2065, MEDIUM	2065, HIGH
220000	Towamba River	34.3	31%	-9%	-36%	15%	-20%	-50%
221000	East Gippsland	44.8	22%	-11%	-39%	12%	-25%	-51%
222000	Snowy River	41.6	21%	-12%	-34%	14%	-24%	-47%
223000	Tambo River	29.5	20%	-14%	-40%	11%	-28%	-55%
224000	Mitchell River (vic)	62.7	1%	-14%	-35%	3%	-28%	-53%
225000	Thomson River	65.2	2%	-14%	-31%	1%	-24%	-49%
226000	Latrobe River	68.1	5%	-18%	-33%	-3%	-28%	-51%
227000	South Gippsland	55.3	6%	-20%	-40%	-6%	-33%	-60%
228000	Bunyip River	49.6	3%	-20%	-40%	-7%	-30%	-56%
229000	Yarra River	77.2	2%	-14%	-31%	2%	-22%	-48%
230000	Maribyrnong River	30.5	13%	-20%	-48%	6%	-36%	-67%
231000	Werribee River	29.5	11%	-17%	-40%	4%	-32%	-58%
232000	Moorabool River	22.8	14%	-18%	-42%	12%	-34%	-62%
233000	Barwon River	19.0	12%	-18%	-47%	1%	-39%	-67%
234000	Lake Corangamite	14.2	15%	-24%	-53%	-1%	-46%	-68%
235000	Otway Coast	89.6	2%	-15%	-34%	-3%	-28%	-53%
236000	Hopkins River	20.7	11%	-27%	-50%	-4%	-44%	-68%
237000	Portland Coast	33.6	10%	-26%	-47%	-6%	-46%	-66%
238000	Glenelg River	25.7	-1%	-31%	-49%	-3%	-51%	-67%
239000	Millicent Coast	9.3	6%	-23%	-46%	-1%	-43%	-64%
401000	Upper Murray River	83.8	13%	-11%	-31%	8%	-20%	-46%
402000	Kiewa River	112.4	8%	-11%	-30%	3%	-21%	-47%
403000	Ovens River	78.0	3%	-14%	-34%	1%	-24%	-50%
404000	Broken River	17.0	6%	-18%	-42%	5%	-29%	-61%
405000	Goulburn River	61.7	2%	-12%	-31%	2%	-22%	-47%
406000	Campaspe River	22.7	8%	-20%	-46%	3%	-37%	-68%
407000	Loddon River	7.8	17%	-17%	-45%	19%	-37%	-68%
408000	Avoca River	5.2	29%	-13%	-43%	27%	-18%	-60%
409000	Murray-Riverina	2.9	29%	-15%	-43%	34%	-21%	-68%
410000	Murrumbidgee River	14.4	23%	-8%	-35%	18%	-17%	-48%
412000	Lachlan River	5.4	28%	-8%	-42%	21%	-20%	-58%
413000	Benanee	1.9	35%	-10%	-40%	50%	-6%	-56%
414000	Mallee	1.1	23%	-11%	-51%	23%	-20%	-59%
415000	Wimmera-Avon Rivers	6.8	22%	-15%	-43%	10%	-28%	-61%

Apx Table A.5 Percentage changes to river-basin aggregated annual rainfall under emissions pathway RCP8.5 relative to 1975–2014

BASIN ID	BASIN NAME	BASELINE MEAN ANNUAL RAINFALL (MM)	2040, LOW	2040, MEDIUM	2040, HIGH	2065, LOW	2065, MEDIUM	2065, HIGH
220000	Towamba River	872	7%	-2%	-10%	9%	-1%	-14%
221000	East Gippsland	941	7%	-1%	-11%	8%	-1%	-15%
222000	Snowy River	813	8%	-1%	-10%	8%	-5%	-15%
223000	Tambo River	786	6%	-3%	-11%	7%	-4%	-17%
224000	Mitchell River (vic)	953	4%	-2%	-10%	2%	-5%	-19%
225000	Thomson River	859	4%	-2%	-11%	2%	-4%	-20%
226000	Latrobe River	919	3%	-4%	-11%	2%	-4%	-17%
227000	South Gippsland	872	3%	-4%	-12%	2%	-4%	-16%
228000	Bunyip River	860	3%	-4%	-11%	2%	-5%	-16%
229000	Yarra River	961	4%	-3%	-11%	2%	-4%	-21%
230000	Maribyrnong River	676	3%	-2%	-12%	3%	-5%	-22%
231000	Werribee River	619	2%	-3%	-12%	2%	-6%	-21%
232000	Moorabool River	596	2%	-3%	-12%	2%	-6%	-21%
233000	Barwon River	650	2%	-3%	-11%	1%	-5%	-20%
234000	Lake Corangamite	629	2%	-4%	-12%	0%	-5%	-19%
235000	Otway Coast	950	2%	-4%	-12%	1%	-6%	-19%
236000	Hopkins River	634	2%	-4%	-12%	1%	-6%	-21%
237000	Portland Coast	724	3%	-5%	-11%	0%	-8%	-19%
238000	Glenelg River	655	1%	-5%	-13%	1%	-8%	-22%
239000	Millicent Coast	533	1%	-6%	-15%	1%	-9%	-23%
401000	Upper Murray River	1053	7%	-1%	-8%	8%	-3%	-14%
402000	Kiewa River	1143	6%	-3%	-9%	4%	-2%	-16%
403000	Ovens River	962	5%	-3%	-9%	4%	-4%	-18%
404000	Broken River	573	6%	-4%	-14%	7%	-3%	-18%
405000	Goulburn River	767	4%	-3%	-14%	2%	-4%	-21%
406000	Campaspe River	596	2%	-2%	-15%	3%	-6%	-23%
407000	Loddon River	459	3%	-3%	-14%	3%	-6%	-23%
408000	Avoca River	358	5%	-4%	-16%	7%	-3%	-21%
409000	Murray-Riverina	394	7%	-4%	-15%	9%	-2%	-19%
410000	Murrumbidgee River	542	8%	0%	-11%	12%	-1%	-15%
412000	Lachlan River	458	8%	-2%	-13%	8%	-1%	-13%
413000	Benanee	289	8%	-1%	-18%	10%	-2%	-22%
414000	Mallee	306	5%	-5%	-18%	7%	-7%	-24%
415000	Wimmera-Avon Rivers	394	2%	-4%	-13%	4%	-6%	-22%

