A literature review of past and projected changes in Victorian rainfall and their causes, and climate baselines

Surendra P. Rauniyar, Scott B. Power and Pandora Hope

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EXECUTIVE SUMMARY

In this review we synthesize the current knowledge on the attribution of the rainfall changes in Victoria in recent decades, its implication for the selection of a climate baseline, and key issues remaining unresolved. We also provide a few preliminary results from the new research project that help to clarify some of the issues.

This review fulfils Task 1: Review literature on past and projected Victorian rainfall and on the detection and attribution of recent multi-decadal changes in Victorian rainfall of a DELWP/Bureau of Meteorology Project called "Estimating and Assessing a Baseline for Seasonal Rainfall Relevant to Decision-Making". This project is an element of the Victorian Water and Climate Initiative (VicWaCI). Note that we extended the task to include a synthesis of literature and provide insights on the definition and use of climate baselines.

A synthesis of the key issues and our main conclusions follows.

What has happened to Victorian rainfall?

Victoria experiences large variability in rainfall, from interannual to decadal timescales, including severe floods and droughts (Hope et al. 2017). Three prolonged periods of below-average rainfall occurred during the instrumental period: the Federation Drought (1896 – 1905), the World War II Drought (1936 – 1945) and the Millennium Drought (1997 – 2009). In fact, despite the occurrence of several wet years during the 1950s and 1970s, and more recently in 2010-2011, annual rainfall declined by approximately 2 mm per decade since 1960 (Grose et al. 2015a). This decline was driven by a downward trend in "cool season" (April to October) rainfall. Here we show that the dry conditions from 1997 to near-present appear extreme in the context of the instrumental record.

What caused the observed changes in Victorian rainfall?

On the basis of our review of research and other syntheses (e.g., CSIRO 2010, 2012; Timbal and Drosdowsky 2013; Cai et al. 2014; Grose et al. 2015; Timbal et al. 2015, 2016; Hope et al. 2017) and our preliminary results, we conclude that:

- the dry conditions in Victoria from 1997 to near-present appear to be partially caused by anthropogenic climate change and partly caused by natural climate variability.

- a major focus for the research to date for SE Australia has been on the characteristics of the drying and the impact of anthropogenic forcing on drivers of climate variability in Victoria (e.g., El Niño-Southern Oscillation, the
Subtropical Ridge, the Hadley Circulation, the Southern Annular Mode, the Indian Ocean Dipole, and the Interdecadal Pacific Oscillation).

- research directly examining the changes in Victorian precipitation in climate models under anthropogenic and natural forcing has been limited.

- the relative importance of anthropogenic forcing and natural climate variability to the recent drying is unclear. Further research is needed to clarify the magnitude of their relative contribution.

We will provide an estimate of the relative importance as part of our DELWP/Bureau project in the future.

**How well do climate models simulate Victorian rainfall?**

Recent studies have shown that the performance of models varies regionally and that performance also depends on which climatic variable is considered and the scoring measure used. In general, CMIP5 climate models – the models used in the IPCC (2013) report and the NRM report (CSIRO and Bureau of Meteorology 2015) - show an overall improvement in simulating several climate variables (e.g. temperature and rainfall) and large-scale climate drivers compared with the previous generation of climate models. Despite these improvements, CMIP5 models still exhibit deficiencies in regions and phenomena that influence Victorian climate. In line with previous research our preliminary research shows that the CMIP5 models:

- provide a reasonably accurate simulation of the timing of the observed seasonal cycle of temperature. However, the overwhelming majority of CMIP5 models overestimate the annual cycle of temperature, with the multi-model mean slightly too high year round.

- simulate the timing of seasonal rainfall pattern adequately, but the models tend to be too dry over most of Victoria in all seasons except summer.

Bhend and Whetton (2015) found that fewer than 10 per cent of CMIP5 models reproduce the significant drying in Victoria in autumn while the majority of the models are not able to reproduce the observed rainfall trends across Victoria over the last 30 years. However, they noted that the extent of the areas for which these discrepancies exist is not larger than expected due to the pronounced variability on inter-annual to decadal scales.

CMIP5 models have also been assessed on their ability to simulate key features of atmospheric circulation and modes of climate variability that affect Victorian rainfall. For example, Timbal et al. (2016) found that many CMIP5 models adequately simulate the broad characteristics (strength and location) of the subtropical ridge, including its seasonal cycle. Similarly, Grose et al. (2015b) found that CMIP5 models simulate an
intensification and poleward shift of the STR under global warming, contributing to reduced rainfall in the cool season over Victoria. However, they found that the models underestimate the historical trends in the STR intensity and the magnitude of the correlation coefficient between inter-annual STR intensity and Victorian rainfall. The authors inferred that CMIP5 rainfall projections for Victoria during the cool season in response to the STR changes may be underestimated.

Some studies suggest that the models underestimate natural, internally generated decadal climate variability in the tropical Pacific - a region of high importance for climate variability in Australia (Kociuba and Power 2015; Power et al. 2017; Henley et al. 2017; England et al. 2014).

Given the limitations of current models, it will be worthwhile for us to consider those models that best simulate Victorian climate as part of our future investigations, as well as trying to include new models if they show improvements in their simulation of Victorian climate or improvements more broadly.

**What is projected for Victorian rainfall?**

To better understand whether the recent dry decades are consistent with the ‘fingerprint’ of climate change as projected under greenhouse gas forcing increases in the future, we reviewed the findings of several previous studies that examined projections for Victorian rainfall. A summary is given in the body of the report for SEACI Phases 1 and 2, VicCI, and NRM reports. A brief summary of some of this information is given here.

VicCI, for example, provided projections from CMIP5 models for late 21st century, relative to 1986-2005, under a high greenhouse gas emissions scenario called RCP8.5. A decline in cool season rainfall of \(-13\%\) \((-34\%\) to \(+4\%\)) in the Murray Basin in Victoria and \(-15\%\) \((-31\%\) to \(+4\%\)) in south-west Victoria is being projected. Better performing models exhibited a stronger rainfall decline for all Victoria under RCP8.5, from a median of \(-8\%\) to \(-14\%\).

Statistically and dynamically downscaled results exhibit greater agreement in median rainfall changes during winter and spring, whereas the projections for other seasons look rather different. A clear explanation for why the different downscaling techniques give such great differences in projected rainfall is an important subject for further research.

The NRM Southern Slopes Cluster Report (Grose et al. 2015a) – that also focussed on CMIP5 models - found that almost all models project a reduction of mean annual rainfall across the Southern Slopes which largely consists of southern Victoria. They also concluded that natural climate variability may remain "the major driver" of rainfall changes by 2030 even as anthropogenic changes become apparent. Grose et al. (2015a) also found that there is high confidence in projected rainfall decreases in winter and spring in the Southern Slopes under higher emissions (RCP8.5) from 2050 to 2090, but with some differences within the region and between seasons. By 2090, spring rainfall is
projected to decrease across the Southern Slopes by around -25 to +5 % under RCP4.5 and -45 to +5 % under RCP8.5 relative to 1986 - 2005.

On the other hand, there is no clear agreement among the models on the sign of future rainfall change during summer. Also, most models project little change in autumn across the Southern Slopes Cluster. However, this disagrees with post-1960 trends as autumn declines have been more significant than spring changes. Besides, there are known deficiencies in the simulation of the current climate in autumn. This observation-model discrepancy lowers the confidence we have in both projections and in our ability to quantify the relative importance of anthropogenic forcing and natural changes in the recent multidecadal drying that has occurred in Victoria.

What is a baseline, and what factors need to be considered when choosing a baseline?

A baseline is generally regarded in climate science as an historical period which is chosen to best represent the current climate of a region. A baseline in climate science typically serves two main purposes: 1) it is used as a reference against which recent observations are compared and 2) it can be used as a benchmark to evaluate projected changes in climate for planning and management processes. The World Meteorological Organization (WMO) recommends using a period of at least 30 years (e.g. 1981–2010) as a baseline to compute the climatological standard normals, while IPCC has used the 1986–2005 period as a baseline in its fifth assessment report (IPCC 2013) as a reference period in its assessment of climate change.

Water managers appear to use the term "baseline" and "current climate" interchangeably, even though their "baseline" data is actually used as a source of information for what the range of possible climatic conditions might be over coming years for planning purposes. From this perspective, this use of "baseline" is a form of persistence projection, assuming that climatic conditions over coming years will be drawn from a population with the statistics of climatic conditions experienced during the baseline period. This is a different form of "baseline" to what is usually used in climate science.

