# Climate Change Projections

Latrobe Valley Regional Rehabilitation Strategy

## Method report and user guidance

| Final_v1

19 December 2017

Prepared for the Department of Environment, Land, Water and Planning

# Climate Change Projections

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| Project No: | IS216600 |
| Document Title: | Method report and user guidance |
| Document No.: | |
| Revision: | Final_v1 |
| Date: | 19 December 2017 |
| Client Name: | Latrobe Valley Regional Rehabilitation Strategy |
| Client No: | Prepared for the Department of Environment, Land, Water and Planning |
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| Author: | Rachel Brown |
| File Name: | \\jacobs.com\ANZ\IE\Projects\03_Southern\IS216600\21 Deliverables\ProjectReport\LVRRS_Clima |

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## Document history and status

| Revision | Date | Description | By | Review | Approved |
|---|---|---|---|---|---|
| Draft | 27 Nov 2017 | Draft climate change projections and application guidelines | Rachel Brown (Jacobs)<br>James Bennett (CSIRO)<br>Michael Grose (CSIRO)<br>David Robertson (CSIRO)<br>Rory Nathan (Melb Uni)<br>Francis Chiew (CSIRO)<br>Nick Potter (CSIRO) | CSIRO, Melb Uni | Greg Hoxley |
| Final | 8 Dec 2017 | Incorporates DELWP feedback | James Bennett, Rachel Brown | Jacobs | Greg Hoxley |
| Final v1 | 19 Dec 2017 | Incorporates Director feedback | Rachel Brown | Jacobs | Greg Hoxley |

## Contents

# Executive Summary

In May 2015 the Victorian Government re-opened the Hazelwood Mine Fire Inquiry, to examine, among other things mine rehabilitation options for the Latrobe Valley's three brown coal mines. Volume IV of the Hazelwood Mine Fire Inquiry report found that, with the current knowledge available, some form of pit lake is the most viable rehabilitation option for the Latrobe Valley coal mines. However, there are significant knowledge gaps that need to be addressed to test the feasibility of the pit lake options. These knowledge gaps will be addressed through the technical studies being completed by the Victorian Government as part of the preparation of the LVRRS.

**Assessment of the feasibility of pit lakes requires an assessment of future climate change.** The pit lakes may take an extended period to fill with water: up to 100 years depending on water sources and final level. In addition, the LVRRS wishes to understand the feasibility of pit lakes over the longer term to 2300. Climate change could impact water availability over the period of rehabilitation, as well as the water balance for the established pit lake over the longer term.

**Methods to project future climate were developed through consensus of experts.** Two technical workshops were held to establish a suitable method to assess the impacts of future climate change. The workshops were attended by climate and hydrological scientists from CSIRO and the University of Melbourne, engineers from Jacobs, representatives from regional catchment management agencies, staff from the Department of Environment, Land, Water and Planning (DELWP), and the Latrobe Valley Mine Rehabilitation Commissioner. Methods were agreed by consensus of scientific and engineering advisors, after considering feedback from DELWP and catchment management agencies. Whenever possible, methods follow the *Guidelines for assessing the impact of climate change on water supplies in Victoria* established by DELWP. Scientists agreed that climate change to 2100 can be quantified with projections from existing studies, while changes to climate beyond 2100 will be assessed qualitatively.

**Changes to 21$^{st}$ century climate can be quantified by applying scaling factors to historical data. Scaling factors are generated from hydroclimate projections produced by the Victorian Climate Initiative.** Scaling factors for rainfall, potential evapotranspiration, temperature and runoff are generated for the Gippsland region. Factors are generated from 42 global climate models (GCMs), for the RCP4.5 (medium) and RCP8.5 (high) greenhouse gas emissions scenarios and for the future periods 2031-2050 and 2056-2075. Factors are generated for annual and seasonal changes. The range of changes is summarised in dry, median and wet scenarios that approximate the 10$^{th}$, 50$^{th}$ and 90$^{th}$ percentiles of the full range of GCMs. Factors are generated for grid cells at a 0.05º (~5 km) horizontal resolution, as well as averaged over four key river basins: the Latrobe River, the Thompson River, the Mitchell River and the Tambo River.

**Where modelling is carried out for the dry, median and wet scenarios, the annual scaling factors should be used.** Dry, median and wet scenarios for a given season are estimated independently of other seasons and annual changes. Using the seasonal scaling factors could overestimate both the dry extreme and the wet extreme when aggregated to annual changes, as this combines different GCMs. Where pit lake rehabilitation strategies are sensitive to seasonally specific climate change, more detailed modelling should consider the seasonal scaling factors from the full range of GCMs.

**Climate projections beyond 2100 are highly uncertain, and depend heavily on the trajectory of greenhouse gas emissions.** The possible range of future climates for 2100-2300 is very wide. Under a high greenhouse gas emissions scenario, temperature changes of +6 to +14 °C are projected with an associated increase in evaporation, and a rainfall decrease of 0-50% (median 25-30%). It is unlikely that Victorian climate will be wetter after 2100 than the current climate.

**Variability of rainfall and runoff at decadal time scales could have a large impact on the filling of pit lakes, in addition to potential impacts of future climate change.** Extended sequences of dry or wet years or decades will impact on the feasibility of pit lakes. Pits filling over a 20–30 year period will be significantly influenced by rainfall and runoff over that period, whilst pits filling over a much longer period will be dependent on the long-term hydroclimatology (or climate change) of the region. Hydroclimate variability over multi-year and decadal scales can be accounted for by using long historical records or stochastically generated climate series.

# 1. Introduction

## 1.1 The Latrobe Valley Regional Rehabilitation Strategy

In 2014 the Victorian Government opened the ‘Hazelwood Mine Fire Inquiry” (the Inquiry), an independent inquiry into the causes and effects of the February 2014 fire at the Hazelwood Coal Mine. In 2016, the re-opened Inquiry made a number of recommendations regarding the planning required to prepare for the closure of the three largest coal mines in the Latrobe Valley: the Hazelwood, Loy Yang and Yallourn open pit coal mines.

The Inquiry concluded that the safest, most viable, practicable and feasible rehabilitation strategy for all three mines would be to fill the open pits with water to create pit lakes. However there were important knowledge gaps which needed to be investigated to be in a position to confirm that pit lakes are feasible for all three mines. For example, the pit lakes may be very large (up to ~1000 GL for a single pit lake), and modelling will be needed to determine whether enough water will be available to fill and maintain the lakes over long time scales.

The Victorian Government committed to developing a Latrobe Valley Regional Rehabilitation Strategy (LVRRS) by June 2020 to help fill current knowledge gaps specific to coal mine rehabilitation. The LVRRS will be informed by an assessment of the potential regional impacts of rehabilitating all three coal mines to pit lakes, with particular attention to water and land stability issues. Additionally, preparation of the LVRRS will include examination of potential end land uses and associated social and economic implications.

The three Latrobe Valley mines, based on the mine operators’ current work plans, will close progressively over the coming decades, and each may take an extended period to fill with water (e.g. up to 100 years depending on water sources). There is therefore a need to project the effect of climate change on the feasibility of the pit lake landforms for each mine in terms of potential pit lake filling times, impacts on regional water supply security and downstream environments, and the long-term viability of the pit lakes themselves. Climate change could impact water availability over the period of rehabilitation, as well as the long-term water balance for the established pit lakes. Given the time frames being considered (e.g. out to 2300), there is a need to consider climate variations due to changes in radiative forcing from greenhouse gas emissions and long-term natural variability in rainfall and runoff.

## 1.2 LVRRS Climate Change Projections Study

The LVRRS Climate Change Projections Study was established to derive hydroclimate projections (rainfall, temperature, evaporation and runoff) for the region around the mines and rivers that drain into the Gippsland Lakes. These projections are needed as input into surface water models, groundwater models and pit water volumetric and quality models that will be used by the Department of Environment, Land, Water and Planning (DELWP) and the Department of Economic Development, Jobs, Transport and Resources (DEDJTR) to inform the LVRRS. To produce these projections, a clear process was established to develop climate change projections that could be consistently applied across LVRRS tasks as needed.

To support the broad requirements of the LVRRS, climate change projections are required for a range of future climate scenarios over this century (including dry, median and wet climate change along with a scenario based on post-1997 step-change). In addition, it is also relevant to provide available information for these scenarios over longer term trajectories through to 2500 where possible. This is necessary given the long time scales relevant to the rehabilitation process.

The latest climate research has been used as the basis for the projections described in this document, including:

- The Victorian Climate Initiative (VicCI) synthesis report (Hope et al., 2017; http://www.bom.gov.au/research/projects/vicci/);
- Climate and runoff projections developed for Victoria through VicCI (Potter et al., 2016); http://doi.org/10.4225/08/5889749204faa);

- Climate change science and Victoria research report (Timbal et al., 2016);
- Guidelines for assessing the impact of climate change on water supplies in Victoria (DELWP, 2016);
- Climate change projections for Australia's NRM regions (CSIRO and Bureau of Meteorology, 2015; www.climatechangeinaustralia.gov.au);
- SDM downscaled climate dataset (Timbal et al., 2009, 2011);
- NARCliM WRF downscaled climate dataset (Evans et al. 2014; dataset: http://www.ccrc.unsw.edu.au/sites/default/files/NARCliM/index.html); and
- CCAM downscaled climate dataset (McGregor, 2005; McGregor and Dix, 2008).

The climate change projections described in this document have been developed based on a method agreed through a collaborative process involving researchers from CSIRO and the University of Melbourne, in consultation with representatives from Jacobs and DELWP. This process was designed to ensure the projections suit the specific challenges of the LVRRS. In addition, Gippsland-based catchment management authorities and water corporations provided input on water management issues relevant to the region. Two major workshops were held where participants articulated the types of information required to support the LVRRS and related technical studies, and the available climate change projections available to support these projects (Section 2.1). The contributions of these participants are reflected in the method and associated commentary in this document.

This study utilises climate projections from previous studies, and does not provide time series outputs. This study provides scaling factors to apply to historical data. A number of appropriate climate projections data sets are available to support this work, which eliminates the need for additional specific modelling. Section 3 summarises the suitability of these datasets for the LVRRS work.

## 1.3 Developing Regional Climate Change Projections

Projecting future climate to 2100 is commonly carried out with coupled ocean-atmosphere Global Climate Models (GCMs). GCMs are large numerical models that resolve physical and biogeochemical processes in the oceans and atmosphere to understand the response of climate to changes in radiative forcing. GCMs are the major tool used by the Intergovernmental Panel on Climate Change (IPCC) to understand possible future changes in climate. GCMs are produced by a large number of different modelling research groups around the world, and vary in spatial resolution and in the methods they use to represent climate processes. These differences can result in different responses in climate to changes in radiative forcing. Climate projections are most robustly represented as an ensemble of model projections to give a range of possible future climates. Future projections for a range of the most recently developed GCMs is available from the fifth phase of the Coupled Model Inter-comparison Project 5 (CMIP5) database (http://cmip-pcmdi.llnl.gov/cmip5/). These model outputs are available for a range of future possible emissions scenarios, called representative concentration pathways (RCPs).

