A synthesis of findings from the Victorian Climate Initiative (VicCI)

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Australian Government
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Environment, Land, Water and Planning

CSIRO

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The Victorian Climate Initiative (VicCI) is supported by funding through the Victorian Department of Environment, Land, Water and Planning (DELWP), in partnership with the Bureau of Meteorology (BoM) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). It is hosted at the Bureau of Meteorology. The role of the VicCI is to ensure that Victoria's water policies and management decisions are effectively informed by earth systems and climate change science.

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Citation: Hope, P, Timbal, B, Hendon, H, Ekström, M, Potter, N. 2017. A synthesis of findings from the Victorian Climate Initiative (VicCI). Bureau of Meteorology, 56pp, Australia.

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Published July 2017

This report is available for download from http://www.bom.gov.au/research/projects/vicci/

Cover photo credit: MacKenzie Falls, Grampians. iStock

Report Production

Technical Edit: Bloom Communication (Karen Pearce)

Creator: Hope, Pandora, author.

Title: A synthesis of findings from the Victorian climate initiative / Hope, P, Timbal, B,
Hendon, H, Ekström, M, Potter, N. ;
technical editor, Karen Pearce.

ISBN: 9780642706935 (ebook: pdf)

Notes: Includes bibliographical references.

Subjects: Climatic changes--Environmental aspects--Victoria.
Climatic changes--Victoria.

Other Creators/Contributors:
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A synthesis of findings from the Victorian Climate Initiative (VicCI)

Contents

About the Victorian Climate Initiative

Victoria experiences a highly variable climate, with large variations in rainfall and streamflow from year-to-year and on longer timescales. A drier climate is projected as a likely response to increased greenhouse gases. However, much uncertainty still remains about the causes, prediction and projection of variations and changes in regional climate and their impacts on water resources over timescales of weeks to decades and beyond.

The Victorian Climate Initiative (VicCI) was a three-year regional research initiative designed to further develop our understanding and prediction of climate impacts on water availability to better inform water managers. Specifically, the research aimed to improve:

1. Understanding of past climate variability and change in Victoria

2. Seasonal climate prediction for Victoria

3. Understanding of future climate and the associated risks to water resources in Victoria.

The VicCI program was launched in May 2013 by the Victorian Department of Environment, Land, Water and Planning (DELWP) with research partners the Bureau of Meteorology and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Research in the program concluded in June 2016.

This synthesis report highlights the key research outcomes and implications for the water sector in Victoria. These are organised around the observation of the climate (Chapter 1), the understanding of physical processes (Chapter 2) and their representation in climate models (Chapter 3). In Chapter 4, new understanding about predictions for the coming season is described while in Chapter 5 improvements to the methods used to derive future runoff projections across the state are detailed.

Readers who want a more detailed picture of the VicCI science are referred to the annual reports[1,2,3] and two further reports focusing on the climate change science and its relevance to Victoria[4] and future runoff projections for Victoria[5].

Summary of key program findings and implications

- Since the turn of the 21st century, Victorian cool season (April to October) rainfall has continued to average about 15 per cent less than last century. This decline is likely to persist and possibly intensify in the longer term, and will occur more evenly across the whole cool season rather than primarily in the early part, as was the case during the Millennium Drought. This change is associated with changes in the global-scale circulation, which are at least partly attributable to anthropogenic influences.
- Streamflows have reduced significantly in response to the cool season rainfall reduction, with reductions in rainfall being amplified in the streamflow response. As the downward trend in cool season rainfall is likely to continue, a less reliable filling season is likely.
- The impacts of the cool season rainfall deficit on streamflows may be partially offset by a possible increase in warm season rainfall (particularly in northern Victoria) due to an expansion of tropical influences (resulting from an expanding Hadley cell and an upwards trend in an index of the Southern Annular Mode). Any increase in warm season rainfall is only expected to partially offset cool season reductions because rainfall during the warmer season does not usually generate sustained streamflows.
- In light of the reductions in cool season rainfall over the past 20 years, it is considered likely that the recent decades provide a better representation of current climate than does the full historical record extending back over the 20th century. This should be a consideration in the evaluation of current and expected future water supply system performance.
- In any one season or year, the impacts of these longer term changes may be intensified or offset by the joint state of key drivers of year-to-year climate variability, specifically El Niño – Southern Oscillation (ENSO: El Niño and La Niña) and the Indian Ocean Dipole (IOD), with the Southern Annular Mode (SAM) also having an impact.

Large-scale climate modes and their influence on Victorian rainfall

La Niña (unusually warm tropical waters to Australia's north and north east) generally brings wet conditions to south-east Australia.

El Niño is often associated with drier conditions.

Negative IOD (unusually warm tropical waters to Australia's north and north west) is often associated with wetter than average conditions for Victoria.

Positive IOD generally brings drier conditions.

High SAM (higher pressures over southern Australia, and anomalous easterly winds) often brings dry conditions to Victoria in winter, but wet in other seasons.

Low SAM is often associated with wet conditions across Victoria in winter, but dry conditions in spring and summer.

- In making short-term assessments of water availability, water managers should consider seasonal forecasts (and associated forecast skill), which naturally synthesise the impacts of these drivers and their interaction with regional climate. Background knowledge of the state of ENSO will also assist in providing general guidance on the climate state from winter through summer, and the IOD from winter through spring.
- Decadal and multi-decadal variations of climate associated with the Interdecadal Pacific Oscillation (IPO) affect both the mean climate of Victoria and its variability. The IPO is naturally occurring and describes the episodic flip-flopping of conditions in the tropical Pacific between a cold phase, which is La Niña-like, and warm phase, which is El Niño-like, with each state lasting ~5-20 years.
- While the IPO is in its cold phase, as was the case from the late 1990s through 2015, there is an elevated spring/summer flood risk in Victoria during La Niña and negative IOD because of the stronger linkages of ENSO and the IOD with Victorian rainfall. However, during the cold phase of the IPO, the likelihood of a positive IOD (dry in Victoria) co-occurring with a La Niña event, as occurred during the Millennium Drought, is also increased, meaning that the large increase in rainfall normally expected during La Niña might not eventuate. However, actual impacts will depend on whether the status of ENSO, IOD and SAM act to reinforce or offset each other.
- The IPO phase affects seasonal predictability as well, with the IPO warm phase promoting longer lead prediction of the occurrence of ENSO and the IOD but reduced predictability of Victorian rainfall because of weakened teleconnections. Water managers could therefore benefit from monitoring the state of the IPO as well as predictions of ENSO and the IOD.
- Forecasting across the autumn period has historically been a ‘predictability barrier’. The Bureau’s new seasonal forecasting model (ACCESS-S1) shows promise in improving forecasts across this barrier. Improved forecasts from ACCESS-S1, which will potentially be of use to water managers for improving short-term outlooks for winter filling, will become available late in 2017.
- VicCI research shows that in broad terms, the range in projected runoff using information from the latest generation of global climate models (GCMs) is similar in magnitude to those from earlier models. 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) and higher potential evapotranspiration. However, there is a wide range in the projections. The better performing models tend to project a drier future than the full ensemble of models.
- Given the range of plausible outcomes in terms of runoff, users of VicCI runoff projections should adopt a scenario-based approach to planning. This means that water resource managers need to ensure that their planning and management processes are robust and adaptive across a wide range of future climate, runoff and streamflow scenarios and are subject to regular review.

1. Learning from the past: observed climate and streamflow variability and change

Key findings

- During the cool part of the year (April to October), as of 2016, Victoria had just experienced its warmest and driest 30-year period in the instrumental record. This period captures important variability including the Millennium Drought and the high rainfall in 2010–12. The dry conditions were in part due to increasing greenhouse gas concentrations, so they may be indicative of a longer-term change.
- Streamflows have been among the lowest on record over the past twenty years, with major catchments across the state experiencing declines in streamflow ranging from 25% to 75%, relative to the period 1975-1997.

Implications

- In the light of the reductions in cool season rainfall over the past 30 years, it is considered likely that the recent decades provide a better representation of current climate than does the full historical record extending back over the 20th century.

Observed Victorian climate variability and change

While Victorian rainfall is historically highly variable, it has shown a marked reduction over the past 30 years, driven primarily by a reduction in the cool-season (April to October) rainfall (Figure 1.1). In contrast, there has been an increase in rainfall in some parts of the state during the warm season (November to March). A reduction in the cool-season rainfall was a characteristic of the Millennium Drought (from 1997 to 2009)[6]. This has persisted since the break of the drought in 2010 through to 2015 (the end date of VicCI data analysis). Overlying this recent trend, strong year-to-year variability continues to be a feature of Victorian climate with occasional extremely wet years such as occurred in 2010 and most recently in 2016.

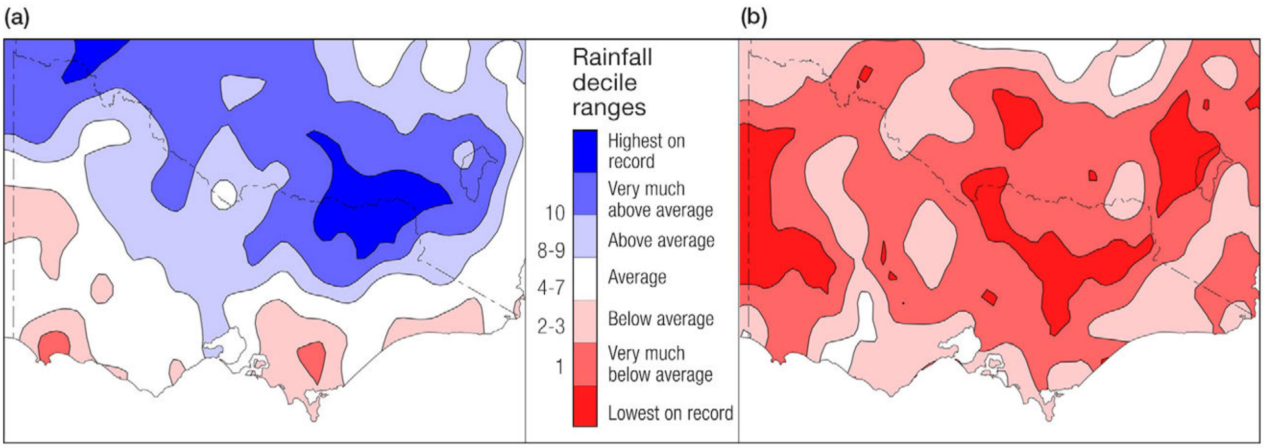


Figure 1.1: Victorian rainfall deciles for Australia for the last 30 years (1986-2015) for (a) the warm season (November to March) and (b) the cool season (April to October).

Left: Cement Creek, Warburton.

Temperatures across Victoria have continued to increase (Figure 1.2) as have global temperatures (black line in Figure 1.2)[7]. Victoria experienced its hottest year on record in 2014, its eighth hottest year in 2015 and sixth hottest year in 2016. These years have contributed to an acceleration of the warming trend in Victoria, particularly during the warm part of the year (for both day time and night time temperatures). During the cool part of the year, day time temperatures have risen, but there is no significant upward trend in night time temperatures. This is likely due to the reduction in rainfall since the mid-1990s, and hence reduced cloudiness, which allows for greater night time heat loss from the surface.

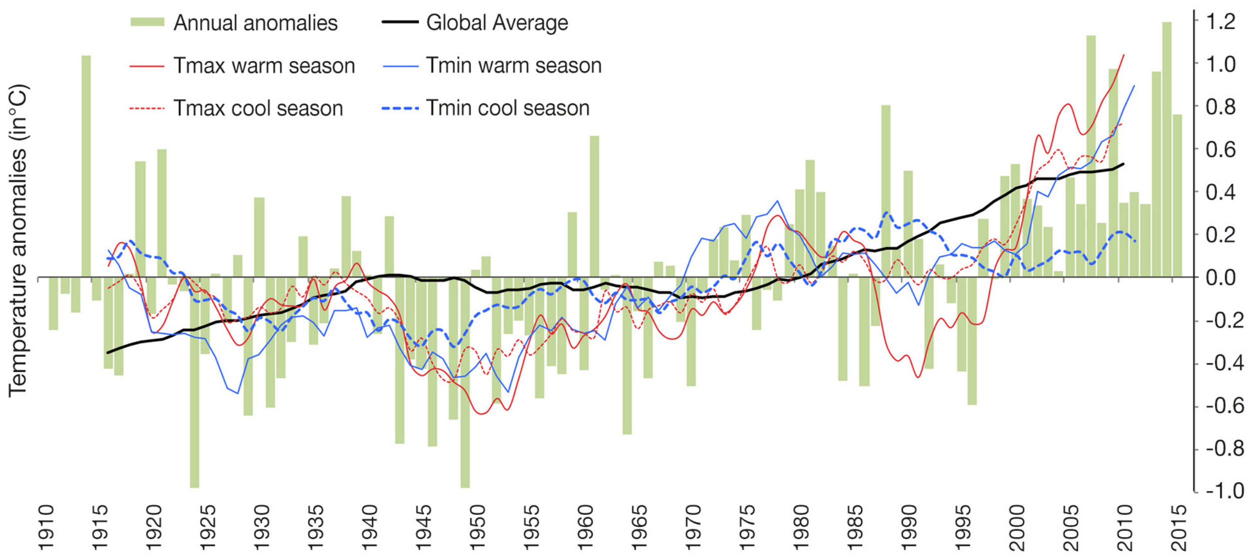


Figure 1.2: Annual Victorian mean air temperature anomalies (in °C) (relative to the 1911 to 2015 average. The black line shows an 11-year running mean of global average temperature anomalies (relative to the 1961–1990 average).

Changes in mean sea-level pressure (MSLP) are useful for understanding recent rainfall changes. The mean winter MSLP has had a strong upward trend across southern Australia since 1980 (Figure 1.3). A measure of the local belt of high pressure, the subtropical ridge (characterised in the Australian region by the intensity and position of the subtropical belt of high pressure around 150°E), is a significant indicator of Victoria's rainfall, especially in the cool season[8]. During the cool season, trends in MSLP suggest a stronger subtropical ridge building in the Bight south-west of Victoria, extending across most of the continent including in the eastern coastal area. This strengthening of the subtropical ridge, which promotes increased air subsidence and deflects rain-bearing weather systems southward, is conducive to a drying pattern across south-east Australia including Victoria.