Key requirements for a baseline defined in the way water managers do are that it should be of sufficient duration to encompass the wide range of natural climate variability, but should also be short enough so as to include the impact of a change arising from global warming. When this is the purpose of a baseline, the approaches taken by WMO and IPCC might not be optimal. For example, a number of studies have found that 30 years or less is not long enough to adequately represent the range of rainfall variability, especially when it is used as a predictive indicator of the conditions likely to be experienced in a given location. Hence, the Guidelines for Assessing the Impact of Climate Change on Water Supplies in Victoria developed by the Department of Environment Land, Water and Planning (DELWP) recommends using 1975 to near-present as a current baseline period for water resources planning and management (DELWP 2016a).
The Bureau of Meteorology (BoM) recently began research on baselines for the Victorian water sector as part of a new program co-funded by the DELWP and the Bureau. As part of this project we will also provide information on the pros and cons of various baseline choices, and we also aim to provide advice on how choosing baselines might be improved. This research will be described at a later date.
1. **INTRODUCTION: THE DELWP – BOM BASELINE PROJECT**

Prior to a series of research projects co-funded by DELWP over the last 15 years, stakeholders were using the full climate record (about 100 years) as the baseline climate for future planning and management of water resources with an assumption of a stationary (i.e. a non-changing average to continue into the future). However, this assumption of stationarity has been challenged by persistently dry conditions over the last twenty years, which raises the issue as to whether the baseline climate (as previously defined by the historical record) is changing.

If the baseline is changing, it is helpful to understand the causes of that change, if these changes are here to stay, and whether there is now the need to allow for the influence of climate change in future planning processes. Given the concerns above, the current guidelines for Assessing the Impact of Climate Change on Water Supplies in Victoria developed by the DELWP recommends using the period from 1975 to near-present as the current baseline period for water resources planning and management (DELWP 2016a). Similarly, some agencies (e.g. energy industries) use the start of Millennium Drought to current (post 1997) period as a baseline, however using post 1997 alone will omit important aspects of the climate variability experienced previously during 1900 – 1996.

The question of which baseline climatology to use depends on the context for which it will be used and has often been governed by availability of the required climate data. For example, the baseline climate may be used to gauge observed change over time — for this application, a number of considerations apply — for example, if tracking climate change, then it makes sense to use a fixed baseline and reference all change to that climatology (generally covering the most recent period of good observations prior to 1900, termed a ‘pre-industrial’ period) and referencing all change to that climatology. However, if we are looking at changes with respect to some application, operational system or, infrastructure, then it makes sense to choose a baseline that is defined in relation to that asset. Typically, this means using a more recent baseline, since most assets are not benchmarked 50 years ago. Similarly, if the baseline is for probabilistic seasonal prediction, it makes sense to use the most recent period/experience, rather than a median from many decades ago.

For rainfall, however, a number of studies have found that 30 years or less is not long enough to adequately represent the range of natural variability, especially when it is used as a predictive indicator of the conditions likely to be experienced in a given location. Victoria just experienced its driest cool season (April – October) rainfall for the last 30 years compared to any 30-year period in the historical record from 1900–2016 (Timbal et al. 2016). Research undertaken during the South-East Australian Climate Initiative (SEACI) Phase 1 (CSIRO 2010) and Phase 2 (CSIRO 2012) and the Victorian Climate Initiative (VicCI; (Hope et al. 2017)) have shown that the baseline climate is likely to be changing as the assumption of a stationary climate has been challenged by the recent persistently dry conditions. Victorian rainfall trends include a known influence from
climate change, thus this recent period could better represent the current baseline. However, the projected rainfall reductions for 2030 across the region (CSIRO and Bureau of Meteorology 2015) are smaller than the observed declines over the last three decades, which highlights that baseline selection poses a significant source of uncertainty in the projection of Victoria’s climate.

To best characterise the baseline climate, the following questions need to be addressed:

- Do the recent decades represent a true baseline, and a good estimate of the climate over the future period considered in key decision-making?
- Is any historical period truly representative of the current state of the climate or the expected climatic conditions over the coming decade?
- What is the relative contribution of anthropogenic forcing and internal variability to Victorian rainfall?
- How best to combine climate change projections with observed climate records to define a baseline that represents the current state of climate?

The Bureau of Meteorology recently began research on baselines for the Victorian water sector as part of a new research program co-funded by the DELWP and the Bureau. We are analysing baselines over the historical period and for coming years and decades to examine the impact of natural climate variability and anthropogenic forcing on the past climate, future climate, and baseline choices.

The purpose of this review is to help inform this research, to synthesize what is already known and what key issues remain unresolved. We will also use this review as a source of information for future research papers we will write as part of the same DELWP/Bureau project. We also provide a few preliminary results from the new research project that help to clarify some of the issues.

A synthesis and interpretation of existing research on the following five issues are given below:

i. What has happened to Victorian rainfall?

ii. What caused the observed changes in Victorian rainfall?

iii. How well do climate models simulate Victorian rainfall?

iv. What is projected for Victorian rainfall?

v. What is a baseline, and what factors need to be considered when choosing a baseline?
2. WHAT HAS HAPPENED TO VICTORIAN RAINFALL?

Historical records show that rainfall over Victoria exhibits a great deal of variability. The annual rainfall map (Fig. 1a) shows that areas associated with higher elevations receive the highest amount of rainfall, followed by the southern coastal regions. Substantially less rainfall occurs over the north-west of Victoria. Rainfall over Victoria occurs predominantly in the "cool season" (Fig. 1b; defined here as April to October) compared to the "warm season" (Fig. 1c; November to March), except in the eastern part of the state where a weaker seasonal cycle dominates. The warm and cool seasons for Victoria consist of the months in which long-term average temperatures are above and below the annual average temperature (Timbal et al. 2016).

Fig. 1: Spatial distribution of mean (a) annual (b) cool season (April-October) and (c) warm season (November- March) rainfall (mm) across Victoria using AWAP 5 km X 5km gridded rainfall product for 1900 – 2016 periods

The long-term average annual rainfall (1900-2016) across Victoria is approximately 660 mm/year. However, it varies considerably from year to year, decade to decade and on longer timescales (Fig. 2) in response to a complex interplay of several large-scale climate drivers and other sources of natural variability (see next section). Victoria has experienced below average rainfall on average since the 1970s (blue dashed line in Fig. 2) due, at least in part, anthropogenic forcing (Timbal et al. 2016; Hope et al. 2017). Despite the occurrence of several wet years during the 1950s and 1970s, and more recently in 2010-2011, Grose et al. (2015a) found a generally negative trend in mean annual rainfall over Victoria. They estimated that the annual rainfall is declining by approximately 2 mm per decade since 1960, with seasonal rainfall trends varying by region. However, Timbal et al. (2016) found that the annual drying trend over Victoria is not statistically significant when the full instrumental record is considered, but strengthens when the recent 50 or 30 years alone are considered.

The instrumental records, which began in 1850s, as well as paleoclimate proxy records from a range of sources (Gallant and Gergis 2011; Gergis et al. 2012) show that Victoria has experienced numerous flooding and several drought episodes. Three prolonged periods of below-average rainfall occurred during the instrumental period (Timbal and Fawcett 2013): the Federation Drought (1896 – 1905), the World War II Drought (1936 – 1945) and the Millennium Drought (1997 – 2009), each with different characteristics (Verdon-Kidd and Kiem 2009; Timbal and Fawcett 2013). To characterize and improve
understanding of past hydro-climate variability and change in the wider south-eastern Australia and Victoria the South-Eastern Australia Climate Initiative (SEACI, (CSIRO 2010, 2012)) and the Victorian Climate Initiative (VicCI; (Hope et al. 2017)) were established in 2006 and 2013, respectively.

Research undertaken during the SEACI Phase 1 (2006 – 2009) and Phase 2 (2009 – 2012) and during the VicCI (2013 – 2016) showed that the Millennium Drought was the most severe protracted drought of the instrumental record (Timbal et al. 2016). It was also the longest drought observed in the historical record (Kiem and Verdon-Kidd 2010; Grant et al. 2013; Cai et al. 2014; DELWP 2016b). It lasted for 13 years with particularly large rainfall shortages compared to any previous historical droughts. The event exhibited lower year-to-year rainfall variability, with a complete absence of wet years or months. Unlike the other droughts that were extended over most of the continent, the Millennium Drought was confined to southern Australia. During the Millennium Drought, much of the continent (except south-west Western Australia) received above average rainfall (Fig. 3). The Millennium Drought also contrasted with other droughts in terms of the seasonal timing of the rainfall reductions. It was characterised by a large decline in late autumn and early winter rainfall, whereas the previous droughts exhibited a larger reduction in

Fig. 2: Time series of the observed mean annual rainfall (grey colour) and the 10-year running mean (black colour) in mm month$^{-1}$ over Victoria, Australia. The horizontal black dashed and dotted lines represent the rainfall averages corresponding to the WMO baseline periods 1961 – 1990 and 1981 – 2010. Similarly, rainfall averages for the CSIRO/BoM baseline period 1986 – 2005 and DELWP adopted baseline period 1975 – current are shown in green and blue dashed lines while for the post 1997 baseline period is shown in red dashed line.
winter-spring rainfall. In addition, there has been a significant warming trend in Victoria over the last 100 years, and the Millennium Drought thus occurred in warmer conditions than the earlier droughts. The combination of higher temperatures and lower rainfall prior to the start of the runoff season (i.e. winter) led to a larger than anticipated decline in streamflow (25 – 75 % relative to pre 1997 period) during the traditional filling season for water storages in Victoria (Timbal et al. 2009).