Global climate models may be too coarsely resolved to offer the kind of spatial detail required to inform regional decisions. Several approaches exist to translate projections from GCMs to regions, including:

1) Statistical downscaling (e.g. Timbal and Jones 2008) uses statistical relationships between GCM outputs and local observations to translate projections at a local scale. The statistical relationships have to be generated during historical periods, during which observations are available. This method assumes relationships between GCM outputs and observations will hold into the future.
2) Dynamical downscaling (e.g. Evans et al. 2014) uses GCM outputs as input into much higher resolution 'regional climate models' (RCMs). RCMs are computationally expensive, but they can help resolve, for example, orographic effects on rainfall at a much finer scale than GCMs.
3) Empirical scaling, which scales fine-scale historical observations by changes projected by GCMs. This is the approach taken by the VicCI (Potter et al. 2016), and is similar to the pattern scaling (Mitchell 2003) based approaches taken in a number of other major hydroclimatological studies in Australia (e.g. Chiew et al. 2009; Post et al. 2012).

Each of these approaches has been conducted over the LVRRS study region. We describe the process through which we chose our method in Section 2, and discuss the technical reasons for this choice in Section 3.1.

# 2. Process for the development of LVRRS Climate Change Projections

## 2.1 Technical workshops

Two technical and stakeholder workshops were held to seek input into the requirements for the climate change projections, to evaluate the suitability of the available datasets and to obtain agreement on the method to apply for this study. Workshop attendees are grouped into three categories:

1) A steering group to oversee the project and confirm the climate projections meet the needs of the LVRRS project;
2) Scientific and engineering advisors to ensure the methods are scientifically robust and fit for purpose; and
3) Stakeholders to ensure the climate change projections will address the needs of the broader water management community.

The first workshop was held on 5 September, 2017 and was attended by the following project team members, climate scientists and technical specialists from DELWP, CSIRO, Melbourne University and Jacobs:

- Brett Davis (steering group - DELWP)
- Natasha Sertori (steering group - DELWP)
- Geoff Steendam (steering group - DELWP)
- Greg Hoxley (engineering advisor - Jacobs)
- Rachel Brown (engineering advisor -Jacobs)
- Katherine Szabo (engineering advisor -Jacobs)
- James Bennett (scientific advisor - CSIRO)
- Francis Chiew (scientific advisor - CSIRO)
- David Robertson (scientific advisor - CSIRO)
- Michael Grose (scientific advisor - CSIRO)
- Rory Nathan (scientific advisor - University of Melbourne)

This workshop discussed technical aspects such as the available projections data sets for the next century, the range of projections of relevance to the LVRRS and consideration of extreme events. The workshop also considered the most appropriate guidance for climate to 2300. The choice of climate projections method was determined at this workshop by consensus of scientific and engineering advisors, with guidance from the steering group.

A second stakeholder workshop was held in Traralgon on 10 October 2017. This involved many of the participants from Workshop 1 in addition to the following attendees:

- Yi Ma (stakeholder - DELWP)
- David Stork (stakeholder - West Gippsland CMA)
- Sean Phillipson (stakeholder - East Gippsland CMA)
- Jolyon Taylor (stakeholder - Gippsland Water)
- Rae Mackay (stakeholder - Latrobe Valley Rehabilitation Commissioner)

This second workshop was an opportunity for the Latrobe Valley water resources management agencies and other technical specialists to articulate the information required to support the LVRRS and related technical studies, and to discuss which of the available climate change data are most suitable to support these projects. Through these conversations, the group identified regional aspects of importance to the LVRRS climate change projections. A particular issue identified in these workshops was the important role that natural decadal variability in rainfall and runoff could have on the feasibility of the pit lakes.

Final decisions on the choice of climate projections and their application were made by consensus of scientific and engineering advisors, after considering feedback from the steering committee and stakeholders. The climate change projections described in this document reflect the outputs from this collaboratively agreed method. The contributions of these participants are reflected in the method and associated commentary in this document.

## 2.2 Overview of Consensus

Numerous different climate change studies have generated outputs which are potentially relevant for the LVRRS suite of projects. In particular, for the projections over the next century (to 2100), four sets of climate outputs from major studies are available (Section 3.1 and Table 3.1). Participants of the two technical workshops agreed that the method of empirical scaling (Potter et al. 2016) conducted for VicCI is the most feasible for the LVRRS, as these projections consider a larger range of global climate models and emissions scenarios compared to the other studies. As a further advantage, data from these projections are readily available. An overview of the consensus approach to generating projections to 2100 is provided in Section 2.3. Specific details of the scaling methods used to generate the LVRRS climate change projections are provided in Section 3.

For the purposes of the LVRRS, technical specialists noted that the range of future climate change represented by the climate change projections is only one source of uncertainty when LVRRS rehabilitation strategies are considered. Uncertainties from other sources may have much greater influence on the choice of rehabilitation strategies, and may require quantification through specific LVRRS studies. These sources of uncertainty could include: changes in the frequency and distribution of rainfall, changes in demand for water by irrigators and industry, changes in the severity and sequencing of multi-year wet and dry periods, and the risk of increased bushfire risk and other land-use changes to streamflow. Further details of these issues are provided in Section 5.5.

While climate change projections for the next century are readily available, potential climate changes beyond this time are more uncertain. For long term trajectories, the most appropriate approach for the LVRRS is to first understand the types of climatic changes that influence the choice of rehabilitation strategy, and then consider whether these changes are physically plausible. To aid in this process, qualitative descriptions of possible climate changes to 2300 based on existing studies are provided in this study. An overview of this approach is described in Section 2.4, and qualitative climate projections beyond 2100 are described in Section 4.

Importantly, the agreed method for the LVRRS climate change projections needs to be compatible with being able to account for natural variability in rainfall and runoff in addition to the impacts of future climate change.

## 2.3 Quantitative Projections to 2100

The approach agreed upon to develop the climate change projections for this century (to 2100) for the LVRRS is summarised as follows:

1) Wherever possible, the projections will draw upon the methods detailed by the DELWP (2016) "Guidelines for Assessing the Impact of Climate Change on Water Supplies in Victoria".
2) Climate change scaling factors for temperature, potential evaporation, rainfall and runoff generated as part of the Victorian Climate Initiative by Potter *et al*. (2016) will be used. These projections cover a wide range of 42 global climate models, cover two future periods (20-year periods centred on 2040 and 2065) and are available for two greenhouse emissions scenarios (RCP4.5 and RCP8.5).
3) Climate change scaling should be applied to historical observations from 1975 onwards, as this period is generally considered to already reflect a climate change signal, compared to climate from earlier in the 20th century.
4) Very long (multi-decade) historical sequences are required to assess the feasibility of sequentially filling large pit lakes from streamflow, in order to account for natural variability at decadal time scales. This can be achieved by using the longest historical records available. To accord with point (3), scaling pre-1975 data to have similar statistical properties (e.g. annual means) as post-1975 data was discussed. This method was impracticable, as long records were not available for all variables (e.g. runoff simulations from Potter et al. 2016 were available only from 1975 onwards). While stochastic procedures are available to

better account for natural variability at decadal time scales, it may not be possible to apply such procedures to the current generation of water resource models that exist for the catchments of interest.

5) The DELWP Climate Change Guidelines recommend the use of annual scaling factors unless results are strongly sensitive to seasonal changes, as seasonal scaling factors are more uncertain. These recommendations are also relevant for the LVRRS, unless seasonal impacts are considered to be important for the situation. This will likely be determined on a project by project basis. The greater uncertainty associated with the seasonal factors is described in Section5.1.3.

6) The most robust way to estimate uncertainty and consider the range of future climate changes is to use the full range of GCMs and emissions scenarios in planning models. However, for practical purposes, scaling factors will be derived and provided for dry, median and wet scenarios.

A detailed description of the method is given in Section 3.

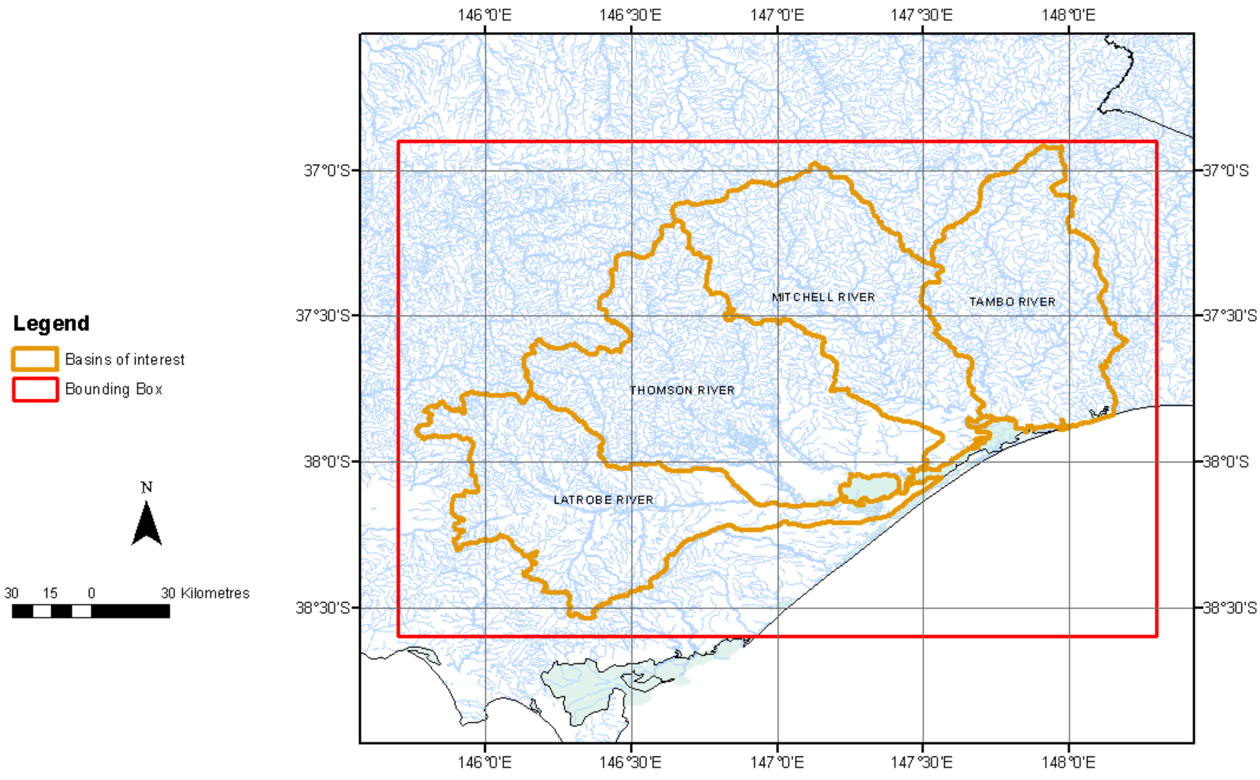


Figure 2.1 : Gippsland domain (red square) and basins (orange boundaries) for which GCM outputs are ranked to identify dry, median and wet scenarios.