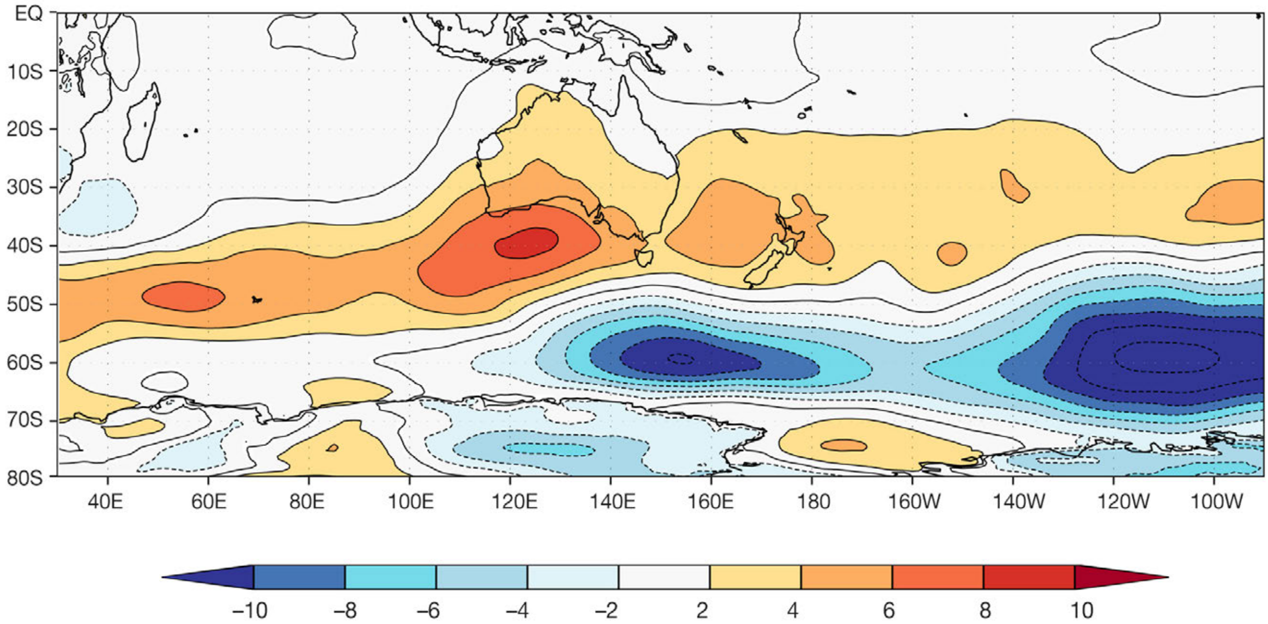


Figure 1.3 Trend in winter mean sea-level pressure from 1980 to 2016 (Pa/year).

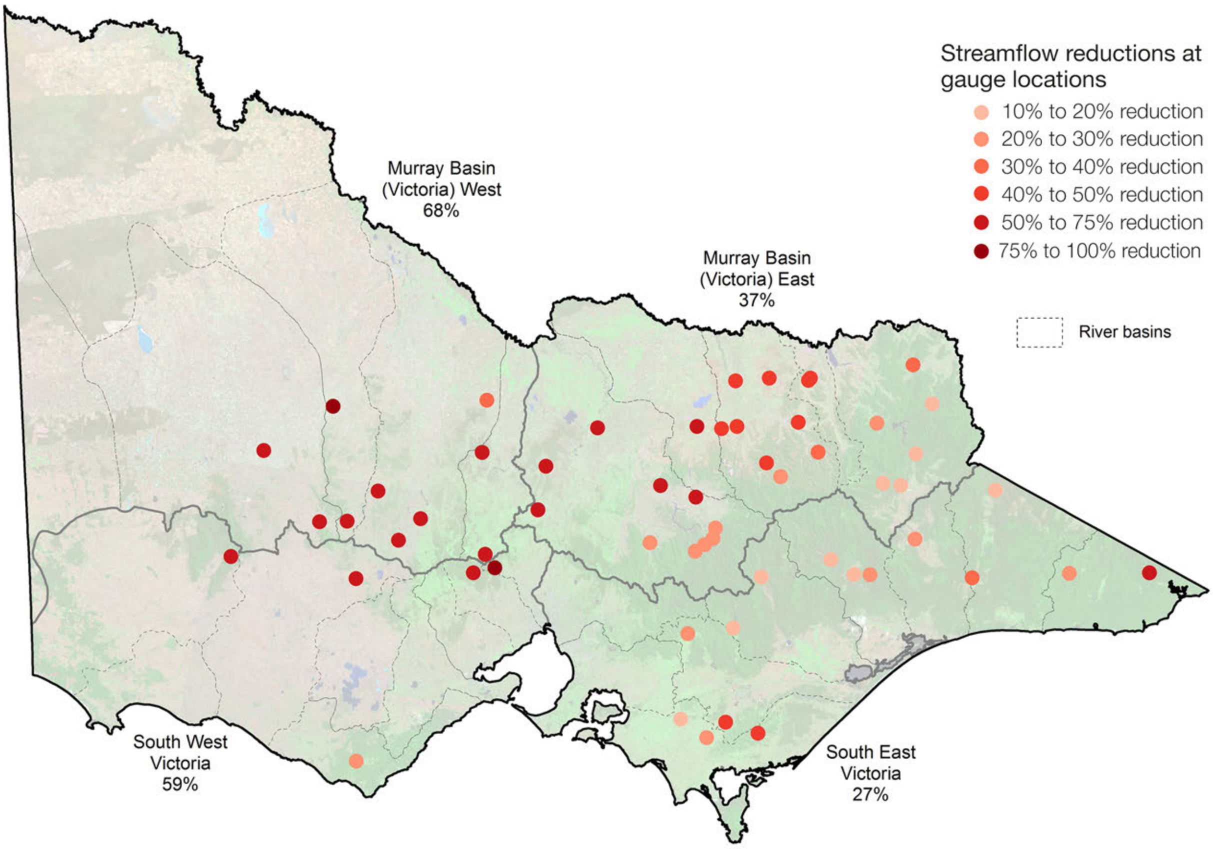
Implications for water availability

Historically, the cool season provides most of the runoff to Victoria's rivers. Hence, the recent decline in cool season rainfall has led to reduced streamflows in major river systems. The Millennium Drought was broken in the years between 2010 and 2012[9]. High rainfalls resulted in extensive floods in many parts of the State and streamflows were markedly above the long-term average. However, during 2013-2015 streamflow returned to levels similar to those recorded during the Millennium Drought.

As an example of how unusually dry the last few decades have been, the total inflows to the Melbourne Water supply systems from 1996 to 2015 were the lowest 20-year inflows on record, with a reduction of 25% relative to the historical record going back more than 100 years. Similarly, River Murray inflows over 1996-2015 have also been the lowest on record at 35% of the long-term average. Overall, declines in streamflow across Victoria for the period March 1997 to February 2014 compared to March 1975 to February 1997 vary between 25% and 75% reduction (Figure 1.4), with the largest declines experienced across the western part of the State (as estimated using the Bureau of Meteorology Hydrologic Reference Stations[10] for unregulated catchments with minimal land use change).

Streamflow typically reduces by around two or three times the percentage reduction in rainfall, and, indeed VicCI research has shown proportionally larger declines in streamflow than in rainfall in many catchments since 1997. However, in some locations the magnitude of the streamflow decline was larger than expected. The South Eastern Australian Climate Initiative (SEACI) and other research[11] has identified some potential contributing factors to this larger than expected decline, including the proportionally higher reduction in autumn and winter rainfall (which in turn has high impact on runoff since most of Victoria's runoff occurs in the winter months), changes in the daily rainfall distribution and rainfall sequencing, the lack of high rainfall years and higher temperature increasing potential evaporation. However, the reasons are still not fully understood and this is an area for further research.

(a)



(b)

Figure 1.4: Average change in streamflow for 1997–2014 compared to 1975–1997 at (a) gauge locations and (b) averaged across climatologically different parts of the state. The greatest reduction (around 60%) was seen in West Victoria.

2. Understanding climate variability and change

Key findings

- The key modes of climate variability that affect Victorian rainfall are the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM).
- The dominant impact of ENSO and the IOD on rainfall is during winter/spring, although strong ENSO events may also have an impact on summer rainfall.
- SAM has different impacts in different seasons, with high SAM being associated with winter drying but a wetter spring/summer. Expected positive trends in SAM resulting from global warming are expected to result in drier winter and wetter summer seasons.
- The large-scale circulation affecting Victorian climate has been changing over the last 50 years due to anthropogenic forcing (human induced, such as fossil-fuel burning) and natural fluctuations. The Hadley circulation has been expanding, the subtropical ridge has been strengthening, and the storm track has been shifting poleward.
- During the cool season, the changes associated with a strengthening subtropical ridge and poleward shift of the storm track contribute to the observed decline in rainfall. The long-term decline of cool season rainfall associated with these changes in large-scale circulation is likely to continue.
- During summer, the changes primarily associated with an expanded Hadley circulation bring wetter conditions to Victoria.
- The expansion of the Hadley circulation is linked to global warming. However, the recent enhanced expansion in the Australian sector (compared to the American and African sectors) is linked to the cold phase of the Interdecadal Pacific Oscillation (IPO). When the IPO shifts to its warm phase the extra expansion in the Australian sector may reduce.

Implications

- The downward trend in cool season rainfall is likely to continue, resulting in reduced runoff and a less reliable water storage filling season. However, future trends in warm season rainfall are less clear. Positive trends in SAM and expansion of the Hadley circulation are linked to higher warm seasonal rainfall. Positive SAM trends are likely to continue, however, the current expansion of the Hadley circulation may decrease when the phase of the IPO changes. It is therefore not yet clear to what extent warm season rainfall increases might be expected in the future, and whether they will help offset the decline in cool season rainfall.
- The status of the key climate drivers (ENSO, IOD and SAM) and associated trends, provides some guidance to short- to medium-term outlooks of water availability. Background knowledge of the state of ENSO can assist by anticipating a persistence of the rainfall anomalies from winter through summer, while the status of the IOD provides information from winter through spring. SAM, which largely fluctuates independent of ENSO and the IOD, can act to enhance or offset the impacts of ENSO and IOD.
- Years with extremely low or extremely high rainfall will continue to occur episodically because of the behaviour of ENSO, the SAM and the IOD in conjunction with longer-term trends.

Left: Lake Eildon

Weather systems of relevance to Victorian rainfall

Many different weather systems generate rainfall across Victoria, such as the west to east passage of low pressure frontal systems embedded within the mid-latitude storm tracks (Figure 2.1). The path of these low pressure frontal systems is influenced by the local subtropical ridge. During the warmer half of the year (November to April), the subtropical ridge is generally located to the south of the continent. In autumn, the subtropical ridge moves northward and remains over the Australian continent for most of the colder half of the year (May to October). The low-pressure frontal systems tend to occur predominantly south of the subtropical ridge, bringing good rainfall to south-west Victoria. The low pressure centre associated with these systems can also become separated from the westerly storm track (known as ‘cut-off lows’) bringing large rainfall totals across most of southern Australia. “Cut-off lows” are a particularly important source of rainfall for the Murray Basin. On the Australian east coast, lows can sometimes form over the Tasman Sea. These systems are commonly referred to as east coast lows and are associated with heavy rainfall events in south-east Victoria.

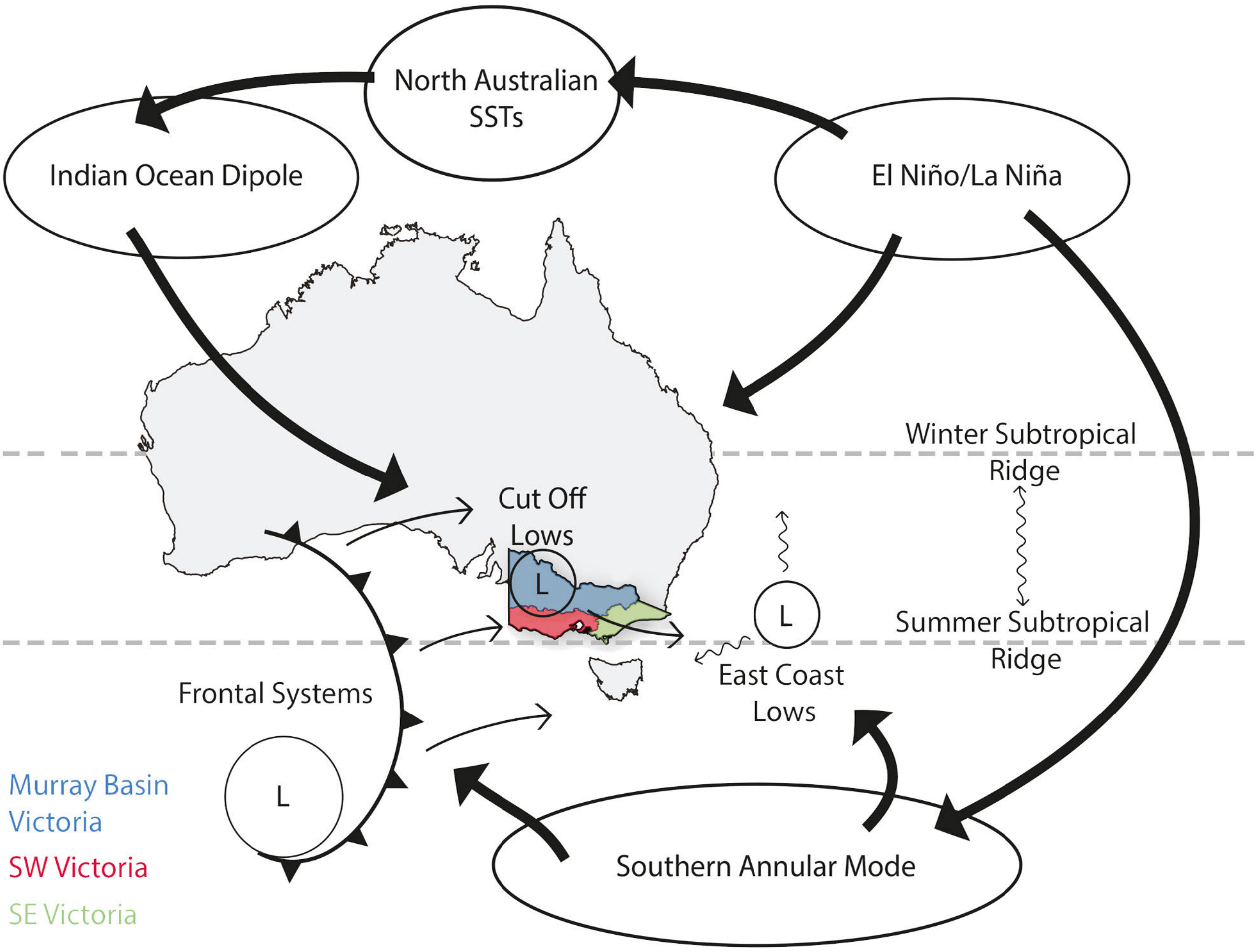


Figure 2.1: Large-scale climate features of relevance to local climate in Victoria. Thick arrows show the influence each climate mode has upon either synoptic weather types affecting Victoria or another climate mode. Thin arrows indicate wind directions associated with certain synoptic weather types. Other features are discussed in this report.

Large-scale modes of climate variability – ENSO, IOD and SAM

A large part of the naturally occurring variability in weather and climate is random and unpredictable on timescales longer than a few days. However, some longer-term variations in the climate at interannual to decadal timescales occur in response to variations of key modes of climate variability. Of primary importance to Victorian climate, ENSO and the IOD[12] are two key modes of variability associated with changes in sea surface temperatures in the tropical Pacific and Indian Oceans, respectively. The primary mode of variability of extratropical circulation is the SAM[13], which is associated with north-south shifts of the jet stream to the south of Victoria. Victoria's climate is modified by these modes as they collectively influence the local weather (Figure 2.1), so they are often referred to as 'drivers'. The importance of these drivers is that they are a source of predictability of climate on seasonal-interannual timescales (e.g., resulting from predictability of ENSO and the IOD) and forced changes in climate will project onto these drivers (e.g.,Antarctic stratospheric ozone depletion acts to drive SAM to its high phase). Thus, understanding how these drivers affect Victorian climate and how these modes ofvariability will respond to climate change can shed light onto future predictability of Victorian climate.