Apx Table A.6 Percentage changes to river-basin aggregated annual potential evapotranspiration (PET) under emissions pathway RCP8.5 relative to 1975–2014

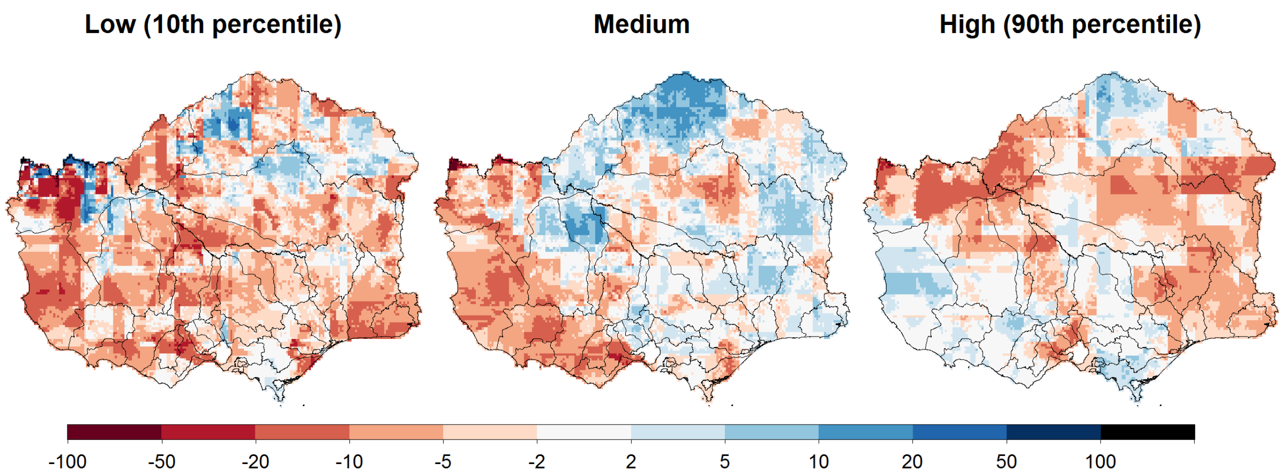
BASIN ID	BASIN NAME	BASELINE MEAN ANNUAL PET (MM)	2040, LOW	2040, MEDIUM	2040, HIGH	2065, LOW	2065, MEDIUM	2065, HIGH
220000	Towamba River	1122	3%	4%	6%	5%	7%	9%
221000	East Gippsland	1100	3%	4%	6%	5%	7%	10%
222000	Snowy River	1113	3%	5%	6%	5%	7%	10%
223000	Tambo River	1104	3%	5%	6%	5%	7%	11%
224000	Mitchell River (vic)	1111	3%	5%	6%	6%	8%	12%
225000	Thomson River	1110	3%	5%	6%	6%	8%	12%
226000	Latrobe River	1091	3%	4%	6%	5%	8%	11%
227000	South Gippsland	1100	2%	4%	5%	4%	7%	11%
228000	Bunyip River	1117	3%	4%	6%	5%	7%	10%
229000	Yarra River	1111	3%	5%	6%	6%	8%	12%
230000	Maribyrnong River	1146	3%	5%	6%	6%	8%	11%
231000	Werribee River	1128	3%	5%	6%	6%	8%	11%
232000	Moorabool River	1127	3%	4%	6%	6%	8%	10%
233000	Barwon River	1126	2%	4%	5%	5%	7%	10%
234000	Lake Corangamite	1135	2%	4%	5%	5%	7%	10%
235000	Otway Coast	1090	2%	4%	5%	4%	6%	10%
236000	Hopkins River	1144	2%	4%	6%	5%	7%	10%
237000	Portland Coast	1113	2%	3%	5%	4%	6%	9%
238000	Glenelg River	1157	3%	4%	6%	5%	7%	10%
239000	Millicent Coast	1243	3%	4%	6%	5%	7%	9%
401000	Upper Murray River	1203	3%	5%	6%	5%	8%	11%
402000	Kiewa River	1233	3%	5%	6%	6%	8%	11%
403000	Ovens River	1247	3%	5%	6%	6%	8%	11%
404000	Broken River	1316	3%	5%	6%	6%	8%	11%
405000	Goulburn River	1230	3%	5%	6%	6%	8%	11%
406000	Campaspe River	1257	3%	5%	6%	6%	8%	10%
407000	Loddon River	1305	3%	5%	6%	6%	8%	10%
408000	Avoca River	1366	3%	4%	5%	5%	7%	10%
409000	Murray-Riverina	1378	3%	5%	5%	5%	8%	10%
410000	Murrumbidgee River	1365	3%	5%	5%	6%	8%	10%
412000	Lachlan River	1452	3%	4%	6%	6%	8%	10%
413000	Benanee	1483	3%	4%	5%	5%	7%	10%
414000	Mallee	1386	3%	4%	5%	5%	7%	10%
415000	Wimmera-Avon Rivers	1313	3%	4%	6%	5%	7%	10%