In spring/summer of 2010 – 2011 and 2011 – 2012, La Niña-driven extreme rainfall resulted in widespread flooding across the region (and throughout Australia) which ended the Millennium Drought. During these periods, all the three key large-scale drivers for rainfall, namely the El Niño-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Southern Annular Mode (SAM), were in phases historically linked to wet conditions in south-eastern Australia, causing the above average annual rainfall totals across the region. However, the late autumn and winter rainfalls continued to be below average even after breaking of the long drought. These characteristics are likely to place the past 30 years rainfall totals outside what would be expected based on internal climate variability only. Internal variability is due to the instabilities that occur naturally within the climate system itself, without any form of external forcing.

Figure 4 shows early results from this new project to detect whether the last 30 years are unusually dry, and outside of what we might expect from internal variability alone. The probability distribution of mean rainfall differences of recent 20-year period (1997 – 2016) and first 60-years (1900 – 1959) of rainfall for cool and warm seasons calculated using re-sampling the full historical period (117 years; 1900 – 2016) 10000 times. The vertical dashed grey lines from left to right show the distribution percentiles at 1%, 5% and 50% level of significance. The position of the observed difference of rainfall (red dashed line) between the average of recent 20-years with the first 60-years periods suggests that the recent decline in cool season rainfall is extremely unusual and is very unlikely (less than 1 % chance) to occur due to the internal variability alone. It is thus likely that there was a response to external forcing, be that human-induced (e.g. rising levels of atmospheric greenhouse gases or aerosol emissions) or natural (solar variability or tropical volcanic eruptions). In contrast, no remarkable change is observed in the warm season rainfall.
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These rainfall declines and their seasonal signature have important implications for water resources. Cool-season rainfall declines are amplified in the runoff resulting from rainfall, but the choice of a downscaling model can influence the estimate of a runoff response to a rainfall decline (Potter et al. 2016). The rainfall-runoff relationship in the catchment itself can change due to extended drought (Saft et al. 2015), in some cases biasing the projections based on rainfall-runoff models developed prior to the drought (Saft et al. 2016).

The location of Victoria between the tropics to the north and the mid-latitudes to the south means that a range of drivers are important for rainfall trends over different parts of Victoria. These drivers can influence warm or cool season rainfall in different ways. Thus, if the trends in each season differ, this can provide insight into the causes of those trends. In the next section we describe the key modes of climate variability that affect Victorian rainfall and how these have been changing over recent years due to anthropogenic forcing and internal fluctuations, and what that means for the recent dry decades.

3. WHAT CAUSED THE OBSERVED CHANGES IN VICTORIAN RAINFALL?

3.1 Introduction

To define an accurate baseline, it is important to understand whether any recent trends are due to an external forcing that might continue into the future, or simply due to an internal climate variability after which the climate is likely to shift back to rainfall totals seen prior to the dry decades.
External forcing of the climate system can be from *human-induced* factors such as increasing levels of atmospheric greenhouse gases, sulphate aerosols in the atmosphere (emitted from, for instance, industry), land cover change and the Antarctic ozone hole. External forcing can also arise from natural factors such as variability in the solar input and volcanic eruptions. Of particular interest is knowing the extent to which trends or changes are due to human-induced forcing or natural variability, be it internally generated or externally forced (e.g. volcanoes). In climate science we call this climate change attribution (IPCC 2013).

To help address this, it is useful to establish whether or not the change of interest – in this case multidecadal drying - is unusual in terms of the variability that might have occurred previously. We saw above that this seems to be the case, as the cool season rainfall averaged over the most recent twenty years is very unusual in the relative to the range estimated by the Monte Carlo experiments (Fig. 4). This suggests that the recent drying might be at least partially driven by external forcing.

On the other hand, the instrumental period is relatively short and it is possible that previous twenty-year periods were as dry or drier as the recent period, during pre-instrumental times. Paleoclimate studies have addressed this issue and they concluded that there have indeed been other significant drought periods (Gergis et al. 2012; Freund et al. 2017). Other studies suggest that there may have been longer dry periods in the last 600 years (Ho et al. 2015).

In trying to establish the cause of change, it is also useful to examine the processes responsible for the drying. This includes a description of all the weather and climate variability factors at play during this period, and whether there are known changes in those factors due to increasing levels of greenhouse gases. Literature taken this approach for the Millennium Drought is reviewed below.

An additional way of determining the extent to which human-induced forcing has caused a change is to use mathematical models of the climate system, with and without human-induced forcing included in the simulations. The difference between the two simulations can then be used to try and quantify the impact of human-induced forcing on the climate system, including Victorian rainfall changes.

Clarifying the extent to which human-induced forcing caused a particular change is called climate change attribution in climate science. Early attribution studies (Karoly and Braganza 2005) used above mentioned methods to assess temperature trends in Victoria. They found that the warming trends in Victoria can be attributed to human-driven increases in the concentration of atmospheric greenhouse gases. Individual broad-scale month-long heat events have also been attributed to greenhouse gas increases (Black et al. 2015; Hope et al. 2016).

There have been few attribution studies of this nature on the causes of the recent dry decades in Victoria. However, if climate projections based on climate models forced with
anticipated future enhanced levels of greenhouse gases also show changes similar to what has been observed, then this can also suggest a human role in the change of interest. So, while projections can provide information on what might happen in the future, that can also assist with explaining what has already occurred. We will return to this point below.

3.2 The cause of Victorian rainfall variability and its impact on recent dry decades

Victorian rainfall mostly stems from synoptic weather systems such as cold fronts, cut-off low-pressure systems, east-coast lows and north-west cloud bands (Pook et al. 2006; Risbey et al. 2009; Gallant et al. 2012). Smaller-scale systems such as thunderstorms can also bring rainfall, and are linked to daily rainfall extremes (Dowdy and Catto 2017). The contribution of each system to the total amount of rainfall varies across Victoria (Murphy and Timbal 2008; Hope et al. 2017; Dowdy and Catto 2017). These rain-bearing systems interact with both tropical (e.g. the El Niño-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Interdecadal Pacific Oscillation (IPO)) and extra-tropical (e.g., SAM) modes of large-scale natural climate variability. These large-scale climate drivers modulate the frequency and intensity of the weather systems of relevance to Victorian rainfall (Risbey et al. 2009; Hope et al. 2017). The large-scale drivers also interact with each other (e.g., La Niña promotes high SAM), and the background trend in tropical ocean temperatures (Lim et al. 2016a). In addition, the meridional (i.e., north-south) atmospheric circulation that transports heat from the tropics through mid-latitudes towards Antarctica, has a large influence on the seasonal variation of Victorian rainfall through its impact on the location and intensity of the sub-tropical ridge (STR). There is also climate variability that occurs on the scale of a decade or more, some of which is linked to the Interdecadal Pacific Oscillation (IPO; (Power et al. 1999a). All these weather systems of relevance to Victorian rainfall and how the large-scale modes of internal climate variability influence these features are shown schematically in Fig. 5 and are also discussed below.

3.2.1 Internal Modes of Climate Variability

3.2.1a The ENSO:

ENSO is the most dominant interannual coupled atmosphere-ocean variability in the tropics (Trenberth and Stepaniak 2001; Curtis 2008), and ENSO has a major impact on rainfall over almost all of Victoria (Power et al. 1999a; Risbey et al. 2009; Timbal et al. 2016). The positive phase of ENSO or the El Niño events are characterised by the occurrence of the coldest sea surface temperature (SST) around northern Australia and the warmest SST in the central equatorial to eastern Pacific Ocean (see e.g., (Australian Bureau of Meteorology and CSIRO 2011, 2014)). The existence of anomalously cold SST surrounding northern Australia leads to an increase in mean sea-level pressure, large-scale subsidence (downward motion of the air) and anomalous flow of easterly winds mostly over the eastern part of Australia. As a result, below average rainfall tends to occur over most of eastern Australia, including much of Victoria. The opposite tends to occur
during the La Niña phase of ENSO, when the warmest SST and region of generally upward air motion are located over the top end of Australia. As a consequence, convection over northern Australia is enhanced and the eastern half of Australia including Victoria tends to receive above average rainfall during La Niña.

Fig. 5: Schematic representation of the key climate drivers of relevance to Victorian rainfall. Thick arrows show the influence of each climate mode has upon either synoptic weather types affecting Victoria or another climate mode. Thin arrows indicate wind directions associated with certain synoptic weather types. (Updated from Hope et al. 2017).