The impacts of ENSO and the IOD are felt primarily in Victoria during winter and spring; however, impacts from strong ENSO events can carry over into summer. Rainfall typically decreases during El Niño and positive IOD events and increases during La Niña and negative IOD events. Positive IOD and El Niño events tend to co-occur as do La Niña and negative IOD events, so they often act together to affect Victorian rainfall. A tripole index of sea surface temperature, which is defined by the areal-average sea surface temperature to the north of Australia minus the mean of the sea surface temperature in the eastern tropical Indian Ocean and western tropical Pacific, is a useful measure to capture the total effect of ENSO and IOD sea surface temperature variations on Victorian rainfall.

These interannual variations associated with ENSO and the IOD are affected on decadal timescales by a pattern of Pacific climate variability referred to as the Interdecadal Pacific Oscillation (IPO, see Text Box 1, page 10). During the cold phase of the IPO (which is La Niña-like), there is increased tendency for positive IOD events to occur in conjunction with La Niña, mitigating the expected increase in rainfall associated with La Niña.

The SAM varies on a timescale of around 10 days, but exhibits strong intraseasonal-interannual variations while also displaying underlying upward long-term trends. SAM in its high phase typically decreases winter Victorian rainfall because it shifts storms southward, away from Victoria. In contrast, high SAM during summer typically increases rainfall because the subtropical dry zone shifts poleward, resulting in an expanded tropical wet zone and increased easterly onshore flow (see Figure 3.3d).

Observed changes in rainfall across Victoria from 1986 to 2015 demonstrate the significance of the large-scale drivers for Victoria's climate. The factor providing the largest contribution is the increasing surface pressure of the subtropical ridge. Other large-scale factors affect the contribution from the subtropical ridge. On longer timescales, these interactions also respond to global climate change.

Text Box 1

The Interdecadal Pacific Oscillation and its impacts

The Interdecadal Pacific Oscillation (IPO) refers to a decadal to multi-decadal variation of surface climate in the Pacific Ocean basin. It has a longer timescale and a broader spatial structure than the El Niño–Southern Oscillation (ENSO). The IPO tends to reside in its cold or negative (La Niña-like) phase for a period ranging from five years to a decade or more and then flip to its warm or positive phase (El Niño-like) (Text Box 1 Figure b). The IPO has been in its negative, or cold, phase since the late 1990s.

In its cold phase, ocean surface temperatures are cooler than normal in the equatorial eastern Pacific and warmer than normal to the north of Australia (Text Box 1 Figure a). It is also warmer in the mid-latitudes of the north and south Pacific, with the warmth extending further poleward than the similar pattern of La Niña. This pattern of ocean surface temperature change is associated with stronger equatorial easterly trade winds in the central Pacific, blowing from cold conditions in the east Pacific toward warmer conditions in the west Pacific. Rainfall tends to be suppressed in the eastern Pacific and increased in the far western Pacific to the north of Australia. The opposite pattern occurs in the warm phase.

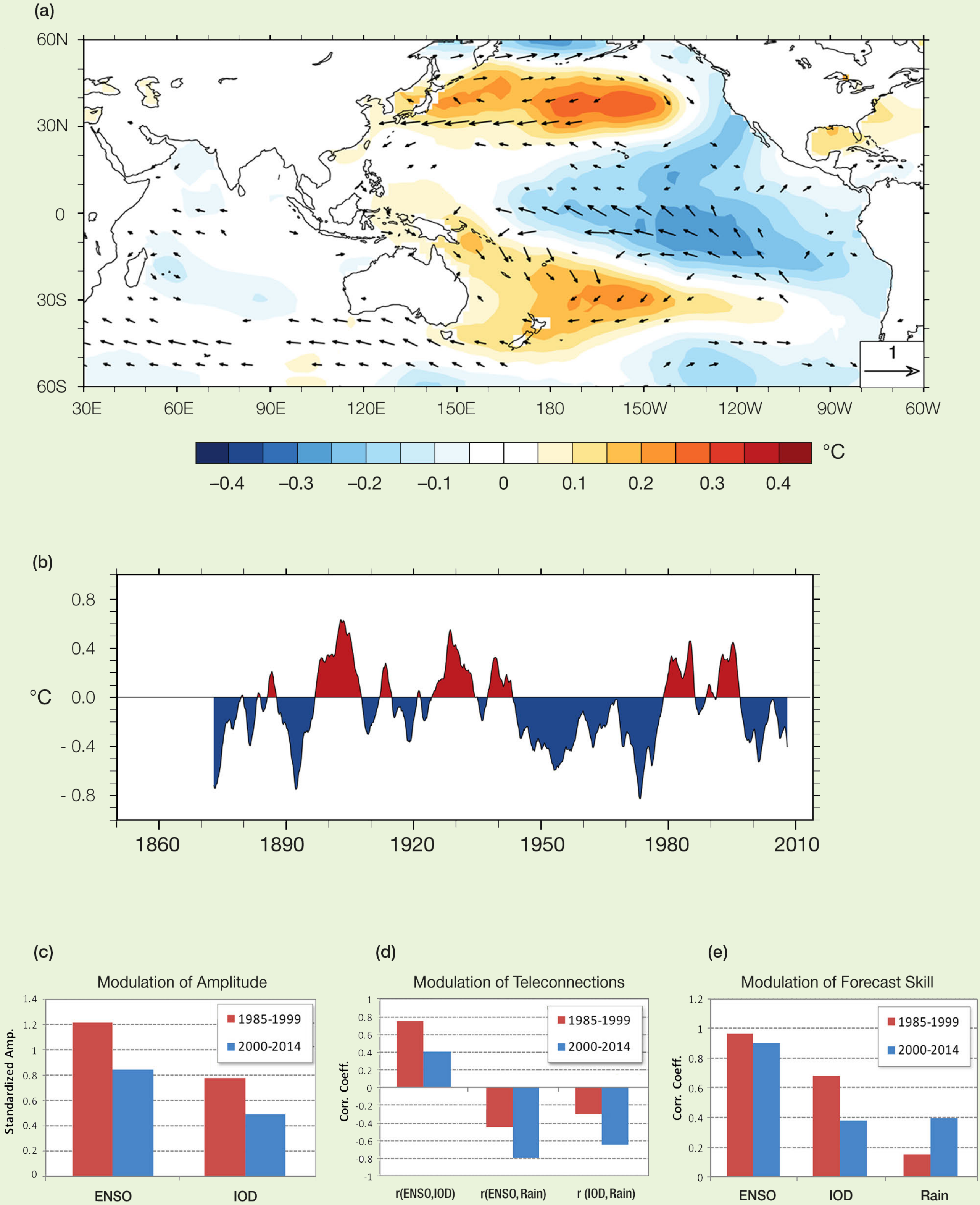
VicCI research shows that during the cold phase of the IPO, the variability of ENSO and the Indian Ocean Dipole (IOD) is weakened[14] (Text Box 1 Figure c). The coupling between ENSO and IOD is also weakened[15] during the cold phase (left column of Text Box 1 Figure d), decreasing the predictability of ENSO and the IOD (left two columns of Text Box 1 Figure e). However, the impacts of ENSO and the IOD on eastern Australian rainfall are strengthened (Text Box 1 Figure d, right two columns), so the short-lead seasonal predictability of eastern Australian rainfall increases (Text Box 1 Figure e, right column). The converse is true during the warm phase of the IPO.

While ENSO and IOD have a strong impact on Victorian rainfall, the wettest conditions occur when La Niña aligns with a negative IOD, and the driest when El Niño occurs with a positive IOD[16,17]. However, during the cold phase of the IPO, the likelihood of a positive IOD (dry in Victoria) co-occurring with a La Niña event, as occurred during the Millennium Drought, is increased[14], meaning that the large increase in rainfall normally expected during La Niña might not eventuate.

Although the impacts of the different phases of the IPO on ENSO, IOD and eastern Australian rainfall seem clear, the cause and predictability of the IPO is still a topic of research. One premise is that the IPO reflects the cumulative effects of random occurrences of a different number or type of El Niño or La Niña events and low-frequency filtering effects of the ocean in response to random forcing from the atmosphere. As such, we are not able to predict swings in the IPO yet.

Text Box 1 figures: (a) Pattern of anomalous surface winds (m/s) and temperatures (°C) during the cold phase of the IPO (the opposite happens during the warm phase). b) Time series of the IPO since 1870[18].

Impact of the warm (red bars) and cold (blue bars) phase of the IPO on c) ENSO and IOD amplitude as depicted by the monthly standard deviation of the Nino3 and DMI indices (see Glossary), d) teleconnection between ENSO and the IOD as depicted by correlation of Nino3 with the DMI, between ENSO and South East Australian rainfall, and between the IOD and South East Australian rainfall, and e) forecast skill for first season prediction of Nino3, DMI, and South East Australian rainfall.


(a)
60N
30N
0
30S
60S
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
1
–0.4
–0.3
–0.2
–0.1
0
0.1
0.2
0.3
0.4
°C
(b)
0.8
0.4
°C
0.0
- 0.4
- 0.8
1860
1890
1920
1950
1980
2010
(c)
Modulation of Amplitude
Standardized Amp.
1985-1999
2000-2014
ENSO
IOD
(d)
Modulation of Teleconnections
Corr. Coeff.
1985-1999
2000-2014
r(ENSO,IOD)
r(ENSO, Rain)
r (IOD, Rain)
(e)
Modulation of Forecast Skill
Corr. Coeff.
1985-1999
2000-2014
ENSO
IOD
Rain

The mean meridional circulation, including the Hadley circulation

While the large-scale modes of variability described above strongly influence Victoria's climate, its mean state is determined by the large-scale mean meridional circulation that transports excessive heat from the tropics towards the polar latitudes. The mean meridional circulation dictates the boundaries between the wet tropics, the dry subtropics and the mid-latitudes that are subjected to rain-bearing synoptic weather disturbances (Figure 2.2). Victoria sits primarily within the dry subtropics, but tropical influences extend southward into Victoria during summer and mid-latitude weather systems extend northward into Victoria during winter.

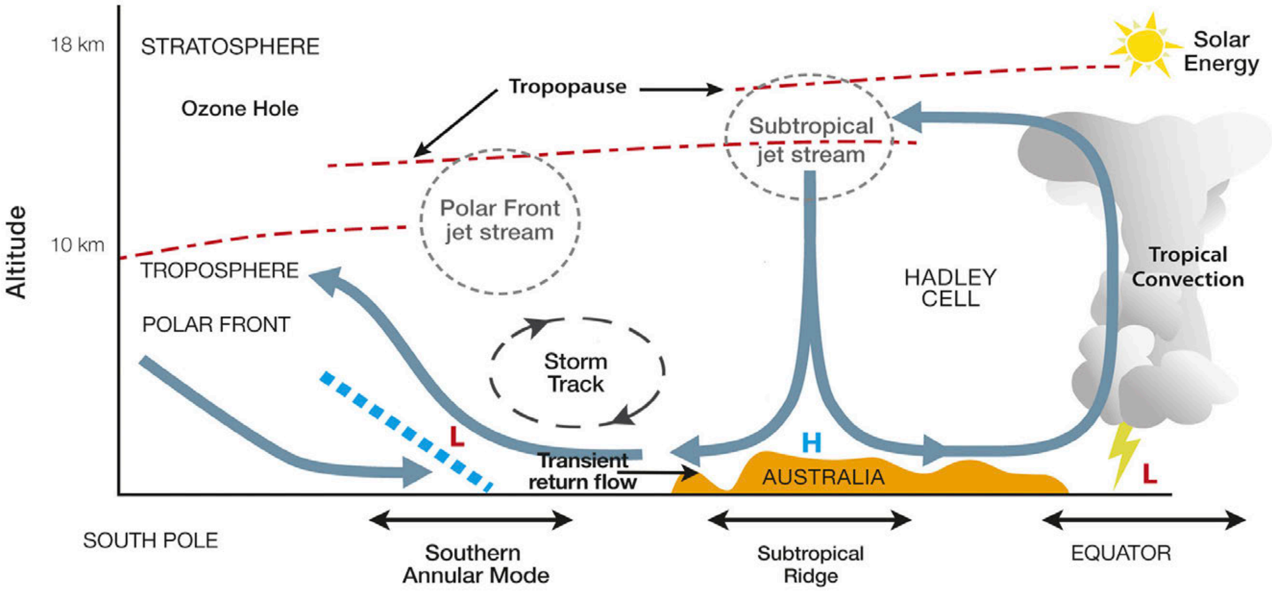


Figure 2.2: Features of the mean meridional circulation

The tropical portion of the mean meridional circulation is referred to as the Hadley circulation, which describes the large-scale overturning circulation with upward motion in the tropics and downward motion in the subtropics. The Hadley circulation forms two 'cells' – one predominantly in the northern hemisphere, and one in the southern, with strong north-south shifts in the location of the upward and downward branches with season. Variability in the Hadley circulation and its interactions with the higher latitude circulation to its south are especially important for Victoria, which is located between ~34-38° S. They determine:

i. The location and intensity of the subsiding branch of the Hadley circulation which suppresses rainfall, including Victoria's rainfall
ii. The southward extent of the wet-tropics, which normally sits northward of Victoria
iii. The intensity and frequency of rain-bearing mid-latitude storms that normally skirt the southern parts of Victoria.

Although the mean meridional circulation can be drawn conceptually as cross-sectional diagrams (Figure 2.2), the actual circulation is highly variable in space and time. Figure 2.3 highlights that there are three localised upward and downward branches of the Hadley circulation associated with regions of strong tropical convection over the tropical Americas, over tropical Africa, and over the Asia-Pacific region which includes Australia[19, 20]. The behaviour of the hemispheric mean Hadley circulation as depicted in Figure 2.2 is largely governed by the behaviour of the Hadley circulation in the Asia-Pacific sector as a result of this sector containing the strongest and most widespread tropical convection.