## 2.4 Qualitative description of possible climate for 2100-2300

The following points summarise the approach agreed upon to assess climate changes to 2300 for the LVRRS:

1) A framework for understanding very long-term changes will be described, including:
   a) the large divergence in possible future climates arising from the wide range of possible emissions scenarios
   b) the large range of possible climate response to each emissions scenario
2) Qualitative description of very long-term changes (to 2300) and implications for the globe and for the Gippsland region, based on:
   a) Review of quantitative changes that are available from GCMs run beyond 2100
   b) Review of changes projected by Earth System Models of Intermediate complexity (EMICS)

3) Review of physical limits to future climate change

The assessment of climate change for 2100-2300 are described in Section 4.

# 3. Methods to project climate to 2100

## 3.1 Choice of projections

High resolution projections are available for the Gippsland region from four recent climate studies, summarised in Table 3.1. Three of these studies – SDM (Statistical Downscaling Method; Timbal et al. 2009), CCAM (Conformal Cubic Atmospheric Model; McGregor & Dix 2008) and NARClim (Regional Climate Modelling Project; Evans et al. 2014) – used formal 'downscaling' methods. Downscaling refers to the use of dynamical regional climate models and/or sophisticated statistical models to produce climate projections at a finer spatial resolution than those from coupled ocean-atmosphere global climate models (GCMs). All downscaling methods are applied to GCMs, and they can result in quite different regional climate projections than those produced from the 'parent' GCM. The fourth study – VicCI (Potter et al. 2016) – derived changes from GCM projections, and applied these to historical observations, with a method called 'empirical scaling'. A consensus decision was made to recommend the use of the VicCI projections for LVRRS, for the following reasons:

1) Empirical scaling is computationally simple, and thus has been applied to a large number of GCMs (up to 42), emissions scenarios (RCP4.5, RCP8.5), and future periods (periods centred on 2040 and 2065). This gives a large range of possible futures, allowing the LVRRS to adequately explore sensitivity to possible future climate change. By contrast, the downscaling studies produced projections for fewer GCMs, a single future period, and single emissions scenario.
2) The VicCI method scales historical observations. This is consistent with the approach DELWP and DEDJTR will take to assess the feasibility of pit lakes, and therefore no new method development was required.
3) VicCI had archived most outputs required by DELWP for the LVRRS, including delta change/change factors for surface temperature, potential evaporation, rainfall and runoff, over the Latrobe Valley region. Other studies were missing one or more of these variables.
4) The mean changes in rainfall projected by VicCI were neither as dry as the SDM projections, nor as wet as the dynamically downscaled projections (Potter et al., submitted). That is, the mean changes produced by VicCI approached a reasonable 'central estimate' of change.

## 3.2 Summary of VicCI methods

### 3.2.1 GCMs and emissions scenarios

A complete description of methods for the VicCI projections is given by Potter et al. (2016), and we offer only a summary here. Forty-two GCMs from the fifth phase of the Coupled Model Inter-comparison Project database (CMIP5; http://cmip-pcmdi.llnl.gov/cmip5/) were used to generate projections (Appendix A). Two Representative Concentration Pathways (RCP) were chosen: RCP4.5, a medium-low greenhouse gas emissions scenario where radiative forcing reaches 4.5 $Wm^{-2}$ over pre-industrial levels and radiative forcing stabilises after 2100 and RCP8.5, a high radiative forcing scenario that reaches 8.5 $Wm^{-2}$ by 2100 and continues increasing afterwards. Of the 42 GCMs, 39 had projections available for RCP4.5. All 42 GCMs had projections available for RCP8.5.

### 3.2.2 GCM current climate and future periods

Empirical scaling was calculated as deviations of climate from two future periods, 2031-2050 (centred on 2040) and 2056-2075 (centred on 2065), from 1986-2005. We will refer to the 1986-2005 period as the 'GCM current climate', following Potter et al. (2016). To carry out rainfall-runoff modelling, the empirical scaling factors were applied to observations for the period 1975-2014 (Section 3.2.4). We will refer to 1975-2014 as the 'baseline period', again following Potter et al. (2016).

Table 3.1 : Climate projections datasets available for the LVRRS region (adapted from Hope et al., 2017)

| Dataset | Reference | Method summary | Emissions scenarios | Baseline climate | Future climate(s) | # GCMs | Grid |
|---|---|---|---|---|---|---|---|
| VicCI (Victorian Climate Initiative) | Potter et al. (2016) | 1. Empirical scaling: change factors calculated from GCMs<br>2. Rainfall scaled by rank<br>3. Applied to AWAP historical observations | RCP4.5<br>RCP8.5 | 1986–2005 | 2031–2050<br>2060–2079 | 39 (RCP4.5)<br>42 (RCP8.5) | 0.05° |
| SDM (Statistical Downscaling Method) | Timbal et al. (2009) | 1. Statistical downscaling with climate analogues<br>2. Analogues derived from historical reanalyses<br>3. Applies analogues to future projections from GCMs | RCP8.5 | 1986–2005 | 2060–2079 | 22 | 0.05° |
| CCAM (Conformal Cubic Atmospheric Model) | McGregor and Dix (2008) | 1. Dynamical downscaling with a stretched grid global model<br>2. Forced with bias-corrected SST from GCMs<br>3. Single atmospheric model | RCP8.5 | 1986–2005 | 2060–2079 | 6 | 0.5° |
| NARClim (NSW/ACT Regional Climate Modelling Project) | Evans et al. (2014) | 1. Dynamical downscaling with the Weather Research and Forecasting (WRF) model<br>2. WRF is a limited area RCM<br>3. Ensemble of 3 WRF configurations | SRESA2 | 1990–2009 | 2056–2075 | 4<br>(x 3 WRF ensemble members) | 0.1° |

### 3.2.3 Empirical scaling

Empirical scaling was applied to three variables: surface air temperature (tas), potential evapotranspiration (PET), and rainfall. tas and rainfall are direct outputs from GCMs. PET was calculated from temperature, solar radiation and vapour pressure outputs from GCMs, using Morten's (1983) algorithm for wet environments. Solar radiation and vapour pressure variables are not available from all GCMs; in these cases, solar radiation and vapour pressure were taken from GCMs whose temperature change most closely matched the target.

Different scaling/delta changes were applied to different variables, as follows:

- tas: delta change (baseline temperature subtracted from future temperature) is calculated for: i) mean annual tas; ii) mean summer tas (Dec-Jan-Feb); iii) mean autumn tas (Mar-Apr-May); iv) mean winter tas (Jun-Jul-Aug); and v) mean spring tas (Sep-Oct-Nov).
- PET: scaling factors (simple ratios) were calculated for annual changes in PET. Ratios are also calculated for each season (DJF, MAM, JJA, SON). For each GCM, seasonal factors were rescaled so that seasonal changes accumulated to annual changes.
- Rainfall: rank-based scaling was applied to daily rainfall. Fifty-three scaling factors were calculated for each season (DJF, MAM, JJA, SON). The first 50 scaling factors were calculated from daily rainfall for each of the top fifty ranked rainfalls drawn from a given season during each 20-year period. The 51st factor was the ratio calculated for the average of the 51-100 ranked rainfalls, the 52nd factor was the ratio for the average of the 101-200 ranked rainfalls, and the 53rd factor was the ratio of the mean of the remaining rainfalls. The process was also carried out for annual rainfall. Seasonal rainfall factors were rescaled so that seasonal changes accorded with annual changes for each GCM.

Finally, scaling factors were regridded from each GCM's native resolution to the 0.05° grid resolution of the Australian Water Availability Project (AWAP; http://www.bom.gov.au/jsp/awap/).

The more complex rank-based scaling was used for rainfall to account for the thermodynamic expectation that a warmer atmosphere will result in more intense short-duration storms, even in regions where mean rainfall decreases (e.g. Held and Soden 2006) if dynamical climate responses are ignored.

#### 3.2.4 Runoff modelling

Empirical scaling was used to scale observed rainfall and PET for the period 1975-2014. Scaled rainfall and PET were then used to force the SIMHYD rainfall runoff model (Chiew et al. 2002) with Muskingum routing. The SIMHYD model was applied in semi-distributed form, where each subarea was equivalent to an AWAP grid cell. SIMHYD and routing parameters were calibrated to 90 Victorian catchments over the period 1974-2014 (1974 was used to warm-up states). To regionalise SIMHYD/routing parameters to ungauged locations, grid cells were assigned parameters from the nearest gauged catchment, as determined by Voronoi polygons.

### 3.3 Generating scaling factors for LVRSS

For PET, rainfall and runoff, a scaling factor, $d$ , is calculated for each grid-cell by a simple ratio:

$$d = \bar{f} / \bar{p}\,, \qquad (1)$$

where $\bar{f}$ is the mean of the future period, and $\bar{p}$ is the mean of the baseline period. We did not replicate the more complex rank-based scaling employed by VicCI because factors had to be applied at the monthly time step as well as the daily time step. At longer accumulation periods, thermodynamic arguments for short-duration rainfalls do not hold, and thus the simpler approach is more suitable.

For tas, we use the delta approach:

$$\mathrm{D} = \bar{f} - \bar{p}\,, \qquad (2)$$

Different values for $\mathrm{D}$ are calculated for each GCM, emissions scenario and period, and for each season and for annual averages.

All values of $d$ and $\mathrm{D}$ are supplied for grid cells within the bounding box shown in Figure 2.1. In addition, values of $d$ and $\mathrm{D}$ are averaged over the Latrobe, Thomson, Mitchell and Tambo basins shown in Figure 2.1. That is, a single value for $d$ and $\mathrm{D}$ is for each basin for annual and seasonal changes, and for both emissions scenarios and both future periods.

#### 3.3.1 Establishing dry, median and wet scenarios

To understand sensitivity to the full range of uncertainty in the VicCI climate projections we recommend that LVRRS rehabilitation options are tested with the full range of uncertainty from all GCMs. However, where a reduced number of scenarios are required, we provide dry, median and wet scenarios that are a sub-sample of the full range available. Following the VicCI projections, we use scenarios that approximate the $10^{th}$, $50^{th}$ and $90^{th}$ percentile from the range of GCMs available. For convenience, we refer to these as 'dry', 'median' and 'wet' scenarios for all variables. The scenarios are calculated using the following steps:

1) Calculate the spatially averaged future mean annual value for each variable over the bounding box. This is in order to keep changes consistent across the region by assigning changes from a single GCM to each scenario.
2) GCMs are sorted from lowest to highest.
3) Dry/median/wet scenarios are assigned on the basis of GCM rank. The definition of dry/median/wet differs with variable (e.g., high temperatures are assigned to the 'dry' scenario), as shown in Table 3.2.

4) Steps 1-3 are repeated for each season.

5) Steps 1-4 are repeated for each variable.

6) Steps 1-5 are repeated for both future periods and both emissions scenarios.

Dry, median and wet scenarios are also spatially averaged over the four catchments shown in Figure 2.1. For the basin scenarios, at Step 1, the values are averaged over each basin (not the bounding box), and all other steps are the same.