The greatest impact of ENSO on Victorian rainfall is primarily felt from winter through spring and into summer seasons only (McBride and Nicholls 1983; Risbey et al. 2009; Hope et al. 2017). Autumn rainfall is less affected by ENSO (Timbal et al. 2016). The fact that the recent multidecadal rainfall decline occurred most strongly in autumn and winter suggests that the drying cannot be explained in terms of ENSO alone. However, the drought breaking rains in spring and summer 2010/11 were strongly dominated by La Niña, enhanced by the observed trend in tropical ocean temperatures (Lim et al. 2016a).

3.2.1b The IOD:

The IOD is another dominant mode of the coupled ocean-atmosphere system which influences the Victorian rainfall at interannual time scales (Murphy and Timbal 2008; Risbey et al. 2009; Hope et al. 2017). However, while El Niño-Southern Oscillation is centred in the tropical Pacific, the IOD is centred in the tropical Indian Ocean (Saji et al. 1999). The IOD is generally derived using the dipole mode index (DMI), which is defined as the difference between SST in the western and eastern equatorial Indian Ocean around Indonesia (Saji et al. 1999). The positive IOD is characterised by the cooler than normal SST around Indonesia which results in an increase in the easterly winds across the Indian Ocean. This condition suppresses the formation of northwest cloud bands by limiting the availability of moist tropical air over Australia, and as a result rainfall is significantly reduced across Victoria (Risbey et al. 2009). Conversely, the negative IOD is characterised by warmer than average SST in the eastern Indian Ocean, resulting in stronger westerly winds across the Indian Ocean. This provides more moisture for frontal systems and lows crossing Victoria and hence widespread and often heavy rainfall prevail across Victoria during the negative IOD phase. The IOD typically starts to develop in early winter, tends to peak in October-November and then rapidly decay around the end of spring. Thus, its greatest impact on Victoria is limited to rainfall during the winter and spring season only. See refs for further details.

Research has shown that the IOD events are generally not independent of ENSO variability (Cai et al. 2011). Hendon et al. (2014a) found that most positive IOD events tend to occur during El Niño events while negative IOD events dominate during La Niña. Victoria experiences widespread rainfall and its wettest conditions when La Niña aligns with a negative IOD as happened during the spring and summer of 2010-2011 that ended the Millennium Drought (Lim et al. 2016b; Hendon et al. 2014a). Conversely, the driest condition prevails when a positive IOD co-occurs with El Niño. Hence, they act together either to significantly reduce or amplify rainfall over Victoria.

Interannual variability of Victorian rainfall associated with the ENSO and the IOD also exhibits marked decadal and multi-decadal variability which are linked to the phases of Inter-decadal Pacific Oscillation (IPO). During the cold phase of the IPO, as we have seen since 2000. Lim et al. (2017) found that the likelihood of a positive IOD co-occurring with a La Nina event is higher, which limits the otherwise enhanced rainfall over Victoria due to La Niña conditions. Such conditions occurred during the La Nina of 2007-8 during the Millennium Drought, which probably suppressed the otherwise wet La Niña conditions during the spring of 2007. Thus, decadal variability likely played a role in the dry conditions since the turn of the century. It is assumed that the IPO is internally driven by the climate system’s own variability and not forced, but this is an area for further research.
3.2.1c SAM and other high-latitude drivers of variability

In addition to the tropical modes of variability, Victorian rainfall is also modulated by the dominant mode of atmospheric variability in the mid- and high latitudes of the Southern Hemisphere, known as the Southern Annular Mode (SAM, (Thompson and Solomon 2002)). The SAM reflects the north-south shifts in atmospheric mass between the pole and mid-latitudes portraying the expansion and contraction of weather systems circulating Antarctica. While SAM varies from days to weeks and years, it is also being driven towards its high phase by increasing greenhouse gases in all seasons and by an increasing size of the Antarctic ozone hole in summer (Kirtman et al. 2013). It is monitored using a SAM index (Marshall 2003). One example of which is the difference in normalized monthly zonal-mean sea-level pressure between 40° S and 65° S. The influence of SAM on Victorian rainfall is dependent on the season and the location (Hendon et al. 2007; Risbey et al. 2009; Timbal et al. 2016). High values of SAM are generally associated with a lower amount of winter rainfall across the western part of Victoria due to a poleward shift of rain-bearing low pressure systems. However, high SAM during spring and summer tends to bring above average rainfall over the eastern coastal region of Victoria by allowing increased incursion of moist air from the Coral Sea and stronger easterly onshore moisture-laden winds and a poleward shift of the downward branch of the Hadley cell (Hendon et al. 2014b). A number of studies (e.g. (Hendon et al. 2007; Timbal et al. 2016; Hope et al. 2017; Nicholls 2010)) have shown that the SAM has exhibited an underlying trend to higher values since the late 1950s with the largest trend in summer and extending to the early part of the autumn (due to the increased size of ozone hole during that time of the year). This may partially be contributing to the recent, observed multidecadal decline in the cool season rainfall, at least during early months of the cool season. Timbal et al. (2016) pointed out that this contribution of high SAM during autumn season may not be independent of the contribution from the STR intensification as a higher SAM also implies an increase in intensity of the zonal belt of high pressure.

As mentioned above, spring-summer season SAM can also respond to ENSO, which can amplify the rainfall response to the strong signals of these climate modes (Hendon et al. 2014a; Lim and Hendon 2015). Variations of the stratospheric polar vortex over Antarctica can also drive swings of the SAM, thereby influencing south-east Australia’s late spring-early summer climate (Lim et al. 2018).

3.2.1d Mean Meridional Circulation (MMC) and sub-tropical ridge (STR)

In addition to the large-scale modes of tropical and extra-tropical variability, Victorian rainfall is greatly influenced by the variations in the location of the descending branch of the mean meridional (north-south) circulation (MMC, Fig. 6) and its interactions with the rain-bearing weather systems at higher latitudes (Hope et al. 2017). As shown in Fig. 6, the tropical portion of the MMC - which is referred as the Hadley circulation - plays a key role in transferring the excess heat from the tropics towards high latitudes. The

descending arm of the Hadley circulation, which tends to reside over Victoria, exhibits strong north-south shifts with season. This is evident as a region of high-pressure systems called the sub-tropical ridge (STR). The STR is associated with relatively dry air and low rainfall. In summer, the STR weakens and it moves southward up to 40° S, while during winter the STR is stronger and moves north to around 30° S. An intense STR is associated with a decline in cool season rainfall, which is exacerbated by the poleward shift of the STR (Timbal et al. 2016).

Research during SEACI and VicCI showed that the MMC and the STR have been changing over the last 50 years. The STR, for example, tended to extend further poleward in the Southern Hemisphere in recent decades than it did previously (Timbal et al. 2016). Lucas et al. (Lucas et al. 2012) showed that the edge of the tropical tropopause has been trending poleward in recent decades with an approximate rate of 0.41 ± 0.37 deg per decade. Nguyen et al. (2013) showed that the Hadley cell is expanding and the position of descending branch of the circulation has shifted further south during the last 30 years. On analysing several climate reanalysis datasets, Nguyen et al. (2013) found that the largest trend in MMC occurred in summer and autumn while smallest in winter. Furthermore, Nguyen et al. (2015) showed that the CMIP5 models are able to simulate the observed Hadley Cell expansion, but exhibit weaker magnitude (i.e. one-fourth of observed) and only when they are run with the observed greenhouse gas forcings as opposed to natural forcings. These changes have been implicated in the observed reduction in cool-season rainfall and greater potential for increases in warm season rainfall (Post et al. 2014).

![Fig. 6: Conceptual diagram of the mean meridional circulation represented as a north-south cross-section across the Southern Hemisphere above eastern Australian longitude. H and L denote regions of high and low pressure at the surface and other features are discussed in the text (from Timbal et al. 2016).](image)
3.2.1e The Interdecadal Pacific Oscillation (IPO)

The Interdecadal Pacific Oscillation (IPO) is a natural, internally generated source of interdecadal variability in the Pacific and beyond (Power et al. 1999a, 2006; Henley et al. 2015) that influences Australia – including Victoria - and many other locations around the world. The IPO modulates ocean temperature, precipitation, river flow, severe weather, flood risk and agricultural production in many parts of the world (Power et al. 1999b,a; McKeon et al. 2004; Callaghan and Power 2011; Power and Callaghan 2016). The IPO also modulates the rate at which the planet warms in response to increasing GHGs (Kosaka and Xie 2013; England et al. 2014; Gillett et al. 2016).