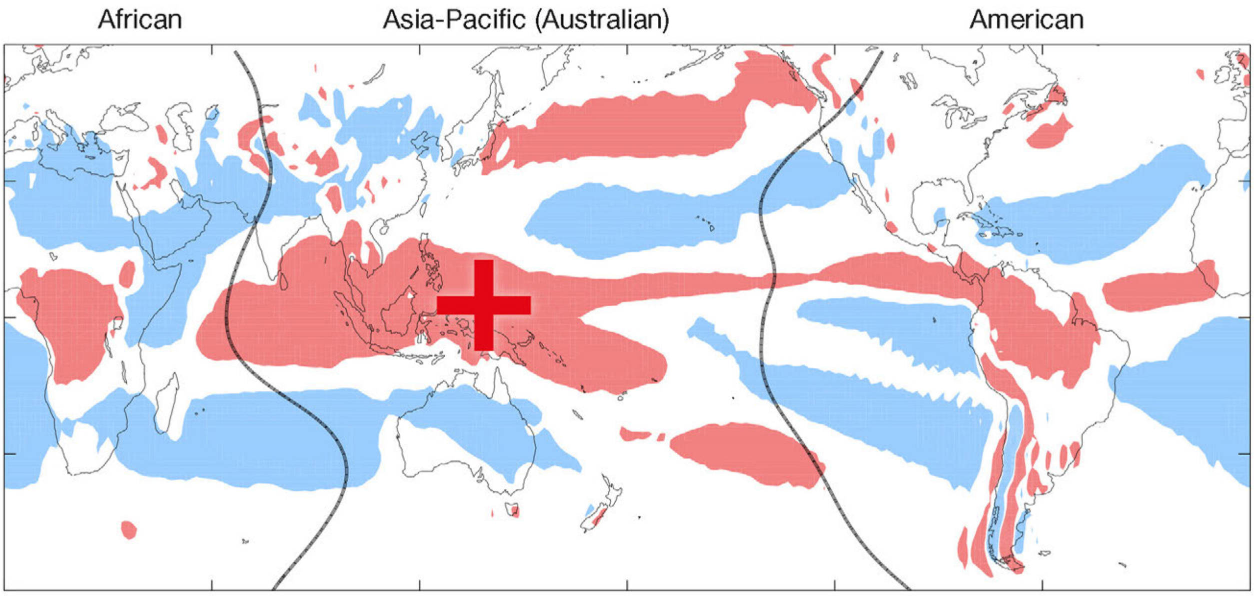


Figure 2.3: Three sectors of the Hadley circulation, delineated by bold black lines. Red generally denotes rising air, while blue generally indicates descending air. The 'plus' shows the region of stronger than expected rising air in the Asia-Pacific sector in recent years, which has resulted in greater poleward expansion of the circulation in the Asia-Pacific (Australian) sector compared to the other two sectors.

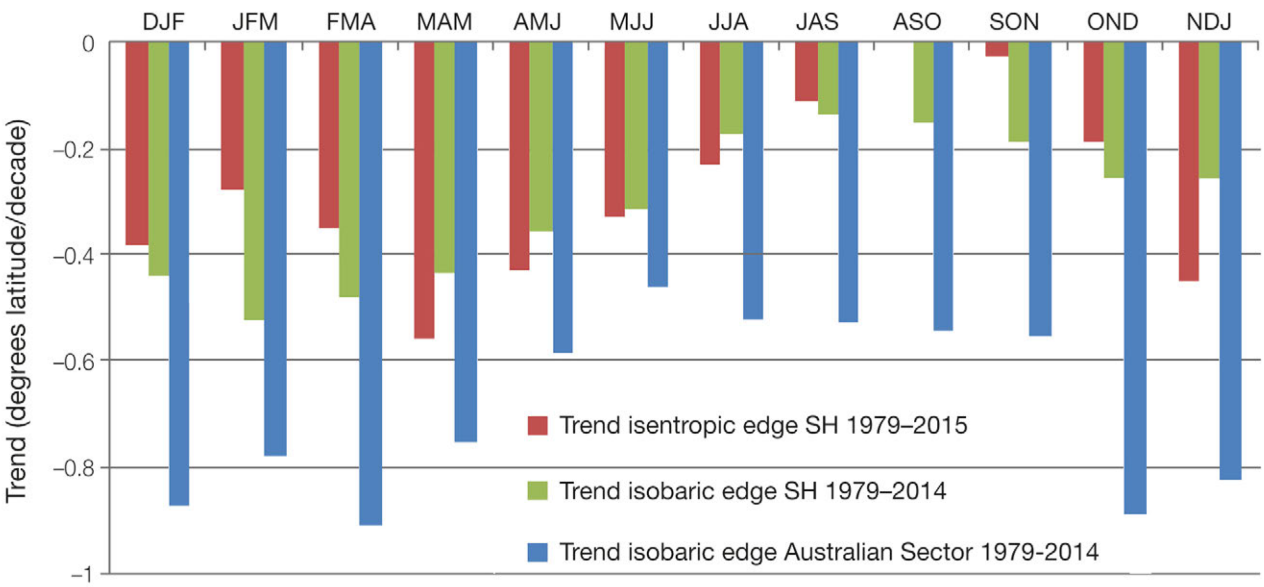


Figure 2.4: Trend from 1979-2014 in the extent of the Southern Hemisphere Hadley circulation, estimated from three different approaches, for three monthly averages (ERA-Interim reanalyses). The scale is degrees latitude southward expansion per decade.

For the Southern Hemisphere, the southward extent of the Hadley circulation has been expanding in recent decades, at around 0.5 degrees (about 50 kilometres) per decade (Figure 2.4)[21]. This expansion is well-defined and significant in summer–autumn, thereby promoting wetter tropical conditions further south into the subtropics. In winter and spring, the expansion is less clear. The expansion is also consistently larger in the Australian sector than for the entire hemisphere; and this amplification is most noticeable in late winter and spring.

Previous work suggests that a part of the overall hemispheric expansion of the Hadley circulation is in response to global warming[22]. Emerging evidence from VicCI demonstrates that this hemispheric and Australian-sector expansion has been modulated by the swing in IPO phase from warm to cold over the past 30 years[2,19]. Previous work combining observations and model results shows that since 1979 about 30% of the Hadley circulation expansion in the southern hemisphere is from natural factors, which includes external natural forcing such as volcanoes and naturally occurring modes of variability such as ENSO and the swing in the IPO[2]. A further 40% of the expansion is forced by Antarctic stratospheric ozone depletion, and greenhouse gas forcing accounts for the remaining 30% of the expansion. Over the longer term (since the 1960s), stratospheric ozone depletion and enhanced greenhouse gases are the dominant factors driving tropical expansion.

The seasonal cycle of the expansion of the Hadley circulation, which peaks in summer–autumn, appears to be partly accounted for by the seasonal cycle of the upward trend in the SAM, which is significant only in summer and autumn. Earlier work in VicCI showed that the SAM and poleward extent of the Hadley circulation are unrelated during winter because of the presence of the winter time subtropical jet, which limits the penetration of mid-latitude storms into the tropics[2].

It is reasonable to expect that the Hadley circulation will continue to expand with global warming due to increasing greenhouse gases[22], even if the Antarctic ozone hole recovers as expected. In the meantime, the modulation of the Hadley circulation due to the sea surface temperature patterns of warming over the past 30 years (i.e. the swing from a warm to cold phase of the IPO) should be expected to reverse sometime in the future with sea-surface temperature patterns becoming more El Niño-like in response to continued greenhouse gas forcing[23]. Hence the expansion in the Australian sector may not be larger than the other sectors (Africa and South America) in the future.

Finally, changes in the annual cycle of Hadley circulation expansion (with stronger expansion in summer and autumn) due to the trend in SAM are likely to disappear. This is because of the two factors that explain past SAM trends: ozone depletion and greenhouse gas emissions. Only ozone depletion has a strong annual cycle and, in the future, due to ozone recovery, this driver of seasonal variation will not apply. There is an important caveat, however: the strength of the interaction between the Hadley circulation (and tropical modes in general) and the SAM currently peaks in late spring and early summer[24,25,26], possibly providing a continued seasonality (peaking in summer) of the future expansion of the Hadley circulation.

Although positive trends in SAM and Hadley circulation expansion are likely to continue to enhance summer rainfall over Victoria, the current rate of Hadley Cell expansion (and therefore the rate of incursion of tropical influences on rainfall) may decrease when the phase of the IPO changes from cold to warm. It is therefore not yet clear to what extent warm season rainfall increases driven by Hadley circulation expansion might be expected to offset the impact on streamflows of ongoing cool season rainfall declines. Research to date has been unable to link Hadley circulation expansion during winter with the ongoing drying trend in wintertime Victorian rainfall. However, preliminary research has indicated that the Hadley circulation has also been intensifying, which is counter to expectations for the response to climate change but which could help account for the strengthening of the subtropical ridge in the Australian sector, hence contributing to the wintertime rainfall decline.

3. The climate models underpinning climate science for Victoria

Key findings

- Most climate models accurately simulate Victoria's annual temperature and rainfall; however, some models incorrectly simulate a summer peak in Victorian rainfall, rather than a winter peak.
- Downscaled rainfall projections at 2 km resolution are better able to capture high intensity rainfall (in the top 90% of rainfall amount) across Victoria than projections at 10 km resolution. Fine scale modelling also improves representation of temporal variability and rainfall dependencies on temperature.
- Some climate models do not accurately simulate the behaviour of key climate drivers for Victoria or their teleconnections to Victoria's rainfall.
- Under a high emissions scenario, projections for Victoria's cool season rainfall at the end of the century show a decline of around 8% (relative to 1986-2005). Across the south western part of the state this decline is about 15%, and the modelled range of possible change is -34% to +4%.
- Selecting only models that better simulate the seasonal cycle of Victoria's rainfall leads to a drier future than the full ensemble. If models that do not simulate the seasonal cycle of Victorian rainfall well are removed from consideration, a drier future by the end of the century is indicated (a rainfall reduction of –14% compared to –8%). If the poorer performing models in terms of climate drivers are also excluded the corresponding figure is –17% compared with –8%.
- The current trend in SAM toward its high phase is projected to continue, leading to drier winters and perhaps wetter summers. The models also project that the Hadley circulation will continue to expand in the future and the subtropical ridge will continue to intensify and move poleward over the century.

Implications

- Projected changes to major climate drivers suggest that the downward trend in cool season rainfall is likely to continue.
- Even with careful selection of models, climate change projections continue to show a wide range of possible and plausible regional rainfall and runoff futures. This range should be considered to provide reasonable bounds for planning purposes, noting also that the generally drier projections from the better-performing models for Victoria suggest that projections in the drier end of the full range may be more likely.
- While fine-scale simulations capture climate features and variability not evident on larger spatial scales, they require a large amount of computer resources and are not currently feasible to run across a large number of climate models. This limits their current practicality for hydrological projections of future water availability.

Left: Stream in Melbourne catchment area. Paul Feikema

Text Box 2

Projecting runoff for a warmer future under climate change

Attempting to understand what the climate and runoff may look like in a future with higher atmospheric concentrations of greenhouse gases presents a challenge for the research community, due to:

- Uncertainties around future emissions
- Uncertainties in the simulation of the climate by global climate models
- Uncertainties in the process of downscaling the coarse-grid climate model outputs
- Uncertainties in the method used to produce catchment-scale streamflow/runoff changes.

It is important to keep these uncertainties in mind when considering guidance on how rainfall and runoff may change in the future.

Climate models

Climate is influenced by many physical, chemical and dynamical processes in the atmosphere, ocean and cryosphere, and by interactions with land surface characteristics. Some of these have a large influence on regional climate (e.g. the impact of the Great Dividing Range on Victoria's climate) while others have wide reaching global influences (such as ENSO). To project future climate, scientists represent knowledge of these processes (movement of heat, moisture and mass) and landscape characteristics (orography and land-use) in global climate models (GCMs). Over the past five decades these models have become increasingly complex and sophisticated, but are still simplifications of reality, both in terms of space and time scales and in their representation of dynamical, chemical, physical and biophysical processes.

Future emissions

The investigation of future climate change requires more than climate models. It is also necessary to predict what greenhouse gas emissions may look like in decades to come. This prediction depends on how global and regional economies develop, changes to vegetation and land use, population growth and other drivers. With such a wide range of possibilities, scientists opt for representing possible futures along several different representative concentration pathways (RCPs)[27]. These RCPs describe different levels of greenhouse gases and pollutants in the atmosphere that could result from a range of different physical and economic scenarios:

- The **high** emissions scenario (RCP8.5) represents a future with little curbing of emissions. Carbon dioxide concentrations continue to rise rapidly and reach a concentration of 940 ppm by 2100 (Red line in left panel of Figure).
- In the **medium** emissions scenario (RCP4.5) emissions peak around 2040, then stabilise at around 2100, with a carbon dioxide concentration of 540 ppm by 2100 (Blue line in left panel of Figure).
- The **low** emissions scenario (RCP2.6) is an ambitious, strong mitigation scenario, with emissions peaking by 2020 then rapidly declining due to emissions reduction and active removal of carbon dioxide from the atmosphere (Green line in left panel of Figure).

Climate models use greenhouse gas concentrations defined by the RCPs as inputs, thus giving the climate response following each emission pathway into the future. Together, the RCPs span a range of plausible futures. Opting to use a single RCP implies that certain pathways have been judged to be less relevant to the intended

application. Decisions about choosing an RCP have the greatest implications for far-future time horizons as the concentrations of long-lived greenhouse gases such as carbon dioxide increase in the atmosphere over time, and higher emission rates have greater cumulative effect on the climate.

Downscaling

Scientists also need to consider how to translate the typically coarse resolution information from global climate models to catchment scale, a process often referred to as downscaling[28]. A wide range of different techniques are available for this process which vary in their complexity and capability to estimate climate change on a finer resolution compared to the global climate model. Methods range from straightforward scaling of observed data using scaling factors, to very fine resolution dynamical modelling using a regional climate model.

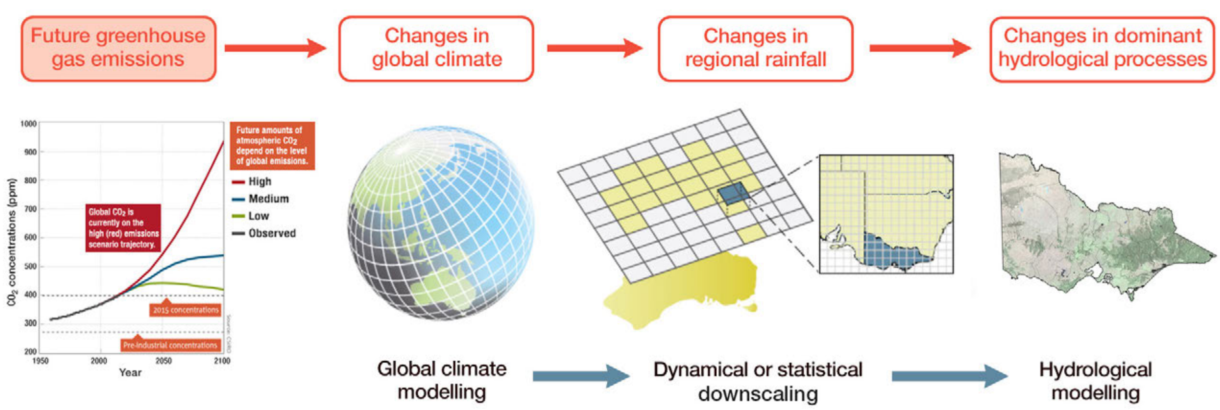
Hydrological modelling

To estimate future runoff, scientists typically use conceptual rainfall-runoff models. These are often models used in an operational setting and are calibrated to observations of the current climate and streamflow. When applied to a future climate, calibrations are assumed to remain constant. If the catchment experiences significant changes to its biophysical characteristics, this assumption may not hold true. Hence, in addition to uncertainty in the climate data, uncertainties also exist in the hydrological modelling.