Note that scenarios are assigned completely independently for each season and for each variable. That is, the ‘dry scenario’ calculated for annual rainfall will not necessarily agree with the ‘dry’ scenario calculated for summer (DJF) rainfall, nor will it necessarily agree with the ‘dry scenario’ calculated for potential evaporation, as shown in Figure 3.1 and Figure 3.2.

Figure 3.2 shows that runoff is expected to decline under the median scenario in the order of 10-20%, while very sharp declines (of near 50%) could occur under a dry scenario. The rank-based scaling used by Potter et al. (2016) for rainfall can result in larger short-duration rainfalls, even as mean rainfall declines under future scenarios. This, in combination with localised rainfall-runoff model parameters, can lead to high local variation in runoff response under future climate (see, e.g., the median scenario shown in Figure 3.2, which shows both increases and decreases in runoff within a small area). We discuss the implications of this issue in Section 5.1.2.

Table 3.2 : Definitions of dry, median and wet scenarios for each variable.

| Variable | Dry | Median | Wet |
|---|---|---|---|
| tas | 4$^{th}$ Hottest GCM (~90$^{th}$ percentile) | 20$^{th}$ (RCP4.5)/21$^{th}$ (RCP8.5) hottest GCM (~median) | 4$^{th}$ Coolest GCM (~10$^{th}$ percentile) |
| PET | 4$^{th}$ highest PET GCM (~90$^{th}$ percentile) | 20$^{th}$ (RCP4.5)/21$^{th}$ (RCP8.5) highest PET GCM (~median) | 4$^{th}$ lowest PET GCM (~10$^{th}$ percentile) |
| Precip | 4$^{th}$ driest GCM (~10$^{th}$ percentile) | 20$^{th}$ (RCP4.5)/21$^{th}$ (RCP8.5) driest GCM | 4$^{th}$ Wettest GCM (~90$^{th}$ percentile) |
| Runoff | 4$^{th}$ driest GCM (~10$^{th}$ percentile) | 20$^{th}$ (RCP4.5)/21$^{th}$ (RCP8.5) driest GCM | 4$^{th}$ Wettest GCM (~90$^{th}$ percentile) |

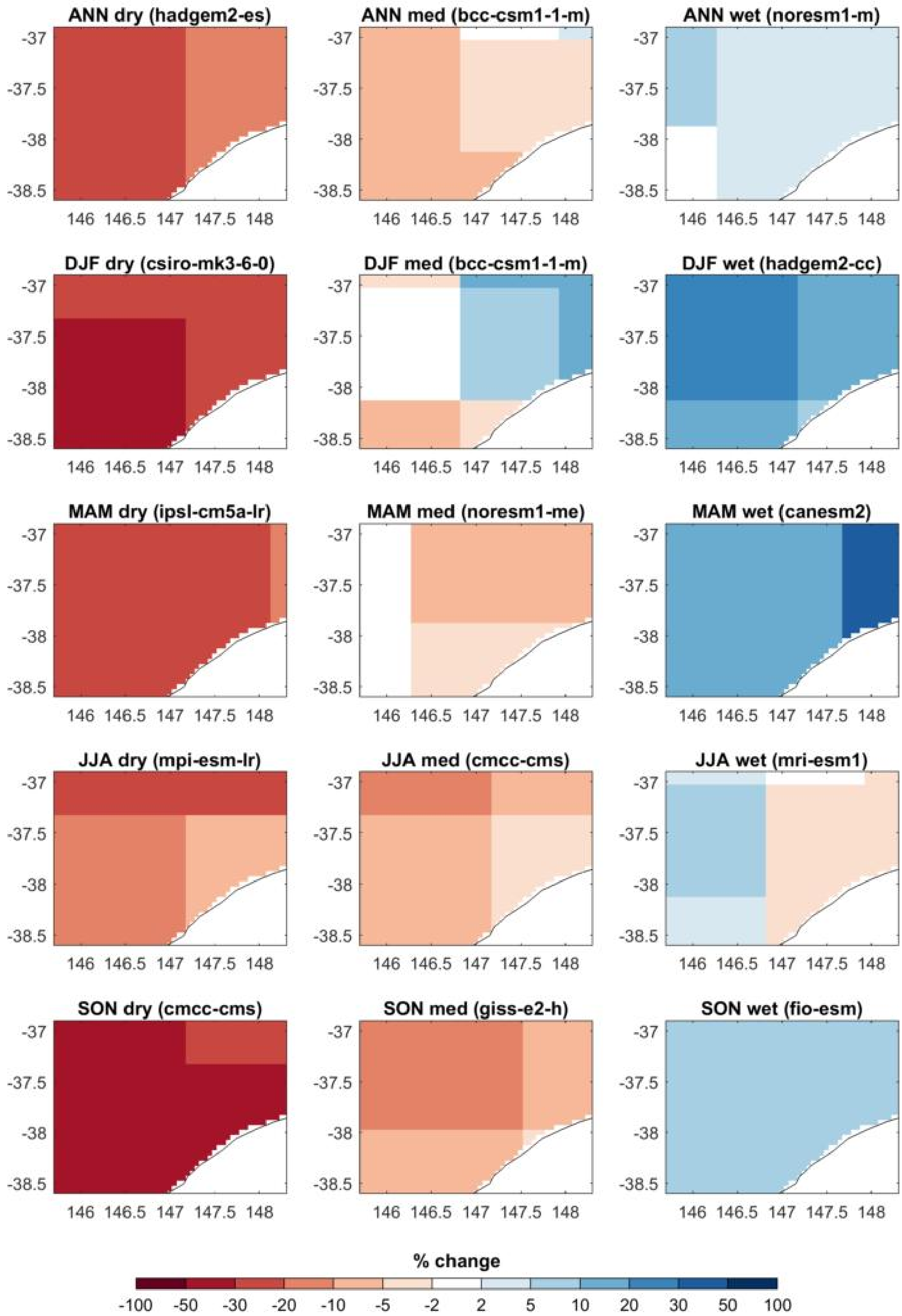


Figure 3.1 : Dry, median (med) and wet change scenarios for rainfall under RCP8.5 for the future period centred on 2065 over the LVRSS region. ANN: annual change; DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November. The GCM that represents each scenario is given in brackets.

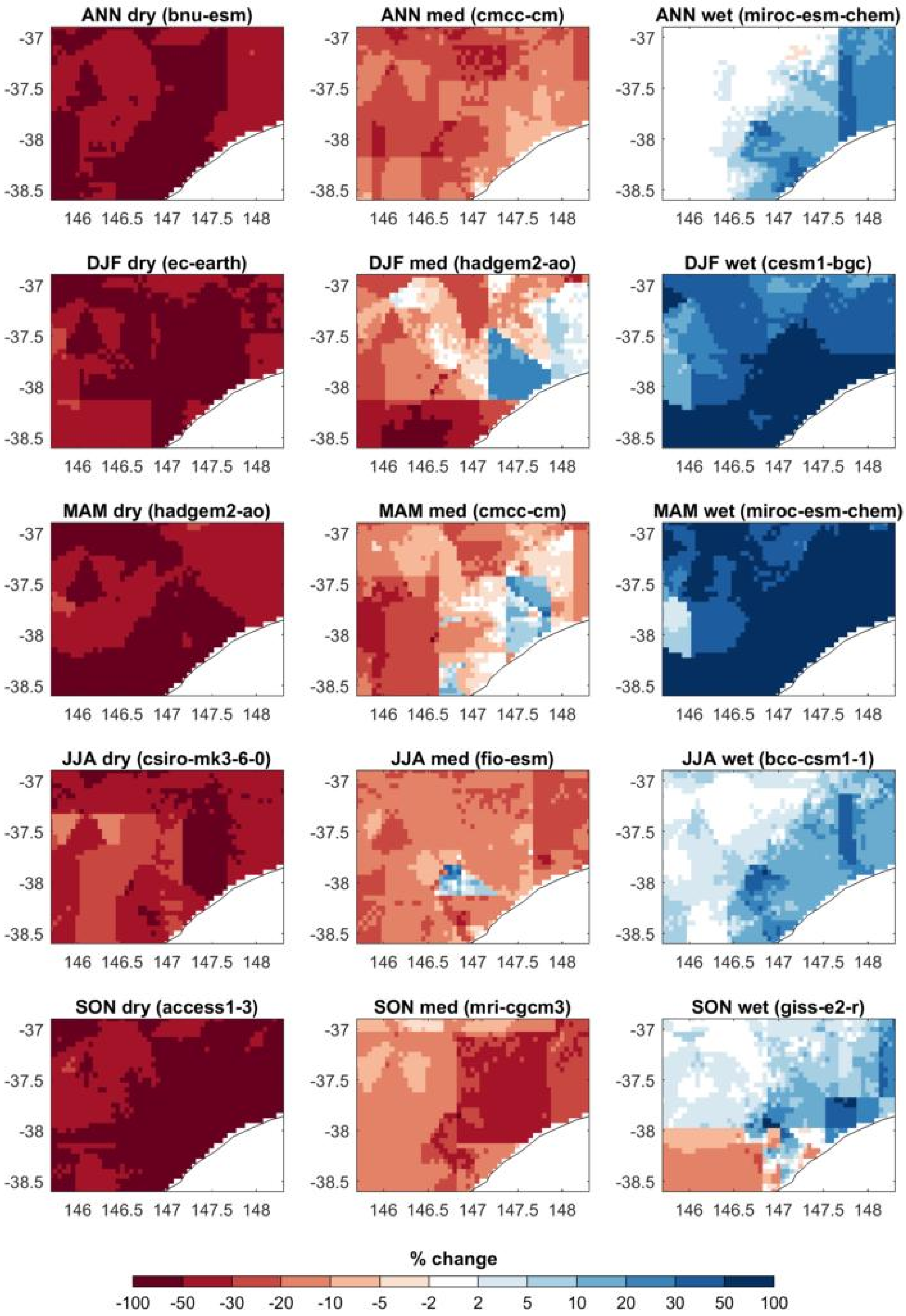


Figure 3.2 : Dry, median and wet change scenarios for runoff under RCP8.5 for the future period centred on 2065 over the LVRSS region. ANN: annual change; DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November. The GCM that represents each scenario is given in brackets.

## 3.4 1997-2014 scenario

In addition to future climate scenarios, a ‘post-1997’ scenario may be useful to inform the LVRRS modelling. To quantify this scenario, seasonal and annual scaling factors/delta values are calculated for the change in mean values from 1997-2014 to 1975-2014, following equations 1 and 2 as described in Section 3.3. AWAP does not have an equivalent variable for tas. We use the average of AWAP minimum temperature (tmin) and maximum temperature (tmax) as a proxy for tas. The difference in mean rainfall from 1975-2014 and 1997-2014 is shown in Figure 3.3.

Gridded runoff simulation time series from the VicCI project were not archived, precluding the calculation of a post-1997 scenario from gridded data for runoff. However, VicCI streamflow simulations at gauge sites are available. These are used, accordingly, to calculate the post-1997 scenario for streamflow/runoff. Gauges of headwater catchments within each of the LVRRS basins were used for calculation (Table 3.3, Figure 3.4). Where more than one headwater gauge is available in a basin (e.g. the Mitchell River), runoff from the gauged catchment areas was averaged to produce one time series. No simulations of headwater catchments were available for the Tambo River. No simulations of headwater catchments were available for the Tambo River. In this case, change factors were transferred from the nearest neighbouring basin, the Mitchell River.