Apx Table A.7 Changes to river-basin aggregated annual average temperature (Tav) under emissions pathway RCP8.5 relative to 1975–2014
Note that these changes are measured in °C rather than percentages

BASIN ID	BASIN NAME	BASELINE MEAN ANNUAL TAV (°C)	2040, LOW	2040, MEDIUM	2040, HIGH	2065, LOW	2065, MEDIUM	2065, HIGH
220000	Towamba River	14.1	1.0	1.4	1.6	1.9	2.4	2.8
221000	East Gippsland	13.8	1.0	1.3	1.7	1.9	2.4	2.9
222000	Snowy River	11.1	1.0	1.4	1.6	1.9	2.5	2.9
223000	Tambo River	12.8	1.0	1.3	1.6	1.9	2.4	2.8
224000	Mitchell River (vic)	11.8	1.0	1.3	1.5	1.9	2.4	2.9
225000	Thomson River	12.6	1.0	1.3	1.5	1.9	2.4	2.8
226000	Latrobe River	13.3	0.9	1.2	1.5	1.7	2.2	2.8
227000	South Gippsland	13.8	0.8	1.1	1.5	1.6	2.1	2.7
228000	Bunyip River	14.3	0.9	1.2	1.5	1.7	2.1	2.7
229000	Yarra River	13.5	1.0	1.3	1.5	1.9	2.3	2.8
230000	Maribyrnong River	13.0	1.0	1.3	1.5	1.9	2.3	2.8
231000	Werribee River	13.5	1.0	1.3	1.5	1.8	2.3	2.8
232000	Moorabool River	13.6	0.9	1.2	1.5	1.7	2.2	2.6
233000	Barwon River	13.7	0.8	1.1	1.4	1.6	2.1	2.6
234000	Lake Corangamite	13.7	0.8	1.1	1.4	1.6	2.0	2.6
235000	Otway Coast	13.6	0.8	1.0	1.3	1.4	1.9	2.5
236000	Hopkins River	13.5	0.9	1.1	1.4	1.6	2.1	2.5
237000	Portland Coast	13.8	0.7	1.0	1.3	1.3	1.9	2.4
238000	Glenelg River	13.7	0.8	1.1	1.4	1.6	2.0	2.6
239000	Millicent Coast	14.9	0.8	1.1	1.5	1.7	2.1	2.5
401000	Upper Murray River	12.0	1.1	1.4	1.7	1.9	2.6	3.0
402000	Kiewa River	12.9	1.1	1.4	1.6	1.9	2.5	3.0
403000	Ovens River	13.5	1.0	1.4	1.6	2.0	2.5	3.0
404000	Broken River	15.1	1.0	1.4	1.6	2.0	2.5	3.0
405000	Goulburn River	13.6	1.0	1.4	1.6	2.0	2.4	2.9
406000	Campaspe River	13.9	1.0	1.3	1.6	1.9	2.4	2.9
407000	Loddon River	15.1	1.0	1.3	1.6	1.9	2.4	2.9
408000	Avoca River	16.1	1.0	1.4	1.6	1.9	2.4	3.0
409000	Murray-Riverina	16.1	1.1	1.5	1.7	2.0	2.5	3.1
410000	Murrumbidgee River	15.4	1.2	1.4	1.7	2.1	2.6	3.2
412000	Lachlan River	16.9	1.2	1.5	1.8	2.1	2.6	3.3
413000	Benanee	17.7	1.1	1.5	1.7	2.0	2.6	3.2
414000	Mallee	16.5	1.0	1.3	1.6	1.9	2.4	2.9
415000	Wimmera-Avon Rivers	15.3	1.0	1.3	1.6	1.9	2.3	2.9