Summary

The output of climate models is the largest source of uncertainty in the runoff simulations from hydrological models[6]. Confidence in runoff projections is thus strongly linked to the credibility of the downscaled climate change signal and the sampling of global climate models.

Four sources of uncertainty in runoff projections



Improving climate models

Climate models of varying degrees of complexity are the basis of routine weather forecasting and seasonal climate prediction, as well as being used for long-term climate change projections. Models are evaluated by comparing their outputs with past observations of climate variables (e.g. temperature and rainfall) and by assessing their capability to simulate large-scale factors that affect local climate (e.g. ENSO, IOD and SAM).

Evaluation shows that these models capture large-scale circulation features well, however there are some systematic uncertainties in projecting climate. The uncertainties arise from the chaotic nature of the climate system and systematic model errors due to misrepresentation or lack of representation of key processes occuring on scales smaller than the grid scale of the computer simulation.

Advances in model development and enhancements in supercomputers aim to reduce all these uncertainties. To account for the uncertainties in individual models arising from both model errors and unpredictable climate variability, researchers generally consider the results of several models i.e. an ensemble. The most recent ensemble for climate projections was provided by the Coupled Model Intercomparison Project 5 (CMIP5)[29]. These CMIP5 models have been run for a standard set of experiments so their capabilities to simulate current and future climates following prescribed greenhouse and air pollution concentrations can be assessed. Modelling groups are currently planning for CMIP6.

Improvements in the Australian Community Climate and Earth System Simulator (ACCESS) seasonal and climate models are ongoing. A substantial upgrade of the available supercomputing capability for operational activities will deliver increased speed and the capacity for increased spatial resolution, resulting in an improved representation of Victoria's climate and its seasonal prediction. A plan is being developed for further improvement to the ACCESS model used for long-term climate projections. While climate modelling has its limitations, investment in national and international development ensures that model skill and model capability improve over time.

Evaluation of climate models

VicCI scientists evaluated climate models in terms of their skill in simulating the climate of Victoria, the large-scale factors that influence variability of Victoria's climate, and the relationship of these large-scale factors to Victoria's climate. These evaluations are important in assessing the uncertainties in the CMIP5 models which were used to develop a set of future projections of Victoria's climate.

Most climate models provide a reasonably accurate simulation of the observed annual cycle of temperature and rainfall in Victoria (see Figure 3.2 for rainfall). However, some yield a summer maximum (rather than winter maximum) in rainfall that may lead to unreliable estimates in future projections. Moreover, climate models with summer maximum rainfall do not capture the observed year-to-year variability of rainfall. The cause for this deficiency appears to be a poor representation of the atmospheric circulation in the tropics to the north and east of Australia.

The ability to simulate both the annual cycle and trends of key climate factors and the linkage (or teleconnection) between these key factors and the climate of Victoria (Figure 3.3) was also assessed. There is a strong relationship between Victoria's rainfall and the pattern of tropical sea surface temperatures to the north of Australia and in the Pacific (due to ENSO) and Indian (due to the IOD) Oceans. Further, the IOD tends to be correlated with ENSO, with positive IOD events occurring with El Niño events. The Intergovernmental Panel

on Climate Change (IPCC) reports that there is some improvement in the representation of ENSO in CMIP5 models compared with the earlier CMIP3 models[30]. However, significant uncertainties remain, especially in the representation of the feedback processes that underpin ENSO. The IOD is also simulated reasonably well in CMIP5 models although some models tend to overestimate the amplitude of IOD events and underestimate its linkage with ENSO.

The seasonality in these tropical modes is well captured by most models (Figure 3.3a), as is the relationship with Victorian rainfall, being strongest in spring (Figure 3.3b). However, although most models capture some of these connections, the relationship varies from model to model.

Variation of the subtropical ridge of relevance to Victoria can be represented by the surface pressure maximum in a north-south slice around 150°E. Many CMIP5 models yield accurate simulations of the seasonal cycle of the subtropical ridge intensity and peak location (Figure 3.3c). However, the observed relationship between the subtropical ridge and Victoria's cool-season rainfall is less well simulated, especially between April and August.

In VicCI, an assessment of the value of very fine resolution simulations that allow convection to be explicitly resolved was made using the US Advanced Weather and Research Forecasting (WRF)[31] model. Simulations were run across Victoria on grid resolutions of 2 km and 10 km over the period 2010–2014. The purpose was to investigate whether the finer resolution (which allows convection to be explicitly simulated within the model) provides a better simulation of regional rainfall relative to a coarser resolution regional model where convection is parameterised. Compared to a 10 km resolution, the 2 km simulations are better able to capture high intensity rainfall (raindays in the top 90% of rainfall amount) across Victoria (Figure 3.1), as well as improved representation of its temporal variability. Currently, the large supercomputing resources required for very fine resolution dynamical downscaling limit its practicality for hydrological projections of future water availability. However, these experiments can provide useful process understanding.

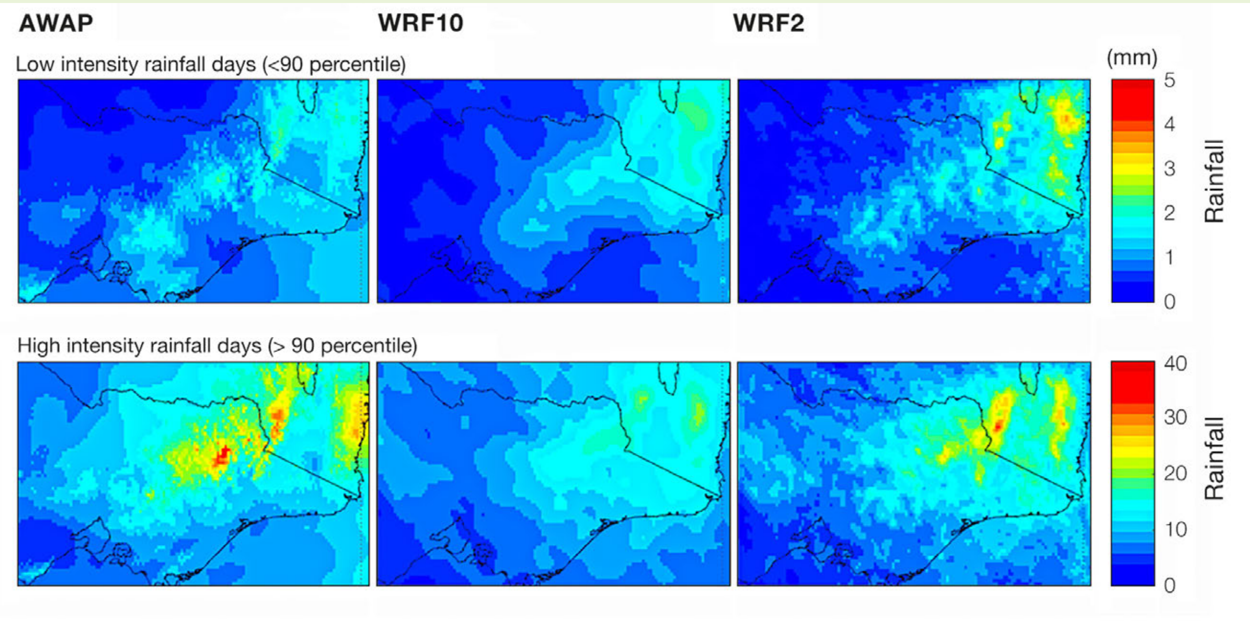


Figure 3.1: Representation of mean and high intensity rainfall in observations (AWAP) and by a regional climate model (WRF) at 2 km or 10 km resolution.

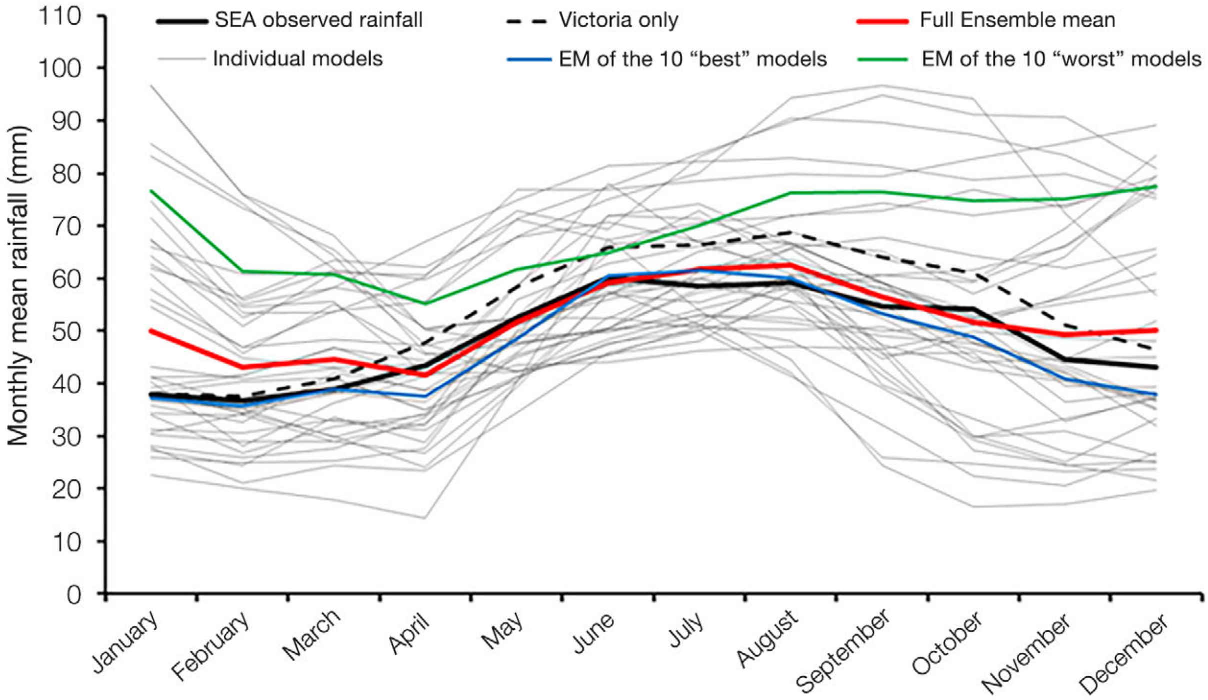


Figure 3.2: The annual cycle of Victorian rainfall. Observations for south-east Australia (solid black line) and Victoria only (dashed black line); ensemble means from all models (red line); models with the best representation of the seasonal cycle (blue line), and models with the worst representation of the seasonal cycle (green line).

Moreover, models tend to underestimate the observed intensification and poleward shift in the subtropical ridge over the last century.

Current climate models can simulate the seasonal influences of SAM on Victoria's rainfall, with a positive SAM causing dry conditions in winter but wetter conditions in the warm season (Figure 3.3d). Climate models are also able to capture the observed positive trend in SAM in recent decades. However, there is a substantial bias in the depiction of the impact of the trend of the SAM on rainfall, with too large an increase in rainfall in summer and too small a reduction in winter when SAM is increased. An additional limitation is that the climate models tend to underestimate the seasonal relationship between ENSO and SAM[32], especially the observed tight coupling of SAM to strong ENSO events in spring/summer. A study of the heavy spring rainfall in Victoria during the major La Niña event of 2010 demonstrated the importance of the alignment of La Niña and positive SAM for causing the high rainfall[16]. An opposite alignment can occur in El Niño events, such as during the spring of 2002, when a strong negative SAM played an important part in a major drought affecting Victoria.

Climate models capture decadal variability, including the IPO, but the amplitude is weaker than observed. The timing of simulated decadal variations is not expected to match the observed variations because much of the observed decadal variability is thought to be generated by interactions within the climate system rather than being externally forced, so the climate model's day-to-day weather, and resulting decadal variability, will differ from that in the observed world. Averaging across a number of models, this source of decadal-scale variability will be smoothed out. As the change in the IPO phase over the past 30 years has promoted the recent expansion of the Hadley circulation, it is likely that the lack of such an IPO signature among the climate models contributed to the underestimation of the recent expansion.

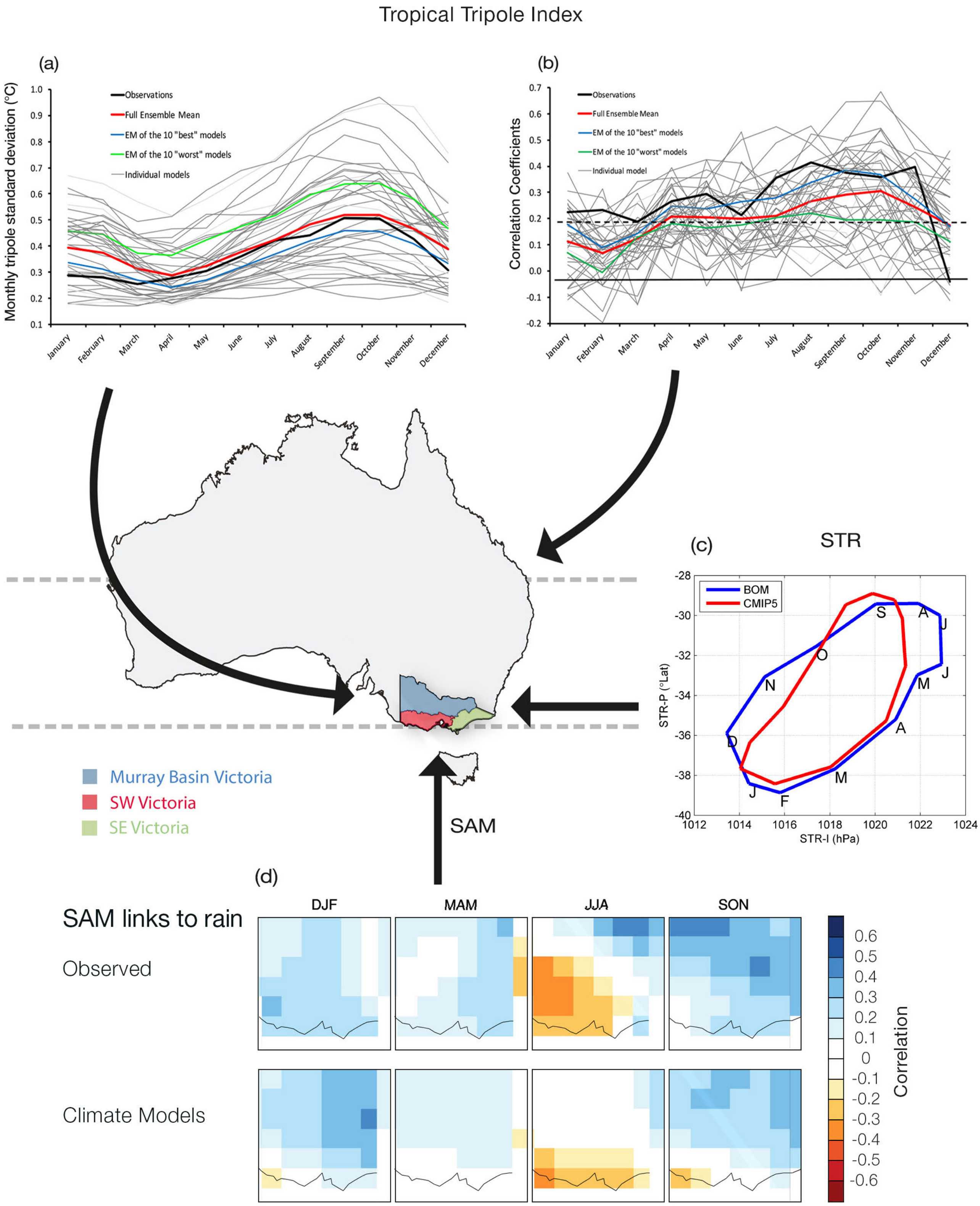


Figure 3.3: Evaluation of the ability of climate models to reproduce the key large-scale drivers of relevance to Victoria and their links to Victorian rainfall. Panels show observed and modelled characteristics for (a) the annual cycle of tropical variability as depicted by the tropical tripole, an index that captures differences in sea surface temperatures north of Australia relative to temperatures in the nearby Indian and Pacific Oceans; (b) the correlation between the tropical tripole and Victorian rainfall; (c) the annual cycle of the subtropical ridge intensity (STR-I) and position (STR-P; starting in January bottom-left, moving counter-clockwise); (d) the correlation between SAM and rainfall across south-east Australia for the four calendar seasons in observations (top panels) and models (lower panel).