The use of simulations at gauges to estimate change in runoff may lead to slight incongruities with other variables calculated from gridded data that cover the entire basin. We expect these incongruities to be minor, but they may have some influence on further modelling carried out for the LVRRS.

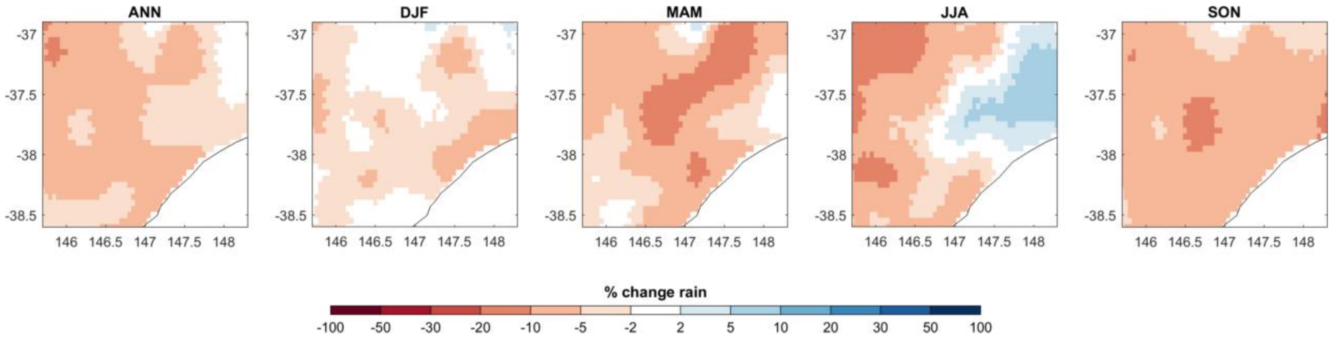


Figure 3.3 : Change in mean rainfall from 1975-2014 to 1997-2014. ANN: annual change; DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November.

Table 3.3 : Gauges used to assess runoff change from 1975-2014 to 1997-2014.

| Gauge Id | River Name | Gauge Name | Latitude | Longitude | Basin |
|---|---|---|---|---|---|
| 224207 | Wongungarra River | Guys | -37.39 | 147.1 | Mitchell |
| 224209 | Cobbannah Ck | near Bairnsdale | -37.66 | 147.35 | Mitchell |
| 224214 | Wentworth | Tabberabbera | -37.495 | 147.39 | Mitchell |
| 225219 | Macalister | Glencairn | -37.516 | 146.57 | Thomson |
| 226222 | Latrobe | near Noojee (U/S Ada R Jun | -37.882 | 145.89 | Latrobe |
| 226226 | Tanjil | Tanjil Junction | -37.98 | 146.19 | Latrobe |

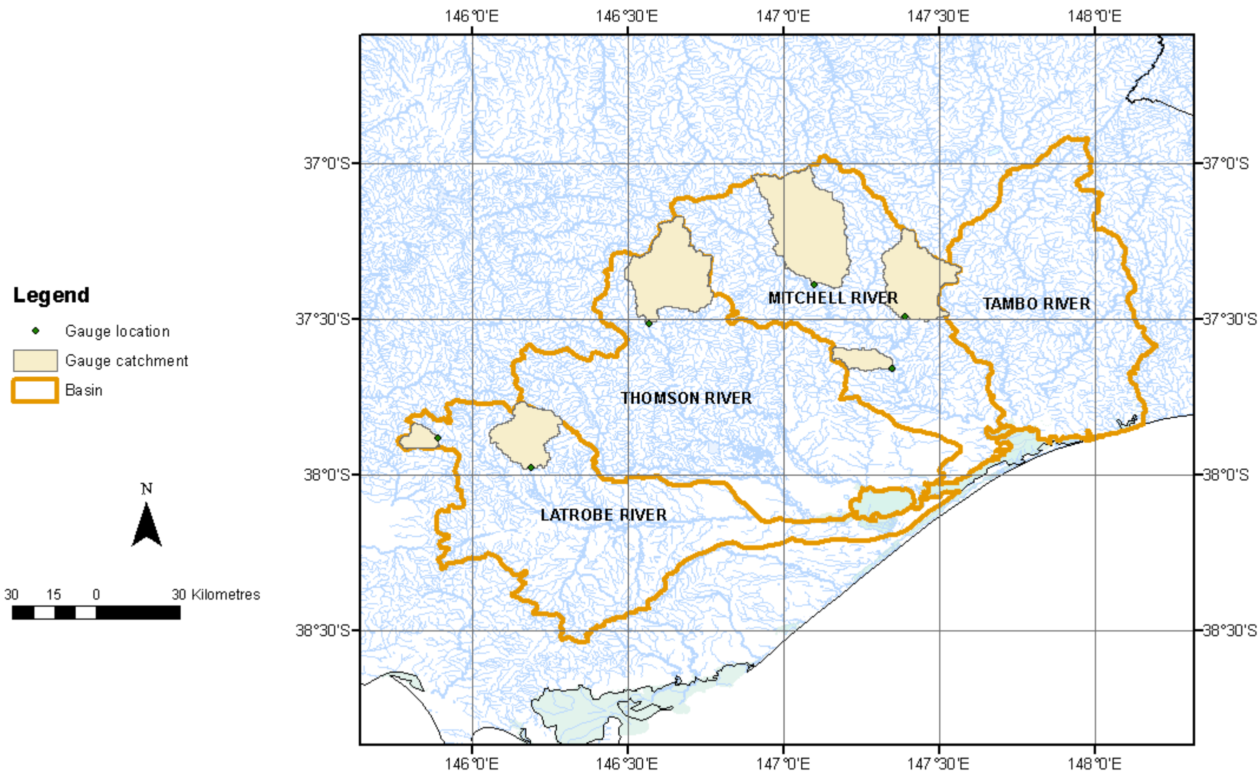


Figure 3.4 : Gauges used to assess runoff change from 1975-2014 to 1997-2014.

# 4. Victorian climate beyond 2100

## 4.1 Introduction

Detailed quantitative assessment of post-2100 is likely to be highly uncertain, and this report focusses on qualitative descriptions of possible future changes to climate beyond 2100. This is in part because projections of climate beyond 2100 are not routinely generated through CMIP5, meaning only a small set of quantitative projections is available from GCMs beyond 2100. But it is also because the range of emissions scenarios becomes increasingly large in the distant future, and responses to these emissions scenarios are similarly highly uncertain.

The climate of Victoria beyond 2100 fundamentally depends on the trajectory of future greenhouse gas emissions. Climate and climate change beyond 2100 are very different under an ongoing high emissions scenario compared to scenarios where atmospheric greenhouse gas concentrations stabilise and reduce. So, even more than projections for 2100, it is essential to take a scenario-based approach when considering the distant future. This means that a range of scenarios should be considered and all treated as equally likely.

In addition, there are a variety of socio-economic pathways that will lead to particular emissions scenario. For example, a low scenario may be reached by transitioning to a low carbon economy in a sustainability paradigm, or may be reached through major inequality, economic crises and collapses. The socio-economic pathway will also be very important to the impact assessment of interest here, where a sustainability pathway will bring different pressures and opportunities for the Gippsland region compared to a scenario of inequality. The Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5, IPCC, 2013) uses a matrix of scenarios with two dimensions to consider the far future: forcing scenarios described by the RCPs and Shared Socio-economic Pathways (SSPs).

The RCPs are defined to 2300, ranging from RCP2.6 where greenhouse gas emissions cease in the 21st Century and concentrations slowly fall, to RCP8.5 with strong ongoing emissions until concentrations stabilise in the 2200s (Figure 4.1). All scenarios assume aerosol forcing will be reduced to low levels during the 21st century.

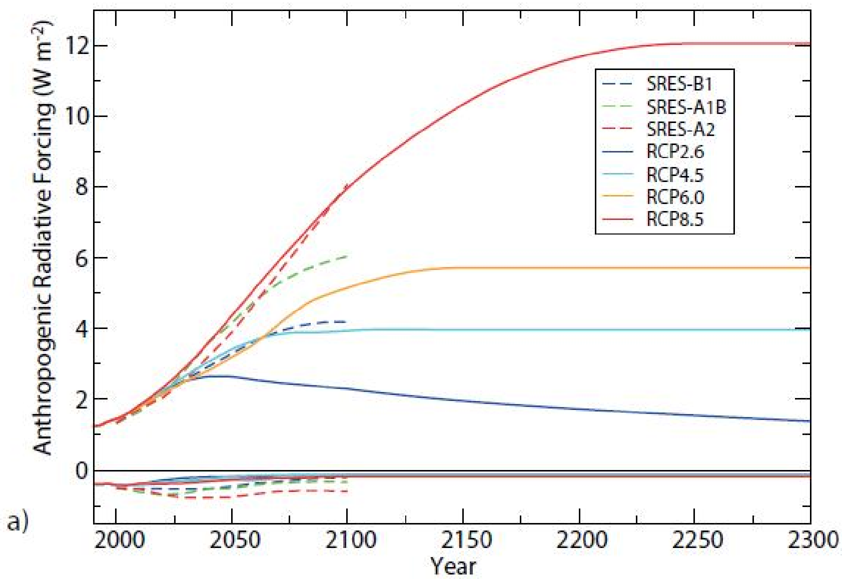


Figure 4.1 : The radiative forcing (enhanced greenhouse effect) under the Representative Concentration Pathways, showing greenhouse gas (positive) and aerosol (negative) forcing. The previous generation SRES scenarios are also shown for reference. Source: IPCC AR5 Chapter 12 (Collins et al., 2013)

## 4.2 Temperature and evaporation

Global temperature change in response to additional greenhouse gas forcing is quantified by indices of climate sensitivity such as Equilibrium Climate Sensitivity (ECS). ECS is defined as the global temperature change given a doubling of atmospheric carbon dioxide. Given uncertainties in feedbacks such as clouds and water vapour, the estimates of ECS have a wide range. AR5 reports a likely range in ECS of 1.5 to 4 °C for each doubling of $CO_2$ (Figure 4.2). ECS is estimated in models at a timescale of 150 years, and at the timescale of 2300 or 2500 other slower feedbacks and earth system changes become relevant (e.g. changes to the carbon and methane cycles, changes to the land surface), meaning the uncertainty becomes even larger. Since feedbacks and earth system changes depend on the forcing, these uncertainties are larger for higher RCPs than lower RCPs. Climate model simulations give an estimate of the global temperature change under the RCPs (Figure 4.3). Victorian temperature change is projected to be similar to the global average (less than northern hemisphere continents, more than the Southern Ocean). Temperature change is a major driver of the projected change in evapotranspiration, with changes to relative humidity, radiation and wind speed generally lesser factors in the change signal.