The IPO SST pattern is very similar to the ENSO SST pattern. This arises because the IPO is, at least in part, a residual of decadal changes in ENSO activity (Power et al. 2006; Power and Colman 2006). This also helps to explain why IPO variability is similar to interdecadal variability in ENSO indices (Power et al. 2006). However, there are robust differences in the IPO and ENSO SST patterns, indicating that this simple explanation is not the entire story. For example, the tropical node of the IPO pattern extends further poleward than its ENSO equivalent. This is thought to arise because ocean physics in the subtropical ocean becomes more important for the IPO than it is for ENSO (Power and Colman 2006).

While the Pacific Decadal Oscillation (PDO; Mantua et al. 1997; Newman et al. 2003) is defined in terms of SST that extends well into the North Pacific, interdecadal variability in the PDO index is also closely related to that of the IPO (Power et al. 2006). In fact, the PDO can regarded as the North Pacific expression of the IPO, with other sources of variability, e.g. variability in the North Pacific's Aleutian Low that is independent of the tropics, included.

Recent studies (e.g. Zhao et al. 2016; Lim et al. 2017) show that the IPO can modulate the strengths and spatial patterns of ENSO and IOD and their teleconnection strengths to south-eastern Australian rainfall. Lim et al. (2017) showed that the ENSO and IOD amplitudes were greater during the warm phase of the IPO in 1980s-90s while the same were weaker during the cold phase of the IPO in 2000s-2010s. However, the impacts of ENSO and IOD on south-eastern Australian rainfall including Victorian rainfall appeared to be greater during the recent cold IPO period because the locations of the maximum SST and convection anomalies during ENSO and IOD were closer to Australia.

3.2.2 Summary of process-based examination of the recent dry decades

There have been many studies describing the drivers of the Millennium drought (See references in (Hope et al. 2017)). However, few have considered that the drought is simply part of a shift to on-going dry conditions, as has been seen in south-west Western Australia. There are parallels in the weather between the two regions, particularly in
Victoria's west (Hope et al. 2010). The winter drying in the south-west of Australia is one of the most robust signals projected under enhanced levels of greenhouse gases (IPCC SPM 2013). From our assessment of the processes that dominated Victoria's climate over the last few decades, there are some that appear to be internally driven (e.g., decadal variability reducing the influence from the La Niña of 2007/08), but some do not (e.g., expansion of the Hadley Cell and a higher SAM). The changes in the Hadley Cell and SAM are both projected as a response to greenhouse gas forcing, and as the rainfall changes occurred in the presence of such changes, some of the decline appears to be anthropogenic climate change, especially the large decline in autumn rainfall.

On the basis of our assessment and other research and syntheses (e.g., CSIRO 2010, 2012; Timbal and Drosdowsky 2013; Cai et al. 2014; Grose et al. 2015; Timbal et al. 2015, 2016; Hope et al. 2017) we conclude that:

- aspects of the drying in parts of Victoria is unusual in terms of the historical record;

  the drying appears to have been partly caused by anthropogenic climate change and partly caused by natural climate variability.

- a major focus for the research to date for SE Australia has been on the characteristics of the drying and the impact of anthropogenic forcing on drivers of climate variability in Victoria (e.g., El Niño-Southern Oscillation, the Subtropical Ridge, the Hadley Circulation, the Southern Annular Mode, the Indian Ocean Dipole, and the Interdecadal Pacific Oscillation).

- research directly examining the changes in Victorian precipitation in climate models under anthropogenic and natural forcing has been limited.

- the relative importance of anthropogenic forcing and natural climate variability to the recent drying is unclear. Anthropogenic climate change has likely exacerbated drying from natural variability, though the magnitude of the anthropogenic drying is uncertain, and further research is needed to clarify the magnitude of the contribution.

- There is scope to provide an estimate of the magnitude of the contribution of anthropogenic forcing to the recent multidecadal drying through the use of climate models and observations. We will provide this estimate in a future study.
4. **HOW WELL DO MODELS SIMULATE VICTORIAN RAINFALL?**

In order to use climate models to assess the contribution of external forcing to the recent cool-season drying, we must first assess if they are fit for purpose. There are a range of metrics used to assess the ability of climate models to simulate Victorian rainfall. These include an assessment of the local seasonal cycle and also large-scale features of importance to Victoria’s rainfall such as the representation of SAM and ENSO.

Many studies have evaluated the skills of climate models in simulating a wide range of climate features by comparing their outputs against a set of high quality observations both internationally (e.g. as part of the IPCC AR5 process), nationally (e.g., (CSIRO and Bureau of Meteorology 2015)) and regionally (e.g., (Moise et al. 2015)). Models were assessed with respect to the observed climatological characteristics (e.g. historical mean and its spatial structure, annual cycle) using the 1986 – 2005 baseline period. In addition, over Australia, how the models simulate the large-scale drivers that influence these characteristics and their teleconnections, and long-term trends were also evaluated (e.g., (Bhend and Whetton 2015; Grose et al. 2015b,a; Timbal et al. 2015)). These studies have shown that the performances of models vary regionally and that performance also depends on which climatic variable is considered. Similarly, the model skill also depends on the scoring measure used. Nevertheless, CSIRO and Bureau of Meteorology (2015) have produced a summary of CMIP5 models (Taylor et al. 2012) scoring low on various skill metrics, by evaluating them over different clusters of Australia as defined in the Natural Resources Management (NRM) project.

In general, model evaluation studies across Australia have found that CMIP5 models show an overall improvement compared with CMIP3 models (e.g., (Murphy et al. 2015; CSIRO and Bureau of Meteorology 2015; Moise et al. 2015)). Increases in horizontal and vertical resolution, an improved representation of climatic processes and the availability of a larger set of ensemble members in CMIP5 are thought to be the main reasons behind the improvement in overall skill. Despite these improvements, CMIP5 models still exhibit the cold tongue bias in the tropical Pacific (Brown et al. 2016) and deficiencies in ENSO (Power et al. 2013; Bellenger et al. 2014), and deficiencies in their simulation of the diurnal cycle of rainfall and the Madden Julian Oscillation (MJO).

Over Victoria, VicCI research (Hope et al. 2017) found that most climate models provide a reasonably accurate simulation of the timing of the observed seasonal cycle of temperature (Fig 7). However, most the overwhelming majority of models (38 out of 46) overestimate the annual cycle of temperature, with the multi-model mean slightly too high year round. This systematic model warm bias is robust and persists irrespective of baseline periods (e.g. 1911 – 2005; 1961 – 1990; 1986 – 2005; not shown). A similar statistic was reported in the NRM Southern Slopes Cluster which includes southern part of Victoria and Tasmania (Grose et al. 2015a). However, it was attributed to poorly resolved Tasmania in the models.
New research in this project, indicates that the warm bias still exists in most of the models even if Tasmania is excluded in the computation. On comparing the annual cycle of pre-industrial (pi-control) runs using 500 years of simulation with the observation over Victoria, we found that most of the pi-control models also simulate warmer annual cycle. On average, the multi-model mean for the pi-control and historical runs are respectively 0.25 °C and 0.60 °C warmer than the observations for the baseline period 1911–2005. This finding suggests that approximately 40% of the warm bias in the historical model runs is inherited from the pi-control runs (Fig. 7).

Fig. 7: Mean annual cycle of (a) surface air temperature over Victoria as simulated by cmip5 models with historical runs (red lines) for the period 1911–2005 and with pre-industrial control runs (green lines) using last 500 years of simulation. Ensemble means of historical and pre-industrial runs are shown respectively, in dark red and dark green colours while the observed climatology based on AWAP for the period 1911–2005 is shown in black line. (b) annual cycle of warming/cooling as simulated by the cmip5 historical runs compared to pre-industrial runs.

A similar comparison was performed for the annual cycle of Victorian rainfall (Fig. 8). It is well known that the timing and magnitude of rainfall tends to be poorly simulated in models with coarser resolutions (CSIRO and Bureau of Meteorology 2015), as rainfall involves small-scale processes which are not well resolved in climate models (Flato et al. 2013). VicCI research found that the majority of CMIP5 models simulate the timing of seasonal rainfall pattern adequately, but with some exceptions. For example, a few models show a reversed annual cycle (i.e., a summer peak in rainfall for Victoria) and there exists large inter-model spread. Moreover, the models with summer maximum rainfall poorly simulate observed year-to-year variability in rainfall. Nevertheless, the multi-model ensemble mean exhibits a seasonal evolution similar to its observed counterpart. However, the multi-model mean rainfall is lower than observed in all seasons except summer. Our analysis shows that the annual cycle of rainfall under historical conditions is slightly drier in the cool season and wetter in the warm season compared with pre-industrial runs of the same models. This indicates that the dry bias and warming bias evident in the historical runs are at least partially linked. Note that the magnitude of
cool season drying in the historical runs with respect to pi-control runs is small compared with the observed decline.