Appendix B Comparison of RCP8.5 and RCP4.5 emissions pathway scenarios

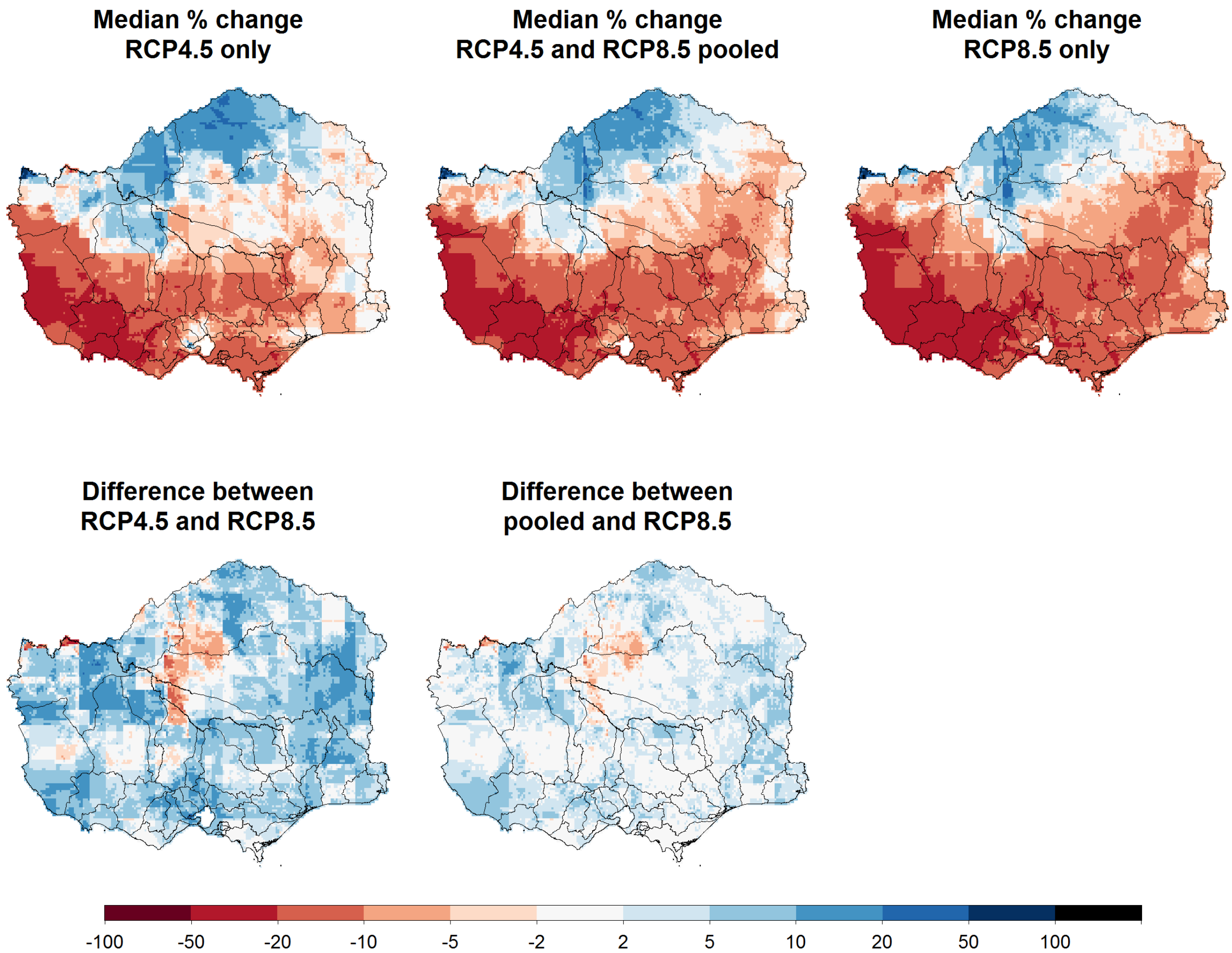
In deriving the runoff projections, RCP8.5 was used exclusively under the warming-weighted approach (see section 2.3.2). From Figure 5, the projected median regional temperature increase under RCP4.5 at 2065 (approximately 1.7°C) is similar to, but slightly larger than, the projected median regional temperature increase under RCP8.5 at 2040 (approximately 1.5°C). Emissions scenario uncertainty is handled under the current approach with the pattern-scaling hypothesis, which holds that the regional runoff response is principally related to the timing of average temperature increases, rather than other differences between emissions scenarios. The similarity of the temperature increases for RCP4.5/2065 and RCP8.5/2040 allow us to examine this hypothesis by comparing the runoff responses at these scenario/date combinations.