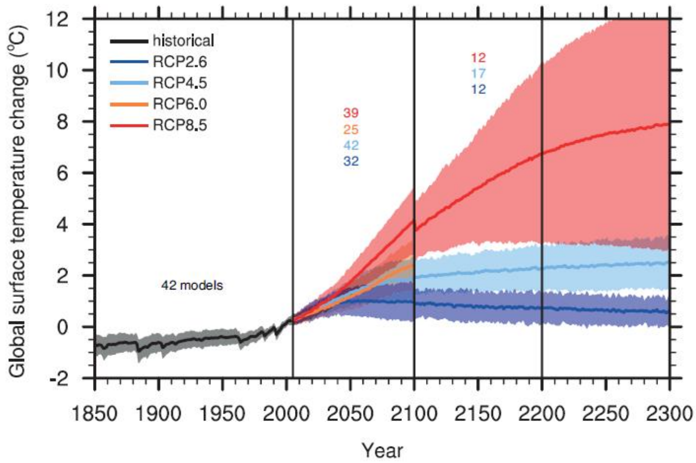


Figure 4.2 : Global temperature change relative to 1986-2005 from CMIP5 global climate models under historical and RCP simulations. Lines show the median of model simulations, shading shows 5-95% of the model range. The number of models in each simulation is indicated by the coloured numbers.

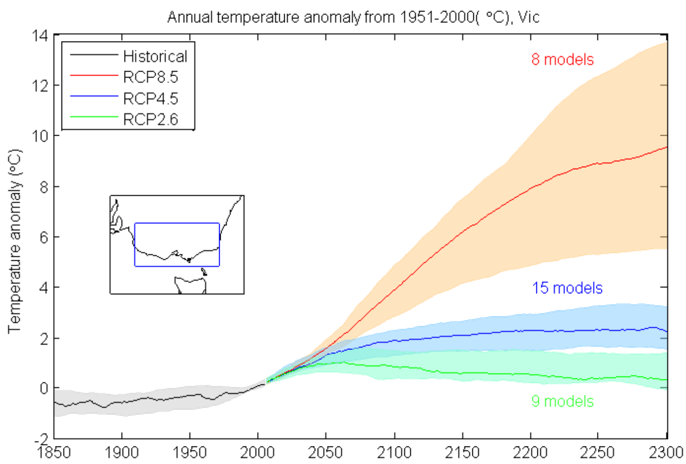


Figure 4.3 : Victorian temperature change in CMIP5 global climate models (as for Figure 4.2, but averaged over the box marked in the figure; slightly fewer models are used, as marked)

## 4.3 Rainfall

Projected changes to rainfall are driven by thermodynamic changes such as an increase in the water-holding capacity of the atmosphere and flow-on effects, and also by dynamic changes such as changes to the dominant atmospheric circulation patterns that affect rain-bearing weather systems. At the global scale, there is a projected increase in rainfall related to the physical limit of temperature increase and thermodynamic changes. However, rainfall change is highly non-uniform and dynamic changes largely outweigh this simple relation to temperature at the regional scale. Therefore, there is no simple physical limit or rule of thumb we can apply to rainfall change for a given location.

Victoria is projected to experience a reduction of cool-season rainfall, primarily due to dynamic changes including a shift in the circulation and the dominant location and strength of the weather systems that bring rain (known as the ‘storm track’). This circulation change is expressed in features such as a more positive Southern Annular Mode (SAM) and a more intense subtropical ridge of high pressure in the mid-latitudes.

In the 21st Century, changes to circulation and rainfall are related to radiative forcing so changes are higher in the higher RCPs than in the lower RCPs. If radiative forcing stabilises, then the projected changes in circulation (e.g. SAM) stabilises and may recover. This is because the surface warming pattern eventually becomes more uniform after initially being enhanced near the equator and delayed over the Southern Ocean (Cai et al., 2003). In summary, the projected response in rainfall is much greater under the higher RCPs, and is lower and potentially more transient under the low RCPs (Figure 4.4).

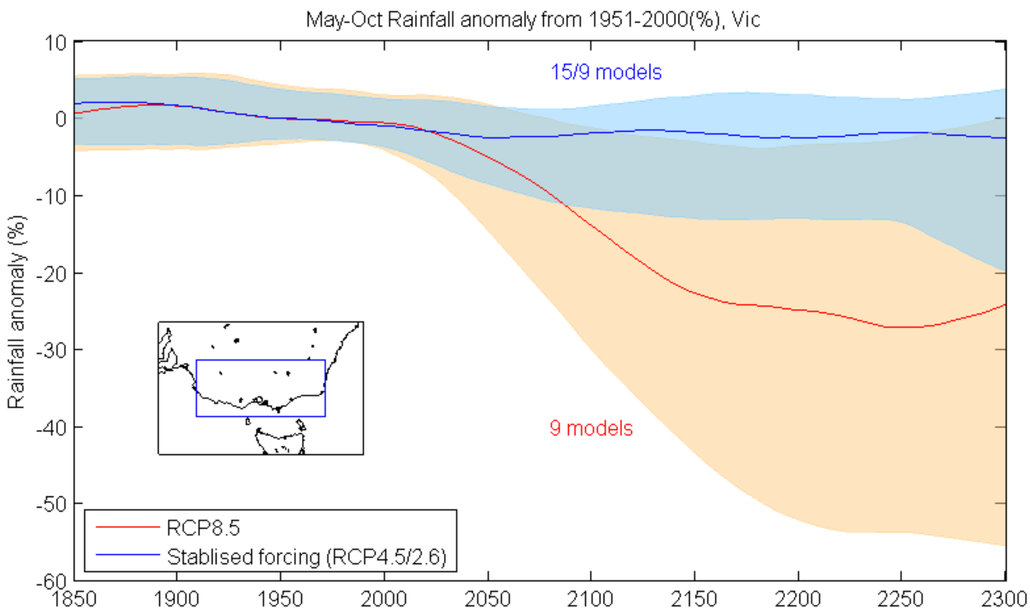


Figure 4.4 : Rainfall projections from CMIP5 GCMs for May-October within the box as marked, for RCP8.5 and RCP4.5/2.6 combined. The line shows the median of models, shading shows the 10-90% range of models using the number of models for each ensemble as marked.

## 4.4 Synthesis

Victoria is projected to experience a warmer and drier climate due to increased radiative forcings, but the magnitude of these projected changes depends on the amount of human influence on the climate (primarily the emissions of greenhouse gases). Beyond 2100, an ongoing high emissions scenario could lead to a temperature change of +6 to +14 °C with an associated increase in evaporation, and a rainfall decrease of 0-50% (median 25-30%). The range of possible change is wide since there are large uncertainties in the response of the system to this level of forcing, including climate feedbacks. Nevertheless, the minimum magnitude of change under this high emissions scenario (e.g. +6 °C), could be expected to lead to fundamental shifts in climate zones, and have profound impacts on all aspects of Victorian society.

Under a low scenario, where emissions plateau and then reduce to zero, temperature increase could be restricted to less than 2 °C both globally and for Victoria, and the projected rainfall decrease for Victoria could be much reduced. (Keeping global temperature rise under 2 °C is the target agreed under the 2016 United Nations Framework Convention on Climate Change 'Paris Agreement'.) However, there are still likely to be impacts caused by human-induced climate change under low emissions pathway, including an increase in temperature, temperature extremes, and potentially a moderate decrease in mean rainfall (in the order of 10-20%).

# 5. Application of the LVRRS Climate Change Projections

## 5.1 Guidelines for application of the hydroclimate projections

The key outputs from this study are scaling factors of change relative to current conditions. Temperature change is reported in degrees Celsius relative to the current baseline (Table 5.1). For all other variables, the change is reported as a ratio relative to the current baseline. Scaling factors/delta values for tas, PET, rainfall and runoff for the RCP8.5 scenario are shown in Table 5.1, Table 5.2, Table 5.3, and Table 5.4, respectively.

### 5.1.1 Applying scaling factors/deltas to point data

For scaling point rainfall/PET/temperature, the scaling factor from the overlying grid cell can be applied. GIS spatial grids are provided to allow DELWP to assign gridded scaling factors/deltas to point data.

### 5.1.2 Applying scaling factors to streamflow

For streamflow, we do not recommend the use of gridded scaling factors. Rather, we recommend the use of catchment aggregated change factors. By integrating over catchment areas, these change factors avoid spurious local variations in runoff response (e.g., the median scenario for DJF in Figure 3.2, which shows both increases and decrease in runoff within a small region).

### 5.1.3 Seasonal versus annual factors

Seasonal scaling factors are generally more uncertain than annual scaling factors (DELWP 2016), and accordingly we generally recommend the use of annual scaling factors, rather than seasonal factors, following the DELWP (2016) guidelines. We note, however that the choice of rehabilitation strategies may be influenced by projected seasonal changes. We recommend that the sensitivity analyses first be carried out to assess the extent to which seasonal changes influence the choice of rehabilitation strategy. If seasonal changes have little effect, annual scaling factors/delta values should be used. Where pit lake rehabilitation strategies are sensitive to seasonally specific climate changes, we recommend using seasonal scaling factors from the full range of GCMs.

### 5.1.4 Considering extremes

The climate change projections provided through this study reflect changes in mean seasonal or average conditions. The challenge of extremes was discussed through the project at length, and it was concluded that predicting extremes is beyond the scope of the current project. This does not mean that future rehabilitation strategies will not be sensitive to changes in extremes, rather it was not feasible to make robust assessments of projected changes to extremes in the time available. It was also noted that it is important to be mindful of the use of appropriate terminology through the LVRRS technical projects and their application of the climate change projections. For instance, “floods” are relevant to the LVRRS in the context of volume and timing for opportunistic filling of pit lakes. However, overland inundation is less relevant to the LVRRS. In the context of droughts, it is important to capture seasonal, annual and decadal variability. The terms “wet and dry sequences” are commonly applied instead of “droughts” and “floods” to minimise confusion in interpretation.

In general, it was agreed that long dry sequences would have a greater impact on the feasibility of pit lakes than long wet sequences. It is not possible to assess possible changes in wet/dry sequences under future climates when scaling historical data. However, incorporating variability under current conditions is likely to be a crucial aspect of assessing the feasibility of the pit lakes, and we make recommendations on how to incorporate natural variability in Section 5.4.