Projections from climate models

Projections of plausible future climates were analysed for Victoria using model output from the CMIP5 model ensemble[4] under two greenhouse gas emissions scenarios (RCP8.5 representing business as usual, and RCP4.5 representing substantial emissions reduction).

Rainfall

In the near future, natural variability, such as the IPO, will tend to mask any forced trend in rainfall; nonetheless, the projections suggest that there will be a cool-season decline in rainfall and the downward trend will be clear later in the century (Figure 3.4). The magnitude of the decline in cool season rainfall is dependent on the emissions scenario, with the projected change (relative to 1986–2005) by the end of the 21st century from the CMIP5 ensemble of models ranging from –20% to +3% for the Murray Basin Victoria and –15% to +4% for south-west Victoria following RCP4.5, to –34% to +4% in the Murray Basin Victoria and –31% to +4%, with a median of –15% in south-west Victoria for RCP8.5. Removing models with bias in their seasonal cycle results in a stronger rainfall decline for all Victoria under RCP8.5, increasing from a median of –8% to –14%.

Note that observations show that the April–October Victorian rainfall total during the Millennium Drought (1997–2009) was 6% lower than in 1986–2005; equivalent to the dry end of the model ensemble range of changes across most of Victoria around 2060. Most models also simulate a shift to drier conditions for warm season rainfall, with less dependence on the emissions scenario.

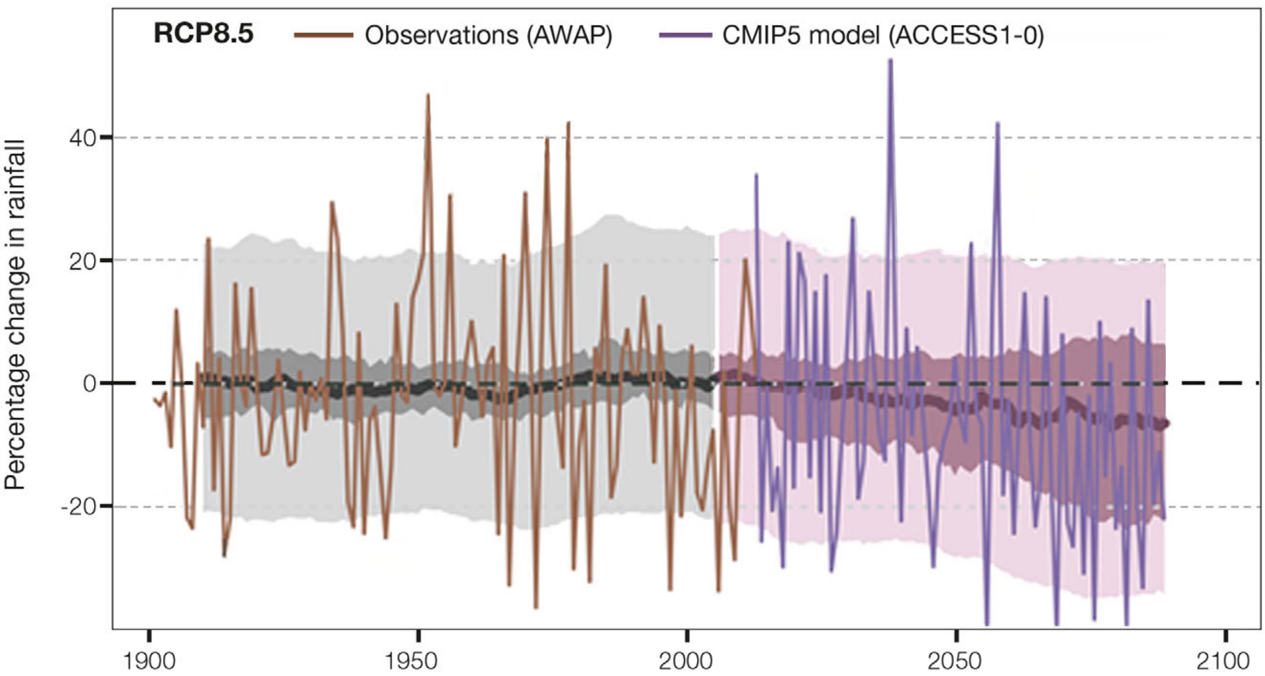


Figure 3.4: Observed annually averaged Victorian rainfall (in brown), and simulated historical Victorian rainfall in grey, with the deeper shade showing the variability across all available CMIP5 models in the 20-year average. Projections of Victorian rainfall from RCP8.5, with purple shading illustrating the spread across all available CMIP5 models, the dark purple line shows the median response. One model's output is shown to highlight the year-to-year variability seen in all models.

ENSO and IOD

Although ENSO and IOD will remain major factors affecting the climate of Victoria, there is substantial uncertainty in the projections of their future behaviour.

The models do not project any consistent trends in the future behaviour of ENSO, but the IPCC[23] has concluded that it is very likely that ENSO will remain the dominant mode of natural variability over this century. Future projections of the IOD are even more uncertain.

About 60% of the range of rainfall projections can be explained by the range in projected shifts in the tropical oceans using an index which captures important aspects of both ENSO and the IOD through the difference in areal-averaged sea surface temperatures north of Australia relative to temperatures in the Indian and Pacific Oceans (tripole index)[33] (Figure 3.5). Downward trends in the tripole index (relative cooling to the north of Australia compared to the nearby Pacific or Indian sea surface temperatures) are generally aligned with downward rainfall trends in July-November Victorian rainfall. This means that uncertainty about future patterns of tropical warming is the largest driver of uncertainties in these rainfall projections.

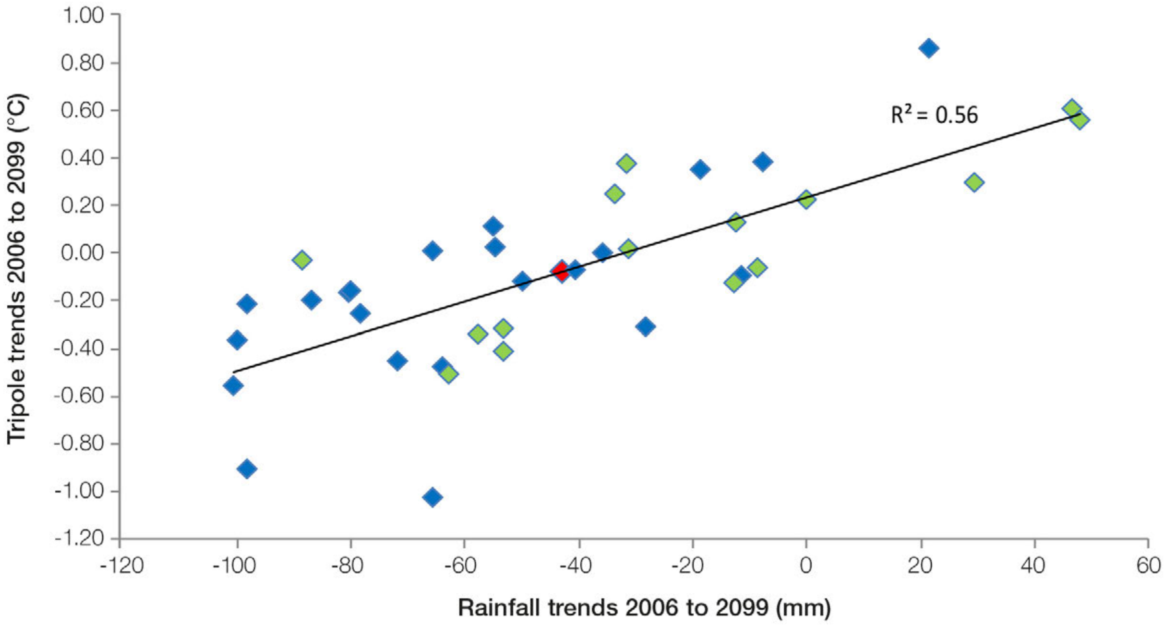


Figure 3.5: Association between July-November Victorian rainfall trends from 2006 to 2099 and corresponding trends in the tripole index. The multi-model mean is marked in red, green diamonds indicate climate models where summer in Victoria is too wet, while models with a more realistic annual cycle of rainfall are shown in blue.

SAM

The model projections show that the current trend in SAM toward its high phase is likely to continue into the future (Figure 3.6), leading to drier winters and perhaps wetter summers. However, part of the current trend (especially in summer) is associated with the historical depletion of Antarctic stratospheric ozone. As stratospheric ozone recovers to its natural level, the trend in SAM will be driven by increasing greenhouse gases alone, without additional ozone-forcing in the warm season.

ENSO can drive wet or dry seasons, and interactions with SAM can enhance those rainfall anomalies. However, climate models do not fully capture the interaction between ENSO and SAM, and thus the intensity of extreme seasons might be underestimated in projections.

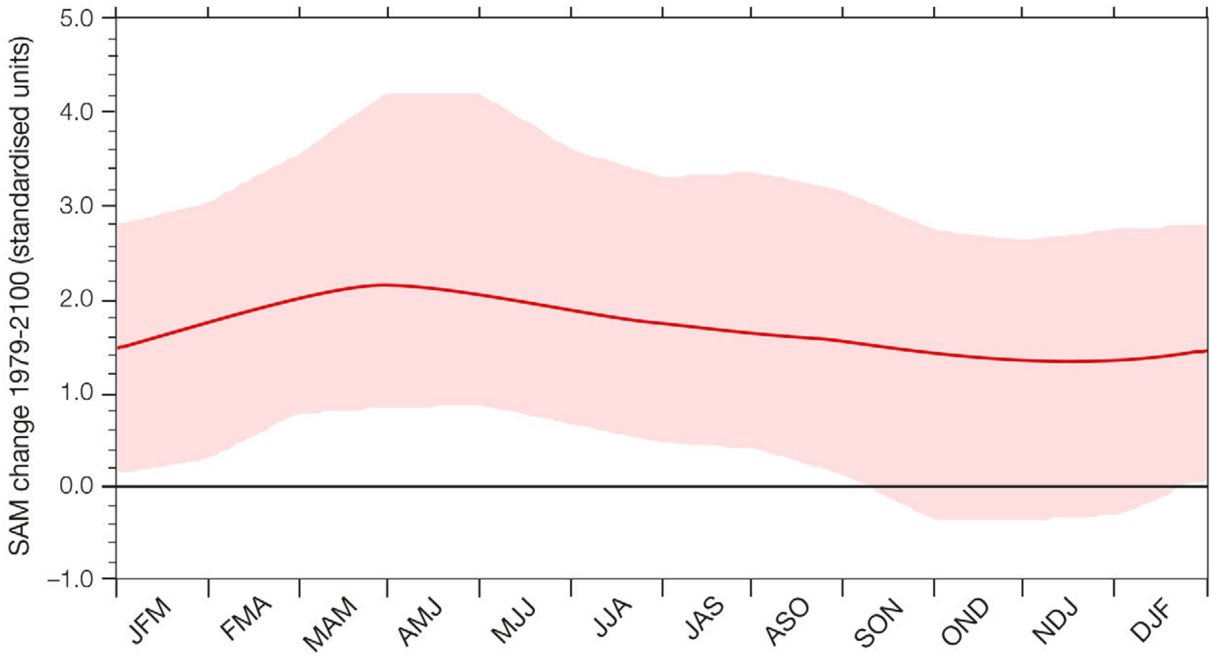


Figure 3.6: The annual cycle of the change in SAM amplitude (after the removal of the ENSO influence) from 1979 to 2100 from CMIP5 models following the RCP8.5 pathway. Prior to computing the 1979-2100 trend, the SAM index was normalised by the standard deviation for each 3-month season of the period 1979-2005. The central red line is the multi-model mean, and the shading shows the range across the models. Note that in all months almost all models project that SAM will shift to its higher phase.

Hadley circulation and subtropical ridge

Associated with the trend in SAM, the models project that the Hadley circulation will continue to expand in the future[22] and the subtropical ridge will continue to intensify and move poleward over the century[34] (Figure 3.7). From the historical record, such trends in the subtropical ridge are associated with a decline in Victoria's cool season rainfall.

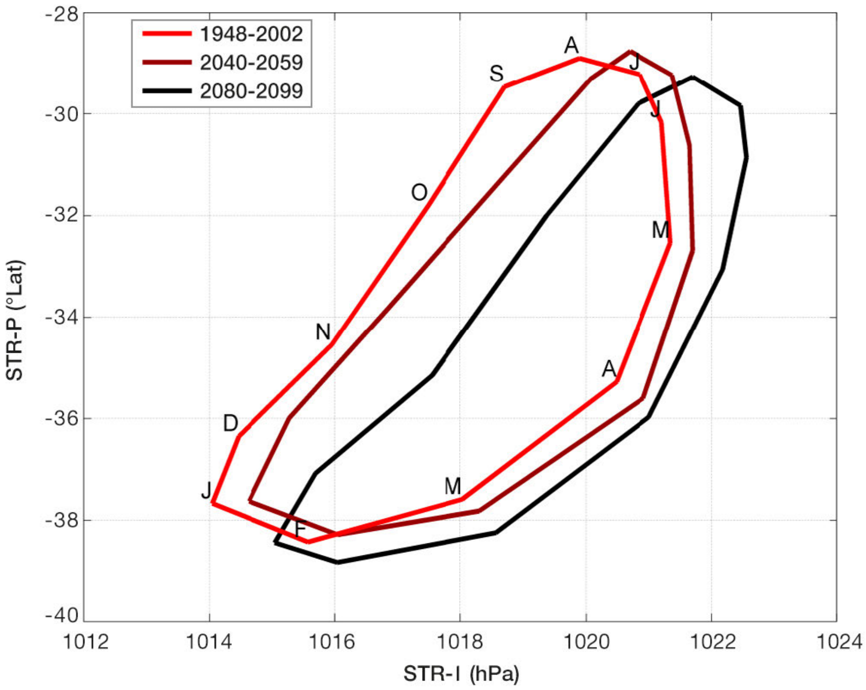


Figure 3.7: The usual peak location (latitude, vertical axis) of the subtropical ridge in the Victorian region in each month[34], and the intensity of the peak (hPa, horizontal axis): during the last half of last century (red), mid this century (dark red) and at the end of this century (black). In each month, the subtropical ridge is becoming more intense, and generally shifting south.