It is also of interest to know if the models replicate observed trends (Chowdhury and Beecham 2010; Power et al. 2017; CSIRO and Bureau of Meteorology 2015). The magnitude of the observed temperature trend between 1910 and 2005 is fairly well matched by the multi-model mean, but with large model spread around this mean (Grose et al. 2015a; Timbal et al. 2016). Similarly, the acceleration of warming since 1960s is also closely matched by the multi-model mean. However, the models failed to capture the distinct seasonal variation in observed temperature trends (i.e. high in winter and low in summer). Grose et al. (2015a) found that rainfall trends in CMIP5 models for 1960–2005 are also not statistically different compared to the observed trend, except in autumn where the rainfall decline is not matched by models. Bhend and Whetton (2015) found that fewer than 10 per cent of CMIP5 models reproduce the significant drying in Victoria in autumn, and majority of the models are not able to reproduce the observed rainfall trends across Victoria over the last 30 years. However, they noted that the extent of the areas for which these discrepancies exist is not larger than expected due to the pronounced variability on inter-annual to decadal scales.

CMIP5 models have also been assessed on their ability to simulate key features of atmospheric circulation and modes of climate variability that affect Victorian rainfall as described in Section 2. Studies undertaken during the VicCI and the NRM projects have shown that most of the CMIP5 models are generally able to simulate the major climate
features (ENSO, IOD, SAM, sub-tropical jet, circulation) and their relationship with Victorian rainfall, however, some systematic errors are evident. For example, Timbal et al. (2016) found that many CMIP5 models adequately simulate the broad characteristics (strength and location) of the STR, including its seasonal cycle. Similarly, Grose et al. (2015b) found that CMIP5 models simulate an intensification and poleward shift of the STR under global warming, contributing to reduced rainfall in the cool season over Victoria. However, they found that the models underestimate the historical trends in the STR intensity and the magnitude of the correlation coefficient between inter-annual STR intensity and Victorian rainfall. These issues suggest that CMIP5 rainfall projections for Victoria during the cool season in response to the STR changes may be underestimated, and this lowers confidence in Victorian rainfall projections using the same models.

VicCI research showed that CMIP5 models are able to simulate the broad characteristics of the SAM, including the observed positive trend in SAM in recent decades. However, there are issues with the finer details of its location and behaviour in climate models. Furthermore, there exists a substantial bias in modelling the impacts of the trend of the SAM on Victorian rainfall. Some models underestimate the winter rainfall decline associated with high SAM, while overestimating the increase in summer rainfall.

In general, there has been an improvement in the simulation of ENSO in climate models archived in CMIP5 compared to CMIP3 models (Guilyardi et al. 2009; Christensen and Al. 2013; Power et al. 2013), mostly due to the reduction in number of poor performing models (Flato et al. 2013). Nevertheless, Catto et al. (2012a,b) found that CMIP5 models are still failing to capture the strength of negative correlations between the equatorial Pacific SSTs and north Australian SSTs during the second half of the year. Weller and Cai (2013) found no substantial improvements in the simulation of IOD pattern and/or amplitude during austral spring in CMIP5 models compare to CMIP3 models. They found that most of the CMIP5 models produce a larger variance of SST over the tropical eastern Indian Ocean near Sumatra-Java region and an IOD amplitude that is far greater than is observed. However, they found that the relationship between rainfall and tropical Indian Ocean SSTs is well simulated.

Timbal and Hendon (2011) developed a tripole index to summarise the tropical influences of both ENSO and IOD on rainfall across Australia. This index takes into account average SSTs over the central Pacific, northern Australia and north western Indian Ocean, providing a stronger relationship with Victorian rainfall compared to ENSO or the IOD index alone. Timbal et al. (2017) analysed the ability of 36 CMIP5 models to reproduce tropical SST variability (tripole index) and its relationship to Victorian rainfall. They found that the climate models produce a realistic annual cycle of tripole index but majority of models systematically overestimate the magnitude of the tropical variability all year round. On the other hand, most of the models tend to underestimate the strength of the relationship of tripole index with Victorian rainfall despite they capture the seasonality of this relationship reasonably (i.e. strongest in spring).
On decadal scales, Kociuba and Power (2015) found that interannual MSLP variability in CMIP5 models was too high while decadal variability was too weak compared to the observations. Similarly, Henley et al. (2017) found that CMIP5 models underestimate decadal-scale IPO tripole index (TPI) variance and the ratio of the decadal-to-total variance compared to observations. Nevertheless, they found that the models credibly represent the observed spatial pattern of Pacific SSTs associated with the IPO, however with an overall bias in the duration of simulated IPO phases. They found that most models overestimated the number of IPO events per century as those models tend to underestimate persistence (Kociuba and Power 2015). Nguyen et al. (2015) found that the change in the IPO phase over the past 30 years has promoted the recent expansion of the Hadley circulation, and it is likely that the lack of such an IPO signature among the climate models may have contributed to the underestimation of the recent expansion in the models.

Given the limitations of current models, it will be worthwhile for us to consider those models that best simulate Victorian climate separately as part of our future investigations, as well as trying to include new models if they show improvements in their simulation of Victorian climate or improvements more broadly.

5. WHAT IS PROJECTED FOR VICTORIAN RAINFALL?

To better understand whether the recent dry decades are consistent with the 'fingerprint' of climate change as projected under greenhouse gas forcing increases in the future, we summarise the findings of several previous studies that examined projections for Victorian rainfall as follows.

5.1 SEACI Phase 1 (CSIRO 2010)

Based on projections from global climate models and associated downscaling, research undertaken during SEACI phase 1 found that south-eastern Australia is likely to be warmer and drier in future decades, especially in the winter. The large majority of the global climate models (out of 15 CMIP3 models) agreed on a reduction in future winter rainfall despite existence of considerable uncertainty in the projections. Chiew et al. (2009) pointed out that the large uncertainty may primarily arise from the different sensitivities of different global climate models to greenhouse gases. Mpelasoka and Chiew (2009) used alternative methods for scaling global climate model output to drive a high-resolution hydrological model. They found that while most models project a wetter future for northern Australia, they project a drier future for southern Australia. Post et al. (2008) estimated that the future mean annual runoff is likely to change by between -30% and 10% in the southern Murray Darling Basin (MDB) and Victoria for a global warming of 0.9°C (2030 relative to 1990). In contrast, they found little agreement in the 15
modelling results in northern MDB with projected future streamflow to be between ±30%.

5.2 SEACI Phase 2 (CSIRO 2012)

During SEACI Phase 2, climate change projections of climate and streamflow for south-eastern Australia for 1 °C and 2 °C of global warming for determining the impacts of a changing climate on future water availability, using improved methods. The best estimate of annual average warming for Australia is 1°C by 2030 relative to 1990 and between 0.8 to 1.8 °C (low emission scenario) and 1.5 to 2.8 °C by 2050 (high emission scenario). These improved results also indicated the likelihood of a warmer and drier future in the southern Murray Darling Basin and Victoria, although there is a large range of uncertainty in the magnitude of the projected reductions in rainfall. Averaged over the southern part of the SEACI region (south of 33° S) mean annual rainfall is projected to reduce by 0 to 9 percent (median of 4 percent) and mean annual runoff by 2 to 22 percent (median of 12 percent) for a 1 °C warming (by approximately 2030 relative to 1990).

The projections indicate a rainfall decline in the cool season (April to October) consistent with expected changes in the large-scale atmospheric and oceanic influences on rainfall in a warmer world. In particular, the models typically show a further intensification of pressure in the sub-tropical ridge and the southward movement of this ridge, resulting in a further southward movement of the westerly wind belt and associated mid-latitude storm tracks. In addition, model results showed that the SAM will trend towards more positive values in a warmer world, leading to drier conditions across south-eastern Australia in winter. There may also be an increase in the number of positive IOD events, bringing drier conditions to south-eastern Australia from winter to spring. There is less agreement among climate models in the northern part of the region. Averaged over the region north of 33° S, for a 1 °C warming, the mean annual rainfall is projected to change by –11 to +4 percent (median of –3 percent) and the mean annual runoff is projected to change by –29 to +12 percent (median of –10 percent). Projected changes for 2 °C of global warming are approximately double those for 1 °C of global warming.

5.3 VicCI Synthesis Report (Hope et al. 2017)

VicCI, researchers analysed projections of plausible future climates for Victoria using model output from the CMIP5 model ensemble under two greenhouse gas emissions scenarios: RCP8.5 representing business as usual increases in greenhouse gases, and RCP4.5 representing substantial emissions reduction. In broad terms, they found that the range in projected runoff using information from the latest models is similar in magnitude to those from earlier CMIP3 models used in SEACI phases 1 and 2 (Hope et al. 2017). Also, in line with the previous studies, VicCI research further strengthened the conclusion that future runoff and streamflow in Victoria is likely to decline, driven by projected declines in future rainfall - particularly cool season rainfall when most of the runoff occurs. By the end of the 21st century, it is projected (relative to 1986–2005) that the magnitude of cool season rainfall decline from –34% to +4% in the Murray Basin Victoria
and −31% to +4%, with a median of −15% in south-west Victoria for RCP8.5 emission scenario. Furthermore, better performing models result in a stronger rainfall decline for all Victoria under RCP8.5, from a median of −8% to −14%.