Table 5.1 : River basin aggregated average annual temperature change under RCP8.5 relative to 1975-2014

| River basin | Change relative the baseline (ºC) | | | | | |
|---|---|---|---|---|---|---|
| | Year 2040 | | | Year 2065 | | |
| | Dry | Median | Wet | Dry | Median | Wet |
| Latrobe | 1.53 | 1.21 | 0.86 | 2.82 | 2.21 | 1.71 |
| Thomson | 1.55 | 1.29 | 0.92 | 2.85 | 2.35 | 1.8 |
| Mitchell | 1.58 | 1.35 | 0.93 | 2.92 | 2.49 | 1.8 |
| Tambo | 1.61 | 1.33 | 0.99 | 2.86 | 2.42 | 1.9 |

Table 5.2 : River basin aggregated change in annual potential evapotranspiration (PET) under RCP8.5 relative to 1975-2014

| River basin | Change relative the baseline (%) | | | | | |
|---|---|---|---|---|---|---|
| | Year 2040 | | | Year 2065 | | |
| | Dry | Median | Wet | Dry | Median | Wet |
| Latrobe | 5.84 | 4.51 | 2.53 | 11.47 | 7.60 | 4.70 |
| Thomson | 5.71 | 4.66 | 2.97 | 11.82 | 7.60 | 5.40 |
| Mitchell | 5.78 | 4.67 | 3.04 | 11.73 | 8.01 | 5.40 |
| Tambo | 5.97 | 4.52 | 2.91 | 11.32 | 7.50 | 4.56 |

Table 5.3 : River basin aggregated change in annual rainfall under emissions scenario RCP8.5 relative to 1975-2014

| River basin | Change relative the baseline (%) | | | | | |
|---|---|---|---|---|---|---|
| | Year 2040 | | | Year 2065 | | |
| | Dry | Median | Wet | Dry | Median | Wet |
| Latrobe | -14.23 | -4.17 | 3.70 | -20.9 | -4.45 | 2.30 |
| Thomson | -14.28 | -2.2 | 4.50 | -20.9 | -4.44 | 3.05 |
| Mitchell | -13.92 | -2.19 | 4.52 | -20.79 | -4.84 | 2.74 |
| Tambo | -10.85 | -2.65 | 6.36 | -17.66 | -5.06 | 9.69 |

Table 5.4 : River basin aggregated change in annual runoff under emissions scenario RCP8.5 relative to 1975-2014

| River basin | Change relative baseline (%) | | | | | |
|---|---|---|---|---|---|---|
| | Year 2040 | | | Year 2065 | | |
| | Dry | Median | Wet | Dry | Median | Wet |
| Latrobe | -35.46 | -10.00 | 22.63 | -49.21 | -17.86 | 10.26 |
| Thomson | -31.26 | -3.71 | 23.38 | -43.99 | -12.24 | 13.86 |
| Mitchell | -30.34 | -6.37 | 22.08 | -49.37 | -15.58 | 12.17 |
| Tambo | -29.69 | -5.23 | 27.42 | -44.10 | -13.86 | 25.56 |

## 5.2 Incorporating post-2100 qualitative projections

Based on the discussion of post-2100 changes in Section 4, we recommend two approaches:

1) As with the projections to 2100, a key message from the projections for 2300 is that it is very unlikely that the mean climate will become wetter than in the 20$^{th}$ century. Therefore, planners should not expect an increase in rainfall or runoff after 2100.
2) The response in temperature, evaporation and rainfall, as well as many extreme events is dependent on the emissions pathway the world follows. Therefore, decisions need to be framed under a risk management framework – the change under a very low scenario could be considered a 'minimum' case to plan for, and the strongest projected change under a high scenario could be considered a low-probability, high-impact case.

## 5.3 Other influences on runoff

Three further recommendations unrelated to future climate change were agreed to at the technical workshops:

1) Elements other than climate change – e.g. societal change, patterns of water consumption, land use change or economic growth or decline – could have a greater impact on the feasibility of pit lakes than changes in future climate. Such factors are beyond the scope of the present study.
2) Long-term natural variability, including interannual and decadal variation in rainfall and runoff, could also be a significant consideration for the feasibility of pit lakes (see Section 5.4).
3) The possibility of increased frequency of bushfire due to increased temperatures and changes in fuel dryness, humidity and wind (CSIRO & Bureau of Meteorology, 2015), may have significant impact on both the quantity and quality of runoff and streamflow. For example, increased incidence of bushfire due to increased temperatures can dramatically alter forest cover (and associated issues, e.g. rates of erosion), which may lead to major shifts in runoff regimes. It is outside the scope of this study to investigate impacts of changes in fire regime.

## 5.4 Length of baseline period: accounting for long-term natural variability in rainfall and runoff

The pit lakes being considered for the LVRRS may be very large (~1000 GL) and are likely to be filled sequentially. Filling all lakes will likely take many decades. Therefore, decadal variability in rainfall and runoff is likely to be an important determinant of the feasibility of any pit lake rehabilitation option. Accordingly, to robustly assess the feasibility of these lakes, long (multi-decade) continuous simulations of rainfall, PET and runoff are required.

The DELWP (2016) guidelines for assessing water availability recommend the use of historical observations post 1975, as climate during this period is likely to be influenced by increased radiative forcing due to greenhouse gas emissions. This provides approximately 40 years of records on which to assess the feasibility of the pit lakes. However, as the guidelines note, 40 years may not be sufficient to encompass the full range of interannual and interdecadal natural variability that could impact the feasibility of pit lakes. We recommend, accordingly, using the longest historical records available (including pre-1975 data).

In the second workshop, methods to scale pre-1975 data to reflect statistics of post-1975 observations were discussed as a possible option for use in by LVRRS. However, incomplete or short observation records for key variables precluded this approach (e.g., AWAP temperature is only available from 1950 onwards). Analysis of rainfall comparing data from 1900-1974 to 1975-2014 showed that rainfall declined by ~3% in the latter period. This compares to reductions >20% under dry future climate scenarios (Figure 3.1). That is, it is likely that scaling pre-1975 data would have a negligible effect on rainfall in comparison to assessing future climate scenarios. Changes in temperature and runoff over the same period may be more marked, and it is possible that scaling of pre-1975 data may be required for these variables. The need to collate and generate new temperature data and runoff simulations will be determined through subsequent modelling studies in the LVRRS.

The DELWP guidelines also provide advice on considering variability through other techniques such as sampling, stochastic data generation or 'back-to-back' representation of dry sequences. If only short data records (<40 years) are available, we recommend that longer time series records be synthesised using stochastic data generation techniques (e.g. McMahon et al. 2008). Stochastic data generation is outside the scope of this study.

## 5.5 Limitations and confidence

There are several limitations inherent in the methods used to generate the VicCI projections, as well as the simplified scaling approach adopted for LVRRS, as follows:

1) The scaling of historical data assumes that temporal and spatial patterns of rainfall that occur in the past will be representative of future patterns. This assumption may not hold for future climate. Of particular concern for this study is long-range variability (at inter-annual to decadal timescales) in rainfall and runoff. VicCI concluded that there was substantial uncertainty about future trends in drivers of long-range variables, such as the El Nino Southern Oscillation or the Indian Ocean Dipole (Hope et al., 2017). Accordingly, scaling long records of observations, as recommended in Section 5.4, should provide reasonably robust assessments to inform preparation of the LVRRS.
2) Runoff projections generated for VicCI use rainfall-runoff model parameters calibrated from historical observations to model future runoff responses to changed rainfall/pet. Several studies (e.g. Saft et al. 2016; Vaze 2010) have shown that rainfall-runoff relationships often change over long periods. It is likely, however, that rainfall-runoff modelling is a relatively small component of overall uncertainty, in particular compared to uncertainties from emissions scenarios and GCMs (see, e.g., Bennett et al. 2012; Teng et al. 2012).
3) Using a simple, single scaling factor for rainfall does not allow increases to short-duration (daily), high intensity rainfalls that may manifest under warmer climates to be represented in the LVRRS climate projections. Accordingly, these methods presented in this study are not suitable for the assessment of changes to floods, particularly over small areas. Assessment of changes to floods is outside the scope of this project (see Section 5.1.4). We note that increases in short duration rainfall do not necessarily increase flooding, in particular over larger catchments, as shown by recent studies (Berghuijs et al., 2017; Wasko and Sharma, 2017).
4) Climate change may have influence runoff through processes not explicitly captured in these projections, for instance as a result of altered bushfire regime. In addition, other societal decisions, such as economic trajectories or land planning choices, may also impact on future runoff. Many of these are beyond the scope of the current project and it is not possible to quantify the volumetric influence on runoff here. However, it is important to note the possibility that these issues may be relevant when considering the feasibility of LVRRS pit lake options.

Despite these limitations, the methods proposed in this study should offer a robust basis for incorporating the effects of climate change into the assessment of the feasibility of pit lakes for the purpose of preparing the LVRRS.

# 6. Recommendations for further work

- If sensitivity analyses indicate that the filling rates are very sensitive to differences in multi-year sequencing of wet and dry periods then it would be appropriate to consider adapting the simulation framework to accommodate stochastic data generation approaches.
- The PET projections generated through VicCI and tailored to the Gippsland Region through this study were based on calculated Morton's (1983) wet PET algorithm. This does not take into account the complexities of estimating evapotranspiration losses from a pit lake. Wind speed, humidity and other variables are likely to influence evapotranspiration rates for these large water bodies. Unfortunately, these variables are not well predicted by GCMs. The PET scaling factors provided in this study reflect changes in Morton ET to provide an indication of shifts and patterns in future evapotranspiration. However, it is acknowledged that further work by individuals is likely to be required to provide specific pit lake evapotranspiration values.
- To establish baseline time series, we have recommended that scaling pre-1975 observations of rainfall is not necessary as the change in rainfall from 1900-1974 and 1975-2014 is small compared to projections of climate change (Section 5.4). However, this does not necessarily hold for other variables such as runoff and temperature, which may have experienced more marked changes between these periods. For these variables, long records or simulations of historical data could be used to scale of pre-1975 runoff or temperature data to establish baseline time series.
- As noted in Section 3.4, for the post-1997 scenario there may be minor incongruities between estimated basin-wide wide changes in runoff and other variables, as runoff was estimated only from headwater catchments. If LVRRS modellers are concerned that their modelling is sensitive to these incongruities, gridded simulations for the period 1975-2014 will need to be regenerated, to allow changes in basin runoff to be estimated from the same spatial extents as other variables.
- As noted in Section 5.3, future changes in fire regime may impact both the quantity and quality of future runoff. These impacts could be investigated if considered relevant for specific studies required through the LVRRS.

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# Appendix A. GCMs used in the VicCI project

Table A.1 : List of GCMs used in VicCI (adapted from Potter et al., 2016)

| MODEL | APPROX. RESOLUTION (LON x LAT) | MODELLING CENTRE (OR GROUP) | Emissions scenarios |
|---|---|---|---|
| ACCESS1-0 | 1.875×1.25 | CSIRO and Bureau of Meteorology (BOM), Australia | RCP8.5<br>RCP4.5 |
| ACCESS1-3 | 1.875×1.25 | CSIRO and Bureau of Meteorology (BOM), Australia | RCP8.5<br>RCP4.5 |
| BCC-CSM1-1-M | 2.8125×2.7906 | Beijing Climate Center, China Meteorological Administration | RCP8.5<br>RCP4.5 |
| BCC-CSM1-1 | 2.8125×2.7906 | Beijing Climate Center, China Meteorological Administration | RCP8.5<br>RCP4.5 |
| BNU-ESM | 2.8125×2.7906 | College of Global Change and Earth System Science, Beijing Normal University | RCP8.5<br>RCP4.5 |
| CANESM2 | 2.8125×2.7906 | Canadian Centre for Climate Modelling and Analysis | RCP8.5<br>RCP4.5 |
| CCSM4 | 1.25×0.9424 | National Center for Atmospheric Research | RCP8.5<br>RCP4.5 |
| CESM1-BGC | 1.25×0.9424 | Community Earth System Model Contributors | RCP8.5<br>RCP4.5 |
| CESM1-CAM5 | 1.25×0.9424 | Community Earth System Model Contributors | RCP8.5<br>RCP4.5 |
| CESM1-WACCM | 2.5×1.8848 | Community Earth System Model Contributors | RCP8.5<br>RCP4.5 |
| CMCC-CESM | 3.75×3.4431 | Centro Euro-Mediterraneo per I Cambiamenti Climatici | RCP8.5 |

| MODEL | APPROX. RESOLUTION (LON x LAT) | MODELLING CENTRE (OR GROUP) | Emissions scenarios |
|---|---|---|---|
| CMCC-CMS | 3.75×3.7111 | Centro Euro-Mediterraneo per I Cambiamenti Climatici | RCP8.5<br>RCP4.5 |
| CMCC-CM | 0.75×0.7484 | Centro Euro-Mediterraneo per I Cambiamenti Climatici | RCP8.5<br>RCP4.5 |
| CNRM-CM5 | 1.40625×1.4008 | Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique | RCP8.5<br>RCP4.5 |
| CSIRO-MK3-6-0 | 1.875×1.8653 | Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence | RCP8.5<br>RCP4.5 |
| EC-EARTH | 1.125×1.125 | EC-EARTH consortium | RCP8.5 |
| FGOALS-G2 | 2.8125×2.7906 | LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS,Tsinghua University | RCP8.5<br>RCP4.5 |
| FGOALS-S2 | 2.8×1.659 | LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences | RCP8.5<br>RCP4.5 |
| IO-ESM | 2.81×2.76 | The First Institute of Oceanography, SOA, China | RCP8.5<br>RCP4.5 |
| GFDL-CM3 | 2.5×2.0 | NOAA Geophysical Fluid Dynamics Laboratory | RCP8.5<br>RCP4.5 |
| GFDL-ESM2G | 2.0×2.0225 | NOAA Geophysical Fluid Dynamics Laboratory | RCP8.5<br>RCP4.5 |
| GFDL-ESM2M | 2.5×2.0225 | NOAA Geophysical Fluid Dynamics Laboratory | RCP8.5<br>RCP4.5 |
| GISS-E2-H-CC | 2.5×2.0 | NASA Goddard Institute for Space Studies | RCP8.5<br>RCP4.5 |
| GISS-E2-H | 2.5×2.0 | NASA Goddard Institute for Space Studies | RCP8.5<br>RCP4.5 |

| MODEL | APPROX. RESOLUTION (LON x LAT) | MODELLING CENTRE (OR GROUP) | Emissions scenarios |
|---|---|---|---|
| GISS-E2-R-CC | 2.5×2.0 | NASA Goddard Institute for Space Studies | RCP8.5<br>RCP4.5 |
| GISS-E2-R | 2.5×2.0 | NASA Goddard Institute for Space Studies | RCP8.5<br>RCP4.5 |
| HADGEM2-AO | 1.875×1.25 | National Institute of Meteorological Research/Korea Meteorological Administration | RCP8.5<br>RCP4.5 |
| HADGEM2-CC | 1.875×1.25 | Met Office Hadley Centre | RCP8.5<br>RCP4.5 |
| HADGEM2-ES | 1.875×1.25 | Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) | RCP8.5<br>RCP4.5 |
| INMCM4 | 2.0×1.5 | Institute for Numerical Mathematics | RCP8.5<br>RCP4.5 |
| IPSL-CM5A-LR | 3.75×1.8947 | Institut Pierre-Simon Laplace | RCP8.5<br>RCP4.5 |
| IPSL-CM5A-MR | 2.5×2.5352 | Institut Pierre-Simon Laplace | RCP8.5<br>RCP4.5 |
| IPSL-CM5B-LR | 3.75×1.8947 | Institut Pierre-Simon Laplace | RCP8.5<br>RCP4.5 |
| 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 | RCP8.5<br>RCP4.5 |
| MIROC-ESM | 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 | RCP8.5<br>RCP4.5 |
| MIROC5 | 1.40625×1.4008 | Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies | RCP8.5<br>RCP4.5 |
| MPI-ESM-LR | 1.875×1.8653 | Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology) | RCP8.5<br>RCP4.5 |

| MODEL | APPROX. RESOLUTION (LON x LAT) | MODELLING CENTRE (OR GROUP) | Emissions scenarios |
|---|---|---|---|
| MPI-ESM-MR | 1.875×1.8653 | Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology) | RCP8.5<br>RCP4.5 |
| MRI-ESM1 | 1.125×1.12148 | Meteorological Research Institute | RCP8.5 |
| MRI-CGCM3 | 1.125×1.12148 | Meteorological Research Institute | RCP8.5<br>RCP4.5 |
| NORESM1-ME | 2.5×1.8947 | Norwegian Climate Centre | RCP8.5<br>RCP4.5 |
| NORESM1-M | 2.5×1.8947 | Norwegian Climate Centre | RCP8.5<br>RCP4.5 |

# Appendix B. LVRRS Climate Change Projections Metadata

Climate change factors to 2100 are provided in a supporting data package for each of the available GCM's for the different emissions pathways and time periods of interest. This appendix summarises the data package to enable effective interrogation of this raw data for LVRRS technical projects.

## B.1 File naming convention

**Gridded data**

The scaling factor data is provided in a CSV file format for compatibility with MS Excel and other readily available data analysis software products. For gridded data for all GCMs, a standardised file naming convention is used, such that:

*[**Variable**]_[**Change type**]_[**Emissions Scenario**]_[**Time Slice**]*.csv

The ***Variables*** term reflects the hydroclimate variables considered in this study, with the abbreviations used in the file naming convention shown in brackets:

- Surface air temperature (tas);
- Rain;
- Potential evapotranspiration (pet); and
- Runoff (runoff).

Change type refers to additive or multiplicated changes, as defined in equations 1 and 2. Change type can be '*delta*' ( D in Equation 1) or '*sclfct*' (reflecting the scaling factor $d$ in Equation 2).

The ***Emissions Scenario*** term reflects the Representative Concentration Pathways (RCPs) from the IPCC Fifth Assessment Report for possible future greenhouse gas emissions (Figure B.1). Data from two alternative scenarios are provided:

- RCP45: the IPCC medium emissions scenario, in which radiative forcing stabilises after 2100; and
- RCP85: IPCC scenario that assumes high radiative forcing with little curbing of emissions in the future.

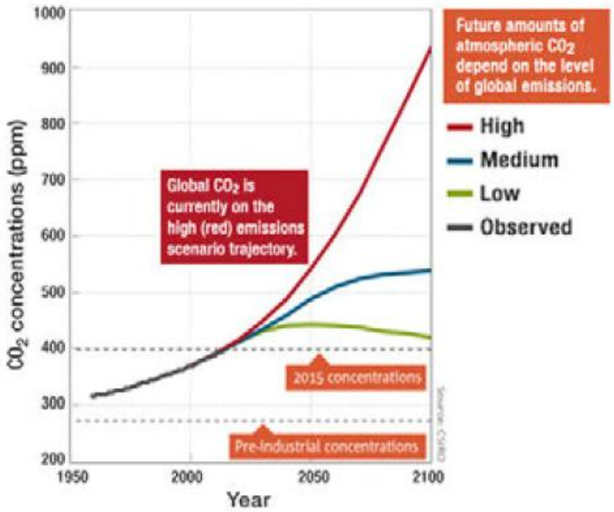


Figure B.1 : Future greenhouse gas emissions scenarios

The ***Time Slice*** term reflects the target dates used in modelling the projections:

- Year 2040: calculated from GCM model simulations over the period 2031-2050; and
- Year 2065: calculated from GCM model simulations over the period 2056-2075.

**Dry median and wet scenarios**

Files that contain dry, median and wet scenarios, rather than the full range of GCMs, have the suffix '_dry_med_wet', e.g.:

runoff_sclfct_RCP45_2040_dry_med_wet.csv

**Basin averaged data**

Files containing basin-averaged data follow the same basic file-naming conventions as for gridded data, but have the prefix 'basin_' added, e.g.:

basin_runoff_sclfct_RCP45_2040.csv

The ***Basin*** term identifies the basin of interest, as follows:

- LAT: Latrobe River Basin
- MIT: Mitchell River Basin
- TAM: Tambo River Basin
- THO: Thompson River Basin

## B.2 Data structure

**Gridded data**

The content of the csv data files has been formatted with a standardised structure.

Outputs from the GCMs are provided based on the GDA 1994 geographic coordinate system, with scaling factors for each 0.05 degree grid cell across the Gippsland domain (refer to Figure 2.1 for this domain area).

Scaling factors for each grid cell are provided by reference to the grid cell centroid. The csv file contains a unique GridID reference that reflects these centroid coordinates converted to a nine digit integer format by:

GridID = [*X coodinate*] x 1,000,000 + AbsoluteValue([*Y coordinate*]*100)

The above GridID is based on grid cell centroid X and Y coordinates that have been derived in the GDA 1994 geographic coordinate system that uses decimal degrees. For example, a grid cell with centroid 145.7 degrees east and -36.95 degrees south would have a GridID value of 145703695.

For each GridID, the csv file contains annual and seasonal scaling factors that relate to each GCM. The data is organised based on GCM, using the model names listed in Appendix A. The data headings are also appended with an abbreviation to reflect the model output annual or seasonal period:

- ANN: annual scaling factors
- DJF: Summer (December, January and February) scaling factors
- MAM: Autumn (March, April and May) scaling factors
- JJA: Winter (June, July and August) scaling factors

- SON: Spring (September, October and November) scaling factors

The full suite of models listed in Appendix A have data available for the RCP8.5 emissions scenario. Three of these models (CMCC-CESM, EC-EARTH, and MRI-ESM1) do not provide data for the RCP4.5 emissions scenario. As such, data for 42 GCMs is available for the high emissions scenario and 39 GCMs are available for the medium emissions scenario.

For rainfall, evapotranspiration and runoff, the data provided in the csv files reflects scaling factors as a percentage of current conditions. As such, values above one represent an increase compared to current conditions, while scaling factors less than one indicate a reduction compared to current conditions. The temperature data is provided as a change in absolute values (ºC) relative the current conditions.

**Dry median and wet scenarios**

For files containing dry, median and wet scenarios, headings have the structure:

***[Season]_[Scenario]_[GCM]***

**Season** is either annual or seasonal data, as described above, and takes values ‘ANN’, ‘DJF’, ‘MAM’, ‘JJA’, ‘SON’. **Scenario** corresponds to the dry, median or wet scenario, taking values of ‘dry’, ‘med’, ‘wet’, respectively. **GCM** gives the GCM that corresponds to each scenario.

**Basin averaged data**

Basin averaged data follows the file conventions listed for both gridded data and dry-median-wet scenario data. It differs from gridded data in that it has as its first column the header ‘basinid’. This identifies the basin, and takes the following values:

- LAT: Latrobe River Basin
- MIT: Mitchell River Basin
- TAM: Tambo River Basin
- THO: Thompson River Basin