Apx Figure B.1 Difference between percentage change in runoff from RCP4.5 at 2065 and scaled percentage change in runoff from RCP8.5 at 2040.
Negative differences (red areas) indicate that the RCP4.5 response is drier than the scaled RCP8.5 response.

Apx Figure B.1 shows the difference between the percentage changes in runoff from the two scenario/date combinations. The percentage changes for RCP8.5 at 2040 are scaled by a factor of 1.7/1.5 to represent the different warming amounts from Figure 5. For the low-impact scenario (10th percentile), the projections from RCP4.5 at 2065 are a bit drier over most of the region, although there is no apparent spatial pattern. The difference between the runoff changes under the medium-impact scenarios has little spatial coherence over the eastern section of the study region, although the western and northern regions (both comparatively drier areas) have more developed responses for the higher temperature increase (i.e. RCP4.5 at 2065). This increased response is in the same direction of change for the projections (cf. Figure 14). The difference between the runoff changes under the high-impact scenario (90th percentile) shows little spatial coherence over most of the study region. These results suggest that approximations of the effect of different scenario/date combinations using the pattern-scaling hypothesis (i.e. by scaling the

RCP8.5 runoff response by different projected temperature increases) can be obtained for the medium response in wetter areas. However, due to the underlying uncertainty, if extrapolations greater than 5 years or so are required for applications, it is recommended that a proper modelling effort be undertaken rather than relying on the pattern-scaling process.



Apx Figure B.2 Medium-impact scenarios at 2065 under RCP4.5, RCP8.5 and pooled emissions scenarios (i.e. RCP4.5 and RCP8.5 combined)

Apx Figure B.2 compares the medium-impact scenarios under RCP4.5 and RCP8.5, as well as the median of the pooled RCP4.5 and RCP8.5 results. The median changes under the pooled scenario is the medium-impact scenario that would have resulted from using the “impact-weighted response” method (see section 2.3.2). Although the spatial pattern under all three options is similar, the median response is less dry under the pooled scenario, and more so under RCP4.5, compared to the response under RCP8.5. Averaged gridcell-wise over the study area, the median runoff responses by 2065 are for reductions in annual runoff of 8.4% under RCP4.5, 11.4% under the pooled results, and 13.7% under RCP8.5. However, when aggregated to Victoria (in a manner consistent with e.g. Table 5), the median responses are for reductions in annual runoff of 11.1% under RCP4.5, 15.0% under the pooled results, and 15.9% under RCP8.5. With the exception of the Mallee basin (which has relatively low rainfall and very little surface water runoff), all surface water basins in Victoria are projected to be drier under the RCP 4.5 medium-impact scenario by 2065.

References

Bureau of Meteorology (2015), Climate change and variability (data resource). Viewed July 2015, <http://www.bom.gov.au/climate/change/>.

Chen, J, Brissette FP and Leconte R (2011) Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. Journal of Hydrology 401, 190–202, doi:10.1016/j.jhydrol.2011.02.020.

Chiew FHS, Peel MC, Western AW (2002) Application and testing of the simple rainfall-runoff model SIMHYD. In: Singh VP, Frevert DK (eds) Mathematical models of small watershed hydrology and applications. Water Resources Publication, Littleton, CO, pp. 335–367.

Chiew FHS, Teng J, Kirono D, Frost AJ, Bathols JM, Vaze J, Viney NR, Young WJ, Hennessy KJ and Cai WJ (2008) Climate data for hydrologic scenario modelling across the Murray-Darling Basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia.

Chiew FHS, Cai W and Smith IN (2009a). Advice on defining climate scenarios for use in Murray-Darling Basin Authority Basin Plan modelling. CSIRO report for the Murray-Darling Basin Authority.

Chiew FHS, Kirono DGC, Kent D and Vaze J (2009b) Assessment of rainfall simulations from global climate models and implications for climate change impact on runoff studies. In Anderssen RS, Braddock RD and Newham LTH (eds) 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, pp. 3907–3913 <http://www.mssanz.org.au/modsim09/I13/chiew.pdf>.

Chiew FHS, Teng J, Vaze J, Post DA, Perraud J-M, Kirono DGC and Viney NR (2009c) Estimating climate change impact on runoff across south-east Australia: method, results and implications of modelling method. Water Resources Research 45, W10414. doi:10.1029/2008WR007338.

Chiew FHS, Kirono DGC, Kent DM, Frost AJ, Charles SP, Timbal B, Nguyen KC and Fu G (2010) Comparison of runoff modelled using rainfall from different downscaling methods for historical and future climates. Journal of Hydrology 387, 10–23, doi:10.1016/j.jhydrol.2010.03.025.

Chiew FHS, Potter NJ, Vaze J, Petheram C, Zhang L, Teng J and Post DA (2014) Observed hydrologic non-stationarity in far south-eastern Australia: implications for modelling and prediction. Stochastic Environmental Research and Risk Assessment 28, 3–15, doi:10.1007/s00477-013-0755-5.