Summary

The future projections for Hadley circulation expansion, high SAM and a stronger and more southerly STR are common across most CMIP5 models and, unlike the tropical variability, uncertainties in these trends do not appear to be the underlying causes for the range of projections of rainfall decline. However, models tend to underestimate the relationship between certain large-scale drivers and Victorian rainfall. Hence, it is possible that the projected rainfall decline is underestimated. Furthermore, a number of the CMIP5 models overestimate summer rainfall in Victoria, causing a bias towards a wetter future climate. When these models are removed from the analysis, the median decline in cool-season Victorian rainfall at the end of the century under RCP8.5 is projected to be larger, increasing from –8 % to –14 %[4]. Considering these model limitations, the drier end of the range of rainfall projections is considered to be more likely than the wetter end of the range.

Natural variability will continue to play a primary role for variation of Victorian rainfall in the next couple of decades, with years of above average rainfall occurring on the backdrop of the ongoing drying trend. However, the forced trends in temperature and cool season rainfall are expected to emerge more permanently outside the bounds of natural variability well before the end of the 21st century.

4. Victorian climate in the coming seasons: predictions and predictability

Key findings

- Despite the ongoing decline in cool season rainfall, year-to-year variations of Victorian rainfall will continue to be large due to the combined effects of ENSO, IOD and SAM. ENSO has an influence from winter through summer, the IOD from winter through spring, while SAM has different impacts in different seasons. Their combined effects can enhance or mitigate the cool season decline and influence future warm season rainfall changes. Extremely wet seasons have resulted from the co-occurrence of La Niña, negative IOD and high SAM, with a further contribution driven by the warming of the seas to the north of Australia. These extremely wet seasons have substantial predictability.
- Predictability of Victorian climate derives primarily from predictability of ENSO and the IOD; however, this predictability is not constant in time as it is influenced by the phase of the IPO.
- While the IPO is in its cold phase, as was the case from the late 1990s through 2015, there is an elevated spring/summer flood risk in Victoria during La Niña and negative IOD because of the stronger linkages of ENSO and the IOD with Victorian rainfall. However, during the cold phase of the IPO, the likelihood of a positive IOD (dry in Victoria) co-occurring with a La Niña event, as occurred during the Millennium Drought, is also increased, meaning that the large increase in rainfall normally expected during La Niña might not eventuate. However, actual impacts will depend on whether the status of ENSO, IOD and SAM act to reinforce or offset each other.
- In a positive IPO, the likelihood of 'dry' ('wet') ENSO events occurring in conjunction with 'dry' ('wet') IOD events will increase. However, the associated impacts on Victorian rainfall tend to be weaker, due to weaker teleconnections.
- The Bureau's seasonal forecasting system captures the influence of changes in the state of ENSO, IOD, SAM and the phase of the IPO, as forecasts are initialised using the observed state of the full ocean, atmosphere and land.
- The Bureau's new seasonal forecast system has improved capability to forecast across the so-called autumn predictability barrier, hence potentially providing improved prediction of early winter rainfall which is important for water storage filling.

Implications

- Extreme rainfall events are highly predictable months in advance when La Niña, negative IOD and high SAM align in spring, and such information can potentially be used for improved management of Victorian water resources.
- Knowledge of the state of the IPO can provide useful insight into the degree of confidence that one can place in the long lead predictions of ENSO and the value of seasonal predictions.
- During IPO cold phases, as has been the case since 1998, large variations in Victorian climate can be expected from relatively minor ENSO and IOD events due to the stronger teleconnections with Victorian rainfall, and this can be useful information for water resource management.

Left: Mitta Mitta River, Omeo.

- When the IPO switches to a warm phase in the future, ENSO and IOD events will be able to be predicted with a longer lead time than at present, but predictability of the impacts on south-eastern Australian rainfall associated with these events will decrease due to weaker teleconnections.
- In making short-term assessments of water availability, water managers should consider seasonal forecasts (and associated measures of skill and reliability), which naturally synthesise the impacts of ENSO, IOD, SAM and the IPO on Victorian rainfall.
- When the Bureau's new seasonal forecast system becomes operational, water managers should consider the utility of the enhanced seasonal forecast products.

Predictability of Victorian climate

Victorian climate varies strongly from year to year and from decade to decade. These variations act on top of ongoing trends and so can exacerbate ongoing drought conditions, as occurred with the 2002–03 central Pacific El Niño during the Millennium Drought[35]. Natural variability can also act to cause flooding, as seen during the 2010–11 La Niña[17], when La Niña, negative IOD, high SAM and upward trending ocean temperatures to the north of Australian combined to drive record rainfall.

Seasonal prediction for Victoria is dependent on the ability to make seasonal prediction of these modes of climate variability and the ability of the forecast model to match the observed relationship between these modes and the climate of Victoria. In general, ENSO is the most predictable mode of climate variability, with skilful prediction reaching two or three seasons in advance, followed by the IOD, which is limited to about one season in advance. The SAM is only marginally predictable to a lead time of one month, which limits predictability of south-east Australian climate. However, in certain extreme conditions, long lead prediction of the SAM is possible, especially in the presence of strong forcing during La Niña.

The impacts of the interactions between these factors have been examined in VicCI, focusing on the implications for seasonal prediction of Victorian climate. Although the seasonal behaviour of the SAM is less predictable than ENSO or the IOD, it explains a large portion of the spread in rainfall during La Niña and El Niño events. Figure 4.1 shows that the state of the SAM can exacerbate or mitigate dry conditions during El Niño and wet conditions during La Niña. The wettest conditions in spring/summer occur in eastern Australia during La Niña and high SAM (i.e. when the westerly winds are shifted poleward). The driest conditions occur during El Niño and low SAM (i.e. when the mid-latitude westerly winds, normally residing at about 45°S, are shifted equatorward). In contrast, low SAM during La Niña and high SAM during El Niño are seen to reduce the typically expected impacts during ENSO. This result helps explain why some La Niña events are wetter than others and also provides a better understanding of the limit of predictability of Victorian rainfall despite a strong influence of ENSO.

Spring-summer 2010 was an example of how ENSO, IOD and SAM can combine to promote extreme rainfall[36]. During late 2010, record strong La Niña and negative IOD conditions combined with a record high SAM to produce record rainfall in south-eastern Australia. This rainfall was especially important because it broke the Millennium Drought. Modelling studies revealed that the record high SAM was promoted both by the occurrence of La Niña and by the background warming trend of the Indian and western Pacific Oceans[16]. A key implication is that future extreme rainfall events may also be promoted by the occurrence of La Niña and high SAM interacting with the ongoing warming trend of the oceans to the north of Australia.

The promotion of high SAM by La Niña and by the background warming trend of the eastern Indian and western Pacific oceans also meant that the extreme rainfall during spring-summer 2010 was highly predictable

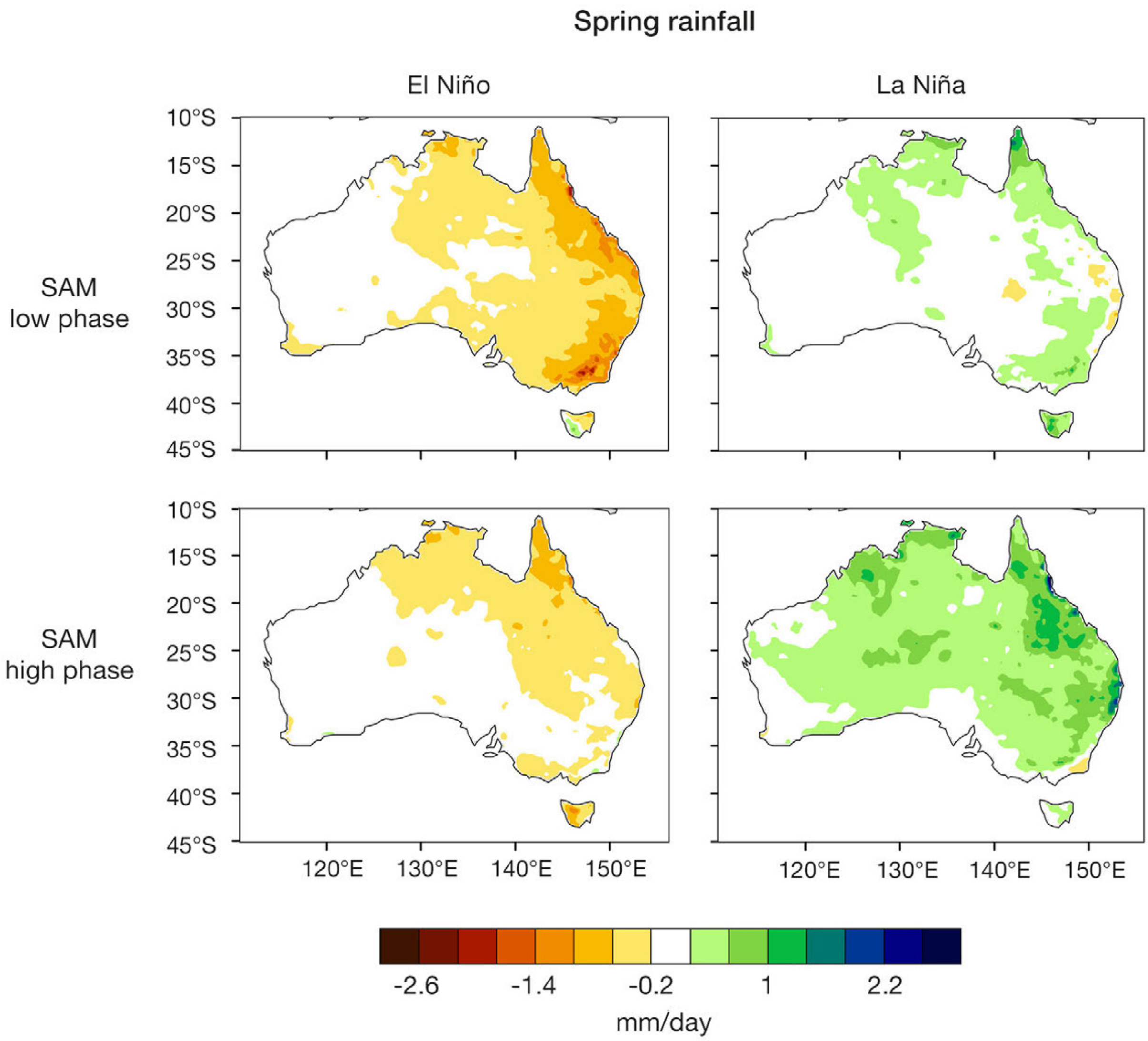


Figure 4.1 Composites of spring rainfall for El Niño (left hand column) and La Niña (right hand column) during 1951–2010. The composites are further broken down for years when the SAM was in its low phase (top row) and high phase (bottom row).

at least one to two seasons in advance[17, 36]. The Bureau of Meteorology seasonal prediction model predicted the extreme rainfall across eastern Australian in spring 2010 up to one season in advance (Figure 4.2). This was achieved from the good predictions of the record high SAM together with the La Niña tropical surface temperature and the associated surface pressure pattern that favoured extreme rainfall over eastern Australia. In this case the SAM, which is normally viewed as being unpredictable beyond a few weeks, was well predicted a season in advance. This was confirmed by remaking the forecasts but using atmospheric initial conditions randomly selected from other years so that the initial condition had no information about the current state of the SAM. The result shows that the good prediction of record high SAM and rainfall were largely unaffected: the long lead prediction of the SAM and high rainfall derived from the strong La Niña and background warming. The implication of this work is that extreme rainfall events are highly predictable months in advance when La Niña, negative IOD and high SAM align in spring, and such information can potentially be used for improved management of Victorian water resources.

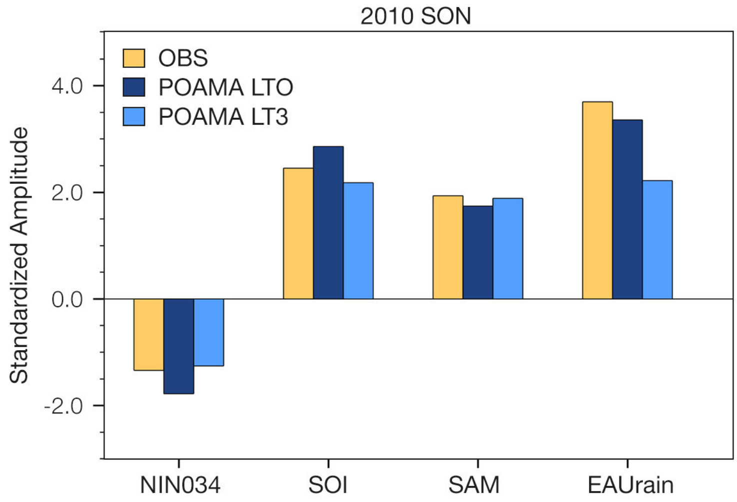


Figure 4.2: Spring 2010 ENSO (the oceanic (Nino34) and the atmospheric components (SOI)), SAM and area-mean eastern Australia rainfall (EAUrain) as observed (yellow bars) and forecast from September (lead time 0 months (LT0), dark blue) and June (lead time 3 months (LT3), light blue).

The pathway by which ENSO and the IOD influence the climate of south-eastern Australia was also further clarified. Earlier work in SEACI showed that the variations of tropical ocean surface temperatures associated with ENSO and the IOD act to perturb the mean distribution of tropical convection. These changes in tropical convection then excite large-scale atmospheric waves called *Rossby* waves that carry the impact to the higher southern latitudes of Australia. Importantly, changes in Indian Ocean surface temperatures are more important for Victorian climate than are those in the Pacific, because *Rossby* waves carry their information eastward and poleward, so that Victoria would be expected to be in the pathway of the waves emitted from the Indian Ocean but not from the Pacific. However, new research in VicCI revealed a more complicated pathway for communication of the impacts from the Indian Ocean to Victorian climate than simply by *Rossby* wave propagation[37]. It involves a complex interaction between the tropically-forced *Rossby* waves and the highs and lows associated with the polar front jet stream. An implication of this work is that predicting Victorian climate is constrained not only by the capability to predict sea surface temperature and convection in the tropical Indian Ocean, which is less predictable than that in the Pacific, but also requires a faithful depiction of the interactions of the tropics with the extra-tropical jet streams and storm tracks. This insight provides a new metric by which to assess climate models' capability to simulate Victorian climate and to guide model development leading to improved seasonal predictions.