Using empirical downscaling, the runoff projections for a future with little curbing of emissions (median of climate models under RCP8.5) show annual runoff decreases of 5–15% over most of Victoria by 2040 and 10–30% by 2065 (relative to 1975-2014), with comparatively larger reductions in south-west Victoria. Plausible runoff futures by 2065 across all emission scenarios range from little change in runoff over most of Victoria under the low-impact scenario, through to runoff decreases exceeding 40% in most regions, with a proportionally larger impact in western Victoria. Statistically and dynamically downscaled results exhibit greater agreement in median rainfall changes during winter and spring, whereas the projections for other seasons look rather different. A clear explanation for why the different downscaling techniques give such great differences in projected rainfall is an obvious subject for further research.

5.4 NRM Southern Slopes Cluster Report (Grose et al. 2015a)

Grose et al. (2015a) found that almost all CMIP5 models project a reduction of mean annual rainfall across the Southern Slopes which largely consists of southern Victoria. They indicated that there is high confidence that natural climate variability will remain "the major driver" of rainfall changes by 2030 even as anthropogenic changes become apparent. They estimated that changes in 20-year annual mean rainfall by 2030 relative to 1986–2005 are about -10 to +5% annually and about -20 to +15% seasonally. The ranges for 2030 primarily reflects uncertainty arising from natural variability.

Similarly, Grose et al. (2015a) also found that there is high confidence in projected rainfall decreases in winter and spring in the Southern Slopes under higher emissions (RCP8.5) from 2050 to 2090, but with some differences within the region and between seasons. This high confidence stems from a good understanding of the driving mechanisms and high agreement between models means. By 2090, spring rainfall is projected to decrease across the Southern Slopes by around -25 to +5% under RCP4.5 and -45 to +5% under RCP8.5. Most models project a decrease in winter rainfall in Victoria of up to -15% under RCP4.5 and up to -30% under RCP8.5 relative to 1986-2005. Summer rainfall is projected to either increase or decrease over Victorian regions and there is no clear agreement among the models on the sign of future rainfall change. Most models project little change in autumn in all regions with in the Southern Slopes. However, this disagrees with post-1960 trends and there are known deficiencies in the simulation of the current climate in autumn. The changes in spring and autumn are the reverse of those observed in recent decades, where autumn declines have been more significant than spring changes. This discrepancy is sometimes referred to as the ‘seasonal paradox’ and it is the subject of ongoing research.
The existence of this discrepancy lowers the confidence we have in projections of autumn rainfall and our ability to quantify the relative importance of anthropogenic forcing and natural changes in the recent multidecadal drying that has occurred in Victoria.

### 5.5 NRM Murray Basin Cluster Report (Timbal et al. 2015)

Timbal et al. (2015) found that the changes in mean rainfall across the NRM Murray Basin Cluster, which largely consists of northern Victoria, are not strongly different relative to 1986 - 2005 to those due to natural variability under any RCP scenarios by 2030. If there is a signal at this stage then it is small compared to natural variability. Under all RCPs, they found that the changes in mean rainfall are around -10 to +5% changes annually, and around -15 to +10 % in winter, and -15 to +15 % in summer. By 2090, changes in winter rainfall span -20 to +5 % under RCP4.5 and -40 to +5 % under RCP8.5, and those in summer rainfall span -15 to +10 % under RCP4.5 and -15 to +25 % under RCP8.5. Recent studies have found similar results (e.g., Hope et al. 2015).

The NRM Murray Basin Cluster report concluded that "considering (1) the physical understanding of the relationship between the Mean Meridional Circulation, the subtropical ridge and rainfall across Victoria; (2) the projections of MSLP increase and STR strengthening, (3) the difficulties that the models have in adequately capturing the observed relationship between STR and rainfall, and (4) the results from downscaling, there is high confidence that cool season rainfall across Victoria will decline in the future. The magnitude of this decline is, however, very uncertain given the large spread in models results. For the warm season, there is medium confidence that future rainfall will remain unchanged. There is also high confidence that natural variability will remain large relative to any anthropogenic changes, at least for the near future (2030)".

### 5.6 More recent studies

It is sometimes argued that confidence in projections can be improved by selecting only climate models that best simulate the weather and climate features that have a strong influence on Australian rainfall. Grose et al. (2015a) adopted this approach and found that 15 climate models passed tests on their representation of local circulation features. The resulting projected change in rainfall for 2080–2099 (relative to 1986–2005) under RCP8.5 showed that the rainfall reductions in winter (July) is even stronger in both the south-west and the south-east of the continent than previously indicated using the full group of climate models. This is consistent with the observed rainfall declines in winter over the last several decades being at the drier end of model projections to 2030.

### 5.7 Summary

In summary, all the above studies that examined projections for Victorian rainfall suggest a greater likelihood of a drier climate for Victoria in response to increased anthropogenic forcings. A decline in cool season rainfall of 8% for late 21st century, relative to 1986 –
2005, is projected by CMIP5 models under a high greenhouse gas emissions scenario called RCP8.5. Across the south western part of Victoria, a larger decline in rainfall is projected compared with northern Victoria. Models which simulate key climate features relevant to Victorian rainfall (e.g., the subtropical ridge, jets, atmospheric blocking, baroclinic instability and storm tracks) more accurately, exhibit a larger rainfall decline for Victoria under RCP8.5. The studies also conclude that natural climate variability may remain "the major driver" of rainfall changes prior to 2030, even as anthropogenic changes become more apparent.

On the other hand, there is no clear agreement among the models on the sign of future rainfall change during summer. Statistically and dynamically downscaled results exhibit greater agreement in median rainfall changes during winter and spring, whereas the projections for other seasons look rather different. For autumn, most host models also project little change in rainfall across Victoria. However, this disagrees with the post-1960 observed trends as observed autumn declines have been more significant than observed spring changes. Deficiencies in the simulation of the current climate in autumn are also apparent. We therefore conclude that these observation-model discrepancies lower the confidence we have in both projections and in our ability to quantify the relative importance of anthropogenic forcing and natural changes in the recent multidecadal drying that has occurred in Victoria.

6. WHAT IS A BASELINE, AND WHAT FACTORS NEED TO BE CONSIDERED WHEN CHOOSING A BASELINE?

6.1 What is a "baseline"?

A baseline is a period which has been chosen to best represent the current climate of a region with which climate change information is usually combined to create a climate scenario (IPCC 2013). It is used for many purposes, for example: 1) it is used as a reference against which recent observations are compared, 2) it is widely used (implicitly or explicitly) for predictive purposes, as an indicator of the conditions likely to be experienced in a given location (Trewin 2007) and 3) it is also used as a benchmark to evaluate the future changes in climate for planning and management processes. Irrespective of purposes, key requirements for a baseline are that it should be of sufficient duration to encompass the range of natural climate variability (e.g., severe droughts or cool seasons), but, given that the climate is likely to be changing due to anthropogenically-driven climate change, the baseline should also be of short enough duration so as to represent the current state of the climate, and minimise the chance of any climate shifts within the baseline period.
6.2 What factors need to be considered when choosing a baseline?

Various baseline periods are currently being in use to estimate and extrapolate the climate statistics, mainly climate normals (e.g., Huang et al. 1996; Wilks 1996; Livezey et al. 2007; Arguez and Vose 2011; Wilks 2013; Wilks and Livezey Robert E. 2013; Hawkins and Sutton 2016; Hawkins et al. 2017). These climate normals have been found useful in an enormous number of many long-term planning and design applications. The World Meteorological Organization (WMO) recommends using a period of at least 30 years (e.g., 1961–1990, 1981 - 2010) as a baseline to compute the climatological standard normals and suggests updating its 30-years baseline every decade with a view to providing a measure of the local climate at a given time (WMO 2017). Intergovernmental Panel on Climate Change (IPCC) has used the 1986–2005 period as a baseline in its fifth assessment report (IPCC 2013) as a reference period in its assessment of climate change. The same period has been used as baseline by the NRM project and BoM for the assessment of climate change over Australia (CSIRO and Bureau of Meteorology 2015). Similarly, National Centers for Environmental Information (NCEI) designed alternative ways of defining “normal” to provide a better estimate of current or future climate conditions in an era of climate change which include Optimal Climate Normal (OCN) approach (Huang et al. 1996) and the Hinge Fit (Livezey et al. 2007). Recognizing SEACI and VicCI research findings, the current guidelines for Assessing the Impact of Climate Change on Water Supplies in Victoria developed by the DELWP recommends using a current climate baseline from July 1975 to date for water resources planning and management across Victoria (DELWP 2016a). Few high-impact assessment agencies use the start of Millennium Drought to current (post 1997) period as a baseline.