Chiew FHS, Teng J, Potter NJ, Ekström M, Petheram C, Zhang L, Post DA and Vaze J (2015) Multiple sources of uncertainty in modelling future hydroclimate. MODSIM2015, 21st International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and

New Zealand. Extended abstract available at: <http://www.mssanz.org.au/modsim2015/documents/MODSIM2015_Abstracts.pdf>.

CSIRO (2008). Water availability in the Murray-Darling Basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia.

CSIRO (2012) Climate and water availability in south-eastern Australia: A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI). CSIRO, Australia.

CSIRO and Bureau of Meteorology (2015) Climate change in Australia. Information for Australia's natural resource management regions: Technical report, CSIRO and Bureau of Meteorology, Australia. <http://www.climatechangeinaustralia.gov.au/en/publications-library/technical-report/>.

CSIRO and Bureau of Meteorology (2016) Climate Change in Australia website (data resource). Viewed March 2016 <http://www.climatechangeinaustralia.gov.au/>.

DELWP (2016) Guidelines for assessing the impacts of climate change on water supplies in Victoria. Final version, December 2016. Department of Environment, Land, Water & Planning.

Duan Q, Sorooshian S and Gupta V (1992) Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resources Research 28, 1015–1031, doi:10.1029/91WR02985.

Ekström M, Kuruppu N, Wilby RL, Fowler HJ, Chiew FHS, Dessai S and Young WJ (2013) Examination of climate risk using a modified uncertainty matrix framework—Applications in the water sector. Global Environmental Change 23, 115–129, doi:10.1016/j.gloenvcha.2012.11.003.

Ekström M, Grose MR, Whetton, PH (2015) An appraisal of downscaling methods used in climate change research. WIREs Climate Change 6, 301–319, doi:10.1002/wcc.339.

Ekström M, Grose M, Heady C, Turner S, Teng J (2016) The method of producing climate change datasets impacts the resulting policy guidance and chance of mal-adaptation. Climate Services 4, 13–29, doi:10.1016/j.cliser.2016.09.003.

Fowler HJ, Blenkinsop S and Tebaldi C (2007) Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. International Journal of Climatology 27, 1547–1578, doi:10.1002/joc.1556.

Friedlingstein P, Andrew RM, Rogelj J, Peters GP, Canadell JG, Knutti R, Luderer G, Raupach MR, Schaeffer M, van Vuuren DP and Le Quéré C (2014) Persistent growth of CO_2 emissions and implications for reaching climate targets. Nature Geoscience 7, 709–715, doi:10.1038/ngeo2248.

Frost AJ, Charles SP, Timbal B, Chiew FHS, Mehrotra R, Nguyen KC, Chandler RE, McGregor JL, Fu G, Kirono DGC, Fernandez E and Kent DM (2011) A comparison of multi-site daily rainfall downscaling techniques under Australian conditions. Journal of Hydrology 408, 1–18, doi:10.1016/j.jhydrol.2011.06.021.

Giorgi F (2008) Regionalization of climate change information for impact assessment and adaptation. WMO Bulletin 57, 86–92.

Grose M, Timbal B, Wilson L, Bathols J and Kent D (2015) The subtropical ridge in CMIP5 and implications for projections of rainfall in southeast Australia. Australian Meteorological and Oceanographic Journal 65, 90–106.

Haylock MR, Cawley GC, Harpham C, Wilby RL and Goodess CM (2006) Downscaling heavy precipitation over United Kingdom: a comparison of dynamic and statistical methods and their future scenarios. International Journal of Climatology 26, 1397–1415.

Hope P, Timbal B, Hendon H and Ekström M (ed.s) (2015) Victorian Climate Initiative annual report 2014–15. Bureau Research Report BRR-005, Bureau of Meteorology, Victoria.

Hope P, Timbal B, Hendon H and Ekström M (ed.s) (2016) Victorian Climate Initiative annual report 2015–16. Bureau Research Report BRR-015, Bureau of Meteorology, Victoria.

IPCC (2001) Climate Change 2001: Impacts, Adaptation, and Vulnerability (edited by McCarthy JJ, Canziani OF, Leary NA, Dokken DJ and White KS). Contribution of the Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (edited by Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and Midgley PM). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jones DA, Wang W and Fawcett R (2009) High-quality spatial climate data-sets for Australia. Australian Meteorological and Oceanographic Journal 58, 233-248.

Jones RN and Durack PJ (2005) Estimating the Impacts of Climate Change on Victoria's Runoff using a Hydrological Sensitivity Model. CSIRO Atmospheric Research Report commissioned by commissioned by the Victorian Greenhouse Unit, Victorian Department of Sustainability and Environment. CSIRO, Melbourne.

Kirono DGC and Kent DM (2011) Assessment of rainfall and potential evaporation from global climate models and its implications for Australian regional drought projection. International Journal of Climatology 31, 1295–1308, doi:10.1002/joc.2165.