Decadal variation in Victoria's climate and predictability

Predictability of Victorian climate derives primarily from predictability of ENSO and the IOD; however, this predictability is not constant in time[14]. Predictions of El Niño made during the 1980s and 1990s were much better at long lead time than those made during the early 2000s (Figure 4.3). VicCI research shows that this variation in predictability is related to the phase of the IPO. The IPO was in its cold phase during 2000–2014, and in its warm phase during 1980–2000. In conjunction with the swing to the cold phase of the IPO at the end of the 20th century, ENSO variability weakened making it less predictable. VicCI research shows that the change in the state of the IPO from warm to cold accounted for the weakening of ENSO variability, reducing the capability to predict ENSO during the IPO cold phase. Although the causes of the swings in the IPO have yet to be established or shown to be predictable, future swings in the IPO can be anticipated to be associated with epochs of high and low ENSO variability and predictability in the future. Furthermore, knowing the state of the

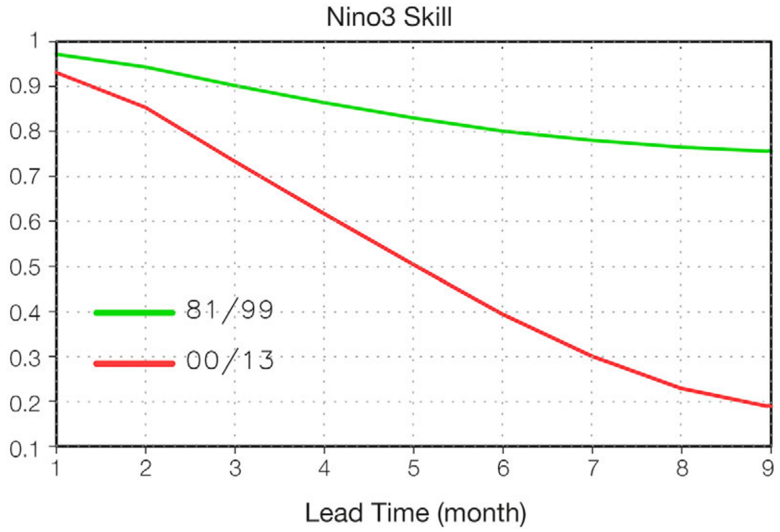


Figure 4.3: Bureau of Meteorology's seasonal prediction system (POAMA) predictive skill (correlation) for the Niño3 SST Index as a function of forecast lead time. The green curve is for forecasts started in the 1980s and 1990s, and the red curve is for forecasts started during the 2000s.

IPO can provide useful insight into the degree of confidence that one can place in the long lead predictions of ENSO and the value of the seasonal prediction.

Equally important to the variation in predictability of ENSO, the impacts of ENSO and the IOD on Victorian climate were also found to vary in conjunction with the state of the IPO[15] (see Text Box 1, page 10). The variations in the impacts of ENSO and the IOD on south-east Australian rainfall result from a shift in the location of the enhanced tropical convection driven by ENSO and IOD towards Australia during the cold phase of the IPO. An important implication is that although long lead prediction (i.e. lead times greater than three months) of ENSO and the IOD is reduced during the cold phase of the IPO, the short lead prediction (lead times less than three months) of rainfall for south-eastern Australia is increased because the strength of the impact due to ENSO and IOD increases. Another implication is that large variations in Victorian climate can be expected from relatively minor ENSO and IOD events during IPO cold phases, which again can be useful information for water resource management.

Progress in seasonal climate prediction

The Bureau's current operational seasonal prediction system, POAMA, is used for seasonal climate prediction and feeds into the Bureau's seasonal streamflow forecasting system. POAMA simulates the interactions between SAM and Victoria's climate well and predicts ENSO and its impacts on south-eastern Australian climate[38]; however, it is a relatively low-resolution model based on developments from the 1990s. POAMA is scheduled to be replaced late in 2017 by the more advanced and higher resolution ACCESS-S model.

ACCESS-S has numerous enhanced features compared with POAMA, especially an increase in spatial resolution from a 250 km to 60 km grid which allows for improved depiction of Victorian climate, as well as updated ocean and atmospheric physics.

The initial evaluation of ACCESS-S for Victorian climate[38] has already demonstrated an outstanding improvement in the capability to predict El Niño across the 'autumn predictability barrier' when onset of El Niño or La Niña typically occurs but is notoriously difficult to forecast. This improved capability to predict El Niño for winter/spring with forecasts initialised in autumn indicates the possibility of improved longer lead prediction of late winter/spring rainfall in Victoria (Figure 4.4). ACCESS-S has skilful prediction in broad areas of Victoria

along and to the north of the Great Dividing Range, where POAMA had none. Such improvements will allow for improved management of water resources during the late winter and spring water storage filling season.

The improved atmospheric initial conditions and modelling capability of ACCESS-S translate into better predictions of the extratropical circulation anomalies that affect Victorian climate. In particular, we are better able to forecast the seasonal mean SAM during the late spring-summer season, when SAM is a significant determinant of the impact of ENSO on Victorian rainfall. Expanded uptake of the seasonal forecast products by water managers could be considered when ACCESS-S becomes operational.

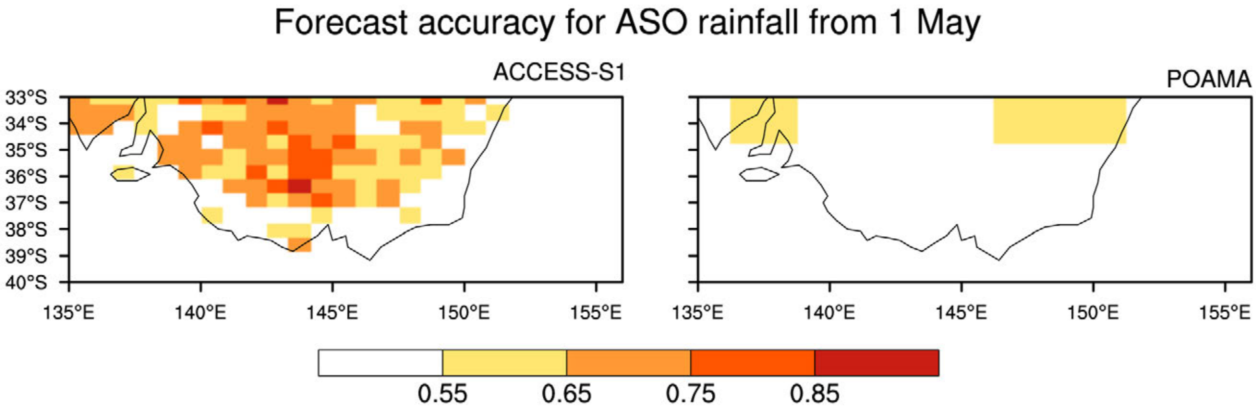


Figure 4.4 Accuracy score (units percentage correct) for predicting rainfall above/below median based on ACCESS-S1 (left) and POAMA (right) for August–September–October using forecasts initialised on 1 May 1990–2012. Scores greater than 0.55 (55%) are considered to be significantly better than chance.

5. Looking to the future: planning Victorian water supply through the 21st century

Key findings

- Future runoff and streamflow in Victoria is likely to decline, driven by projected declines in future rainfall (particularly cool season rainfall) and higher potential evapotranspiration.
- Comparison of different downscaling techniques in VicCI show broad agreement in future reductions in runoff in spring; however in other seasons, agreement on the direction and magnitude of change is low. Further work is required to understand the differing responses across the downscaling techniques.
- 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 the south-west. 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 of greater than 40% in most regions, with a proportionally larger impact in western Victoria. As noted in Chapter 3, better performing models tend to project a drier future than the full ensemble of models.

Implications

- Given the range of plausible outcomes in terms of runoff and streamflow, users of VicCI runoff projections should adopt a scenario-based approach to planning, drawing on information from both outputs and historical data. This means that water resource managers need to ensure that their planning and management processes are robust and adaptive across a wide range of future climate and streamflow scenarios and are subject to regular review.
- Water managers need to recognise that the apparent precision of fine-resolution (in time and space) datasets derived using more complex statistical or physically-based downscaling techniques can introduce extra uncertainties (as outlined in Text Box 2, page 18) and they may not necessarily equate to more reliable information about the nature of the local climate change.
- Future development of runoff projections needs to involve a number of integrated steps, including an improved use of cross-disciplinary knowledge to provide, for instance, the best representation of regional scale changes in rainfall, hydrology and land-surface dynamics under higher carbon dioxide conditions, a warmer climate and altered rainfall and evaporation characteristics.

Left: Maroondah Reservoir

Victoria's runoff, and planning for the future

Information about what changes to expect and when they may occur is the first step towards enabling successful adaptation to a changing climate. VicCI research builds on consideration of climate change impacts in many previous Victorian water resource planning processes, to provide guidance on likely changes to rainfall and runoff to water resource managers across Victoria.

Catchments across Victoria vary greatly both in climate (e.g. rainfall and temperature) and non-climate characteristics (e.g. size, slope, vegetation and water distribution systems), with spatial variability in runoff across the state (Figure 5.1). Higher runoff is generated in the Victorian Alps and in coastal catchments along the southern and eastern coastline. Drier catchments are found on the western slopes of the Great Dividing Range and in the inner western regions of the state.

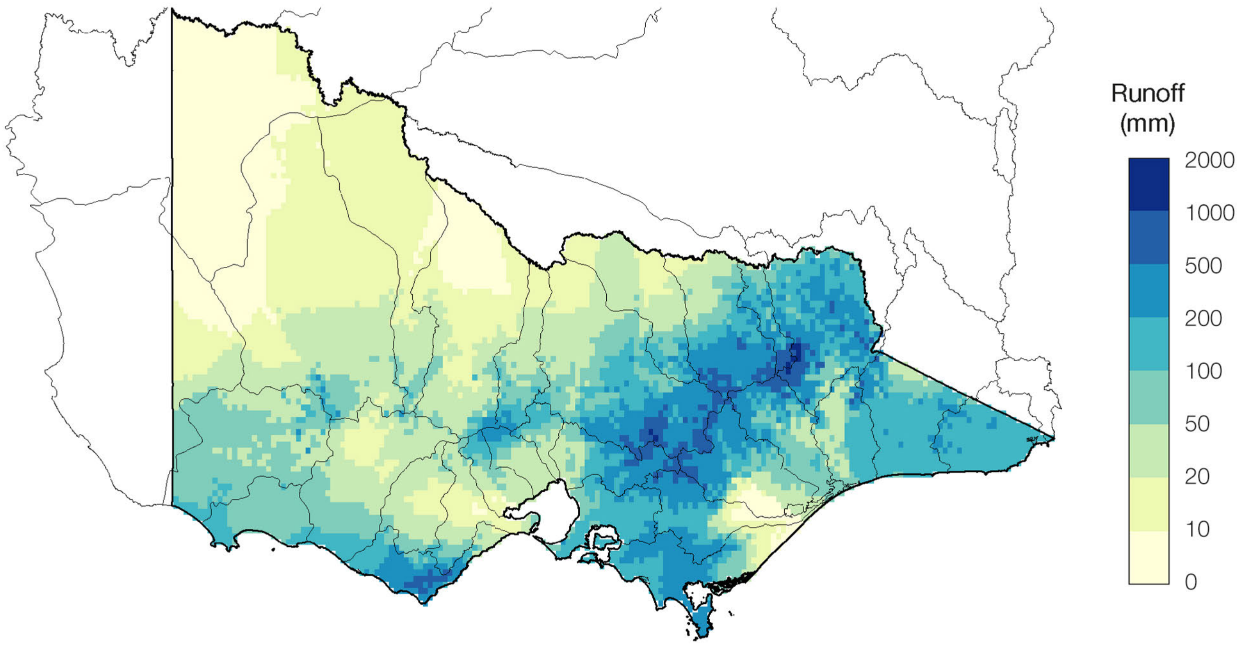


Figure 5.1: Runoff (mm) across Victoria for selected baseline period 1975–2014.

Downscaling climate change signals to catchment scale

Victoria's climate is shaped by marked geographical characteristics such as the land-sea contrast along its coastline and the steep orographic gradients along the Great Dividing Range. These are features that are not well represented in global climate models and are likely to influence how the regional climate may change in the future.

To translate coarse resolution global climate model output (about 200 km) to the more finely resolved climate information needed for hydrological modelling (about 5 km) downscaling techniques are applied to global climate model output. These techniques can vary greatly in complexity, each having a unique set of strengths and limitations.

Dataset	Emission scenario	Current climate	Future climate	Ensemble size	Horizontal resolution
Empirical scaling	RCP8.5[a]	1986–2005	2060–2079	42	0.05° × 0.05°[b]
NHMM	RCP8.5	1986–2005	2060–2079	19	Catchment-based
SDM	RCP8.5	1986–2005	2060–2079	22	0.05° × 0.05°
CCAM	RCP8.5	1986–2005	2060–2079	6	0.5° × 0.5°
WRF	SRES A2[c]	1990–2009	2056–2075	12[d]	0.1° × 0.1°

[a] Representative Concentration Pathway (RCP)[43]

[b] Empirical scaling is regrided to a common resolution, but change signal resolution is limited to individual GCM resolution

[c] Special Report on Emissions Scenario (SRES)[44]

[d] 4 CMIP3 GCMs in combination with three RCMs

Table 5.1: Summary of downscaled datasets available for Victoria: including available years, the ensemble size and the spatial resolution. Empirical scaling: datasets used to derive runoff projections for VicCI[5]; NHMM: the statistical downscaling method Non-homogeneous Hidden Markov Model[39]; SDM: the Bureau of Meteorology statistical downscaling[40]; CCAM: the CSIRO dynamical downscaling Conformal Cubic Atmosphere Model[41]; WRF: dynamical downscaling using WRF from the NSW/ACT Regional Climate Modelling (NARCliM) ensemble[42].

The simplest form of downscaling is empirical scaling. This technique applies the 'change signal' from coarse resolution global climate models to the historical data, preserving the spatial relationships in observed data in the downscaled data. More complex methods use statistical or physically-based models to downscale the climate change signal to finer resolutions. While downscaled data have attractive qualities, they may not necessarily equate to more reliable information about the nature of the local climate change. Individual methods may suffer from method-specific traits, which can influence the downscaling process in different ways[45].

Having noted the caveats with downscaling, the process is nevertheless likely to be beneficial in Victoria. The downscaled datasets that exist for the region (Table 5.1) show seasonal deviations in the change signal from that of global climate models.

A major obstacle to the use of downscaled data in Victoria is the lack of agreement among the rainfall projections from different methods (Figure 5.2). The cause for differences is not fully understood, but is likely to be influenced by the selection of global climate models to be downscaled, the response of the individual dynamical downscaling models to the forcing, or the stability of the association between large-scale weather features and rainfall used in the statistical methods.

Differences in projected rainfall changes are further enhanced in the runoff. Some datasets indicate a drier future, while others suggest a wetter future. These differences are illustrated by runoff projections for a selection of catchments (Figure 5.3, Table 5.2) for summer (Figure 5.4a) and winter (Figure 5.4b) using the datasets listed in Table 5.1. The same rainfall-runoff model is used with the various downscaled climate datasets.