If tracking climate change, then it makes sense to use a fixed baseline and reference all change to that climatology (generally covering a period of good observations, or alternatively a ‘pre-industrial’ period). However, several studies (e.g., Huang et al. 1996; Livezey et al. 2007; Wilks and Livezey Robert E. 2013) have found that WMO-recommended 30-yr normals, even updated every decade, are no longer robust for the design, planning, and decision-making purposes as they are becoming unrepresentative of the current climate due to rapid changes in the global climate. The key problem is that climate normals are calculated retrospectively, but are often utilized prospectively as pointed out by (Arguez and Vose 2011). Specifically, climate normals are calculated using data from a recent N-year period assuming that the climate statistics of a variable is time invariant (stationary) but one of their primary utilities is to provide stakeholders and decision makers with a metric of future climate conditions that can be taken into account in long-term planning considerations. However, recent studies (e.g., Solomon et al. 2007; Milly et al. 2008) have shown that many climate variables (e.g., temperature and rainfall) exhibit significant trend in time series both globally and regionally which violates the assumption of stationarity and a retrospective 30-yr average becomes considerably less useful as an indicator of current and future climate conditions.

Similarly, using most recent and shorter period baseline alone will omit important aspects of the climate variability experienced previously.

### 6.3 Climate Normals in the literature

There has been extensive literature on ‘optimal climate normals (OCN)’ or "optimal sampling period" developed as an aid to making long lead seasonal predictions and for best depiction of the current climate. Huang et al. (1996) and Wilks (1996) found that annually updated climate normals averaged over shorter periods (10 years for temperature and 15 year for rainfall) are better than the WMO specified 30-yr normal, in terms of skill in seasonal temperature prediction in the upcoming year over USA. However, Livezey et al. (2007) found that the OCN method implemented with flexible averaging periods only begins to fail for very strong underlying trends or for longer extrapolations with more moderate background trend. They found that least squares linear trend fits to the period since the mid-1970s could be viable alternatives to OCN when it is expected to fail. According to them an even better alternative are hinge-fit normals (Fig. 9) which are based on modelling their time dependence on the known temporal evolution of the large-scale climate and are implemented with generalized least squares. Livezey et al. (2007) suggested a “hybrid” procedure for defining climate normals, in which the hinge function is used to extrapolate recent trends in cases in which the fitted hinge model is sufficiently strong, with OCN being used otherwise. They also recommended that linear or other trends should never be fit to whole time series and suggested to gain insight about the functional form of regional and sub-regional trends from state-of-the-art qualifying climate models. They also suggested using these models as a tool to test competing empirical methods for estimating and projecting these trends.

Wilks (2013) argued that simply averaging a large number of previous years of data may not be the best method for estimating normals in a changing climate. In his paper, he examined the performance of eight formulations for computing climate normals in both artificial- and real-data settings. Wilks and Livezey (2013) extend the work of Wilks (2013) to address the impact of the data used on the conclusions about alternatives to the standard WMO climate normals. They considered eleven alternatives to the annually updated 30-yr average for specifying climate normals for the purpose of projecting nonstationarity in the mean U. S. temperature climate during 2006 – 12. Their results suggested that the hinge function, although is attractive conceptually for representing accelerating climate changes simply, its use is in general not yet justified for divisional U.S. seasonal temperature or precipitation. They found that averages of the most recent 15 and 30 years have performed better during the recent past for U.S. divisional seasonal temperature and precipitation, respectively.
Arguez and Vose (2011) argued that possible alternative climate normals can be devised by altering one or more of five fundamental attributes of the standard WMO climate normal. According to them, the five important attributes of the normal metric are: 1) it is a temporal average, 2) the average is unweighted, 3) the averaging period is 30 consecutive years, 4) it is a casual filter (using past and current values only), and 5) it is updated once per decade. They pointed out that the standard 30-yr WMO climate normal (e.g. 1981–2010) is an indication of typical climate conditions for 1995/1996 which is the midpoint of the averaging range. On this basis, they argued that the WMO standard climate normals will always be at least 15 years out of date even a new product is released every decade. They suggested a 30-yr average centered on today could be computed from the most recent 15 years of observations along with the forecast for the next 15 years using statistical methods or from downscaled climate model projections.

6.4 Summary

A baseline is a historical period which is chosen to best represent the current climate of a region and serves two main purposes: 1) it is used as a reference against which recent observations are compared and 2) it can be used as a benchmark to evaluate future changes in climate for planning and management processes. The World Meteorological Organization (WMO) recommends using a period of at least 30 years (e.g. 1981–2010) as a baseline to compute the climatological standard normals, while IPCC has used the 1986–2005 period as a baseline in its fifth assessment report (IPCC 2013) as a reference period in its assessment of climate change.
While baseline is defined in terms of "current climate", it is sometimes used as a source of information what the range of possible climatic conditions that could unfold over the coming decade. Key requirements for a baseline defined in this way are that it should be of sufficient duration to encompass the wide range of natural climate variability, but should also be short enough so as to include the impact of changing arising from global warming.

When this is the purpose of a baseline, the approaches taken by WMO and IPCC might not be optimal. For example, a number of studies have found that 30 years or less is not long enough to adequately represent the range of rainfall variability, especially when it is used as a predictive indicator of the conditions likely to be experienced in a given location. Hence, the Guidelines for Assessing the Impact of Climate Change on Water Supplies in Victoria developed by the Department of Environment Land, Water and Planning (DELWP) recommends using 1975 to near-present as a current baseline period for water resources planning and management. Victorian rainfall varies at all temporal scales, and it includes a known influence from climate change.

Victoria just experienced its driest cool season (April – October) rainfall for the last 30 years compared to any 30-year period in the historical record from 1900–2016 (Timbal et al. 2016). It is thus not clear if any historical period is truly representative of the current state of climate or the range of possible climatic conditions will be over the coming decade.

Hope et al. (2017) pointed out that baseline selection poses a significant source of uncertainty in the future projections of Victoria’s climate. The Bureau of Meteorology recently began research on baselines for the Victorian water sector as part of a new program co-funded by the DELWP and the Bureau. We are analysing baselines over the historical period and for coming years and decades to examine the impact of natural climate variability and anthropogenic forcing on the baselines. We have begun to examine baselines in both the observations and a large number of climate models from around the world. This research will be described at a later date. As part of this project we will also provide information on the pros and cons of various baseline choices, and we also aim to provide advice on how choosing baselines might be improved.
REFERENCES


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A LITERATURE REVIEW OF PAST AND PROJECTED CHANGES IN VICTORIAN RAINFALL AND THEIR CAUSES, AND CLIMATE BASELINES


A LITERATURE REVIEW OF PAST AND PROJECTED CHANGES IN VICTORIAN RAINFALL AND THEIR CAUSES, AND CLIMATE BASELINES


———, and Coauthors, 2016: Climate change science and Victoria. 94 pp pp.


### ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AWAP</td>
<td>Australian Water Availability Project</td>
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<tr>
<td>BoM</td>
<td>Bureau of Meteorology</td>
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<td>CMIP3</td>
<td>Coupled Climate Intercomparison Project (Phase 3)</td>
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<td>CMIP5</td>
<td>Coupled Climate Intercomparison Project (Phase 5)</td>
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<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
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<td>DELWP</td>
<td>Department of Environment, Land, Water and Planning</td>
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<td>DMI</td>
<td>Dipole Mode Index</td>
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<td>ENSO</td>
<td>El Nino Southern Oscillation</td>
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<td>IOD</td>
<td>Indian Ocean Dipole</td>
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<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<td>IPO</td>
<td>Interdecadal Pacific Oscillation</td>
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<td>MDB</td>
<td>Murray Darling Basin</td>
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<td>MJO</td>
<td>Madden – Julian Oscillation</td>
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<td>MMC</td>
<td>Mean Meridional Circulation</td>
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<td>MSLP</td>
<td>Mean Sea Level Pressure</td>
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<td>NCEI</td>
<td>National Centers for Environmental Information</td>
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<td>NRM</td>
<td>Natural Resources Management</td>
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<td>OCN</td>
<td>Optimal Climate Normal</td>
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<td>PDO</td>
<td>Pacific Decadal Oscillation</td>
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<td>RCP</td>
<td>Representative Concentration Pathways</td>
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<td>SAM</td>
<td>Southern Annular Mode</td>
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<td>SEACI</td>
<td>South-East Australian Climate Initiative</td>
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<td>SST</td>
<td>Sea Surface Temperature</td>
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<td>STR</td>
<td>Sub-tropical Ridge</td>
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<td>VicCI</td>
<td>Victorian Climate Initiative</td>
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<td>VicWaCI</td>
<td>Victorian Water and Climate Initiative</td>
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<td>WMO</td>
<td>World Meteorological Organization</td>
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