Knutti R, Furrer R, Tebaldi C, Cermak J and Meehl GA (2010a) Challenges in Combining Projections from Multiple Climate Models. Journal of Climate 23, 2739–2758, doi:10.1175/2009JCLI3361.1.

Knutti R, Abramowitz G, Collins M, Eyring V, Gleckler PJ, Hewitson B and Mearns L (2010b) Good Practice Guidance Paper on Assessing and Combining Multi Model Climate Projections. In: Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Assessing and Combining Multi Model Climate Projections (edited by Stocker TF, Qin D, Plattner G-K, Tignor M and Midgley PM). IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland.

McMahon TA, Peel MC, and Karoly DJ (2015) Assessment of precipitation and temperature data from CMIP3 global climate models for hydrologic simulation. Hydrology and Earth System Sciences 19, 361–377, doi:10.5194/hess-19-361-2015.

Meehl GA, Covey C, Taylor KE, Delworth T, Stouffer RJ, Latif M, McAvaney B and Mitchell JF (2007) The WCRP CMIP3 multimodel dataset: A new era in climate change research. Bulletin of the American Meteorological Society 88, 1383–1394, doi:10.1175/BAMS-88-9-1383.

Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, Lamarque J-F, Matsumoto K, Montzka SA, Raper SCB, Riahi K, Thomson A, Velders GJM and van Vuuren DP (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109, article 213, doi:10.1007/s10584-011-0156-z.

Moran R and Sharples J (2011) Guidelines for the development of a water supply-demand strategy: Technical Supplement for Section 3.5 – Forecasting Supply. Victorian Government Department of Sustainability and Environment (DSE), Melbourne, Victoria.

Morton FI (1983) Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. Journal of Hydrology 66, 1–76, doi:10.1016/0022-1694(83)90177-4.

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP and Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. Nature 463, 747–756, doi:10.1038/nature08823.

Peel MC, McMahon TA and Finlayson BL (2004) Continental differences in the variability of annual runoff-update and reassessment. Journal of Hydrology 295, 185–197, doi: 10.1016/j.jhydrol.2004.03.004.

Peters GP, Andrew RM, Boden T, Canadell JG, Ciais P, Le Quéré C, Marland G, Raupach MR and Wilson C (2013) The challenge to keep global warming below 2°C. Nature Climate Change 3, 4–6, doi:10.1038/nclimate1783.

Piani C, Weedon GP, Best M, Gomes SM, Viterbo P, Hagemann S and Haerter JO (2010) Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models. Journal of Hydrology 395, 199–215, doi:10.1016/j.jhydrol.2010.10.024.

Post DA and Moran RJ (2011) Practical application of climate-induced projected changes in water availability to underpin the water planning process in Victoria, Australia. In Chan F, Marinova D and Anderssen RS (eds) MODSIM 2011 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, pp. 3629–3635 <http://www.mssanz.org.au/modsim2011/I6/post.pdf>.

Post DA and Moran RJ (2013) Provision of usable projections of future water availability for southeastern Australia: The South Eastern Australian Climate Initiative. Australian Journal of Water Resources 17, 135–142.

Post DA, Chiew FHS, Teng J, Wang B and Marvanek S (2012) Projected changes in climate and runoff for south-eastern Australia under 1°C and 2°C of global warming. A SEACI Phase 2 special report. CSIRO, Australia.

Potter NJ, Chiew FHS and Frost AJ (2010) An assessment of the severity of recent reductions in rainfall and runoff in the Murray-Darling Basin. Journal of Hydrology 381, 52–64, doi:10.1016/j.jhydrol.2009.11.025.

Potter N, Teng J, Chiew FHS, Ekström M and Zhang L. (2015) Scoping study for the delivery of future runoff projections for Victoria.

Potter N, Chiew F, Zheng H, Ekstrom M, Zhang L (2016) Future hydroclimate projections for Victorian river basins. v1. CSIRO. Data Collection. <https://data.csiro.au/dap/landingpage?pid=csiro:18071>.

Rogelj J, Meinshausen M and Knutti R (2012) Global warming under old and new scenarios using IPCC climate sensitivity range estimates. Nature Climate Change 2, 248–253, doi:10.1038/nclimate1385.

Rummukainen M (2016) Added value in regional climate modelling. WIREs Climate Change 7, 145–159. doi:10.1002/wcc.378.

Smith I and Chandler E (2010) Refining rainfall projections for the Murray Darling Basin of south-east Australia—the effect of sampling model results based on performance. Climatic Change 102, 377–393, doi:10.1007/s10584-009-9757-1.

Taylor KE, Stouffer RJ and Meehl GA (2012) An overview of CMIP5 and the experiment design. Bulleting of the American Meteorological Society 93, 485–498, doi:10.1175/BAMS-D-11-00094.1.

Teng J, Vaze J, Chiew FHS, Wang B and Perraud J-M (2012a) Estimating the relative uncertainties sourced from GCMs and hydrological models in modeling climate change impact on runoff. Journal of Hydrometeorology 13, 122–139, doi:10.1175/JHM-D-11-058.1.

Teng J, Chiew FHS, Vaze J, Marvanek S and Kirono DGC (2012b) Estimation of Climate Change Impact on Mean Annual Runoff across Continental Australia Using Budyko and Fu Equations and Hydrological Models. Journal of Hydrometeorology 13, 1094–1106, doi:10.1175/JHM-D-11-097.1.

Teng J, Chiew FHS, Timbal B, Wang Y, Vaze J and Wang B (2012c) Assessment of an analogue downscaling method for modelling climate change impacts on runoff. Journal of Hydrology 472–473, 111–125, doi:10.1016/j.jhydrol.2012.09.024.

Teng J, Potter NJ, Chiew FHS, Zhang L, Wang B, Vaze J and Evans JP (2015) How does bias correction of regional climate model precipitation affect modelled runoff? Hydrology and Earth System Sciences 19, 711–728, doi:10.5194/hess-19-711-2015.

Timbal B, Ekström M, Fiddes S, Grose M, Kirono D, Lim E-P, Lucas C and Wilson L (2016) Climate change science and Victoria. Bureau Research Reports BRR-014, Bureau of Meteorology, Victoria.

Torma Cs, Giorgi F and Coppola E (2015) Added value of regional climate modeling over areas characterized by complex terrain—Precipitation over the Alps. Journal of Geophysical Research: Atmospheres 120, 3957–3972. doi: 10.1002/2014JD022781.

Van Dijk AIJM (2010) The Australian Water Resources Assessment System. Technical Report 3. Landscape Model (version 0.5) Technical Description. CSIRO Water for a Healthy Country National Research Flagship, Australia. <http://www.clw.csiro.au/publications/waterforahealthycountry/2010/wfhc-aus-water-resources-assessment-system.pdf>.

van Vuuren, DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque J-F, Masui T, Meinshausen M, Nakicenovic N, Smith SJ and Rose SK (2011) The representative concentration pathways: an overview. Climatic Change 109, 5–31, doi: 10.1007/s10584-011-0148-z.

Vaze J, Teng J and Chiew FHS (2010) Assessment of GCM simulations of annual and seasonal rainfall and daily rainfall distribution across south-east Australia. Hydrological Processes 25, 1486–1497, doi:10.1002/hyp.7916.

Vaze J, Chiew FHS, Perraud J-M, Viney N, Post D, Teng J, Wang B, Lerat J and Goswomi M (2011) Rainfall-runoff modelling across south-eastern Australia: datasets, models and results. Australian Journal of Water Resources 14, 101–116.

Viney NR, Perraud J, Vaze J, Chiew FHS, Post DA and Yang A (2009) The usefulness of bias constraints in model calibration for regionalisation to ungauged catchments. In Anderssen RS, Braddock RD and Newham LTH (eds) 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, pp. 3421–3427 <http://www.mssanz.org.au/modsim09/I7/viney_I7a.pdf>.

Westra S, Thyer M, Leonard M and Lambert M (2014a) Impacts of Climate Change on Surface Water in the Onkaparinga Catchment – Volume 2: Hydrological Evaluation of the CMIP3 and CMIP5 GCMs and the Non-homogenous Hidden Markov Model (NHMM). Goyder Institute for Water Research Technical Report Series No. 14/23, Adelaide, South Australia.

Westra S, Thyer M, Leonard M and Lambert M (2014b) Impacts of Climate Change on Surface Water in the Onkaparinga Catchment. Final Report Volume 3: Impacts of Climate Change on Runoff. Goyder Institute for Water Research Technical Report Series No. 14/27, Adelaide, South Australia.

Wilby RL, Hay LE, Gutowski WJ, Arritt RW, Takle ES, Pan Z, Leavesley GH and Clark MP (2000) Hydrological responses to dynamically and statistically downscaled climate model output. Geophysical Research Letters 27, 1199–1202, doi:10.1029/1999gl006078.

Zhang L, Hickel K, Dawes WR, Chiew FHS, Western AW and Briggs PR (2004) A rational function approach for estimating mean annual evapotranspiration. Water Resources Research 40, W02502, doi:10.1029/2003wr002710.

Zhang L, Potter N, Hickel K, Zhang Y and Shao Q (2008) Water balance modeling over variable time scales based on the Budyko framework – Model development and testing. Journal of Hydrology 360, 117-131.

Zhang Y, Viney N, Frost A, Oke A, Brooks M, Chen Y and Campbell N (2013) Collation of Australian modeller's streamflow dataset for 780 unregulated Australian catchments. CSIRO Water for a Healthy Country National Research Flagship, Austrlalia.

CONTACT US
t 1300 363 400
+61 3 9545 2176
e csiroenquiries@csiro.au
w www.csiro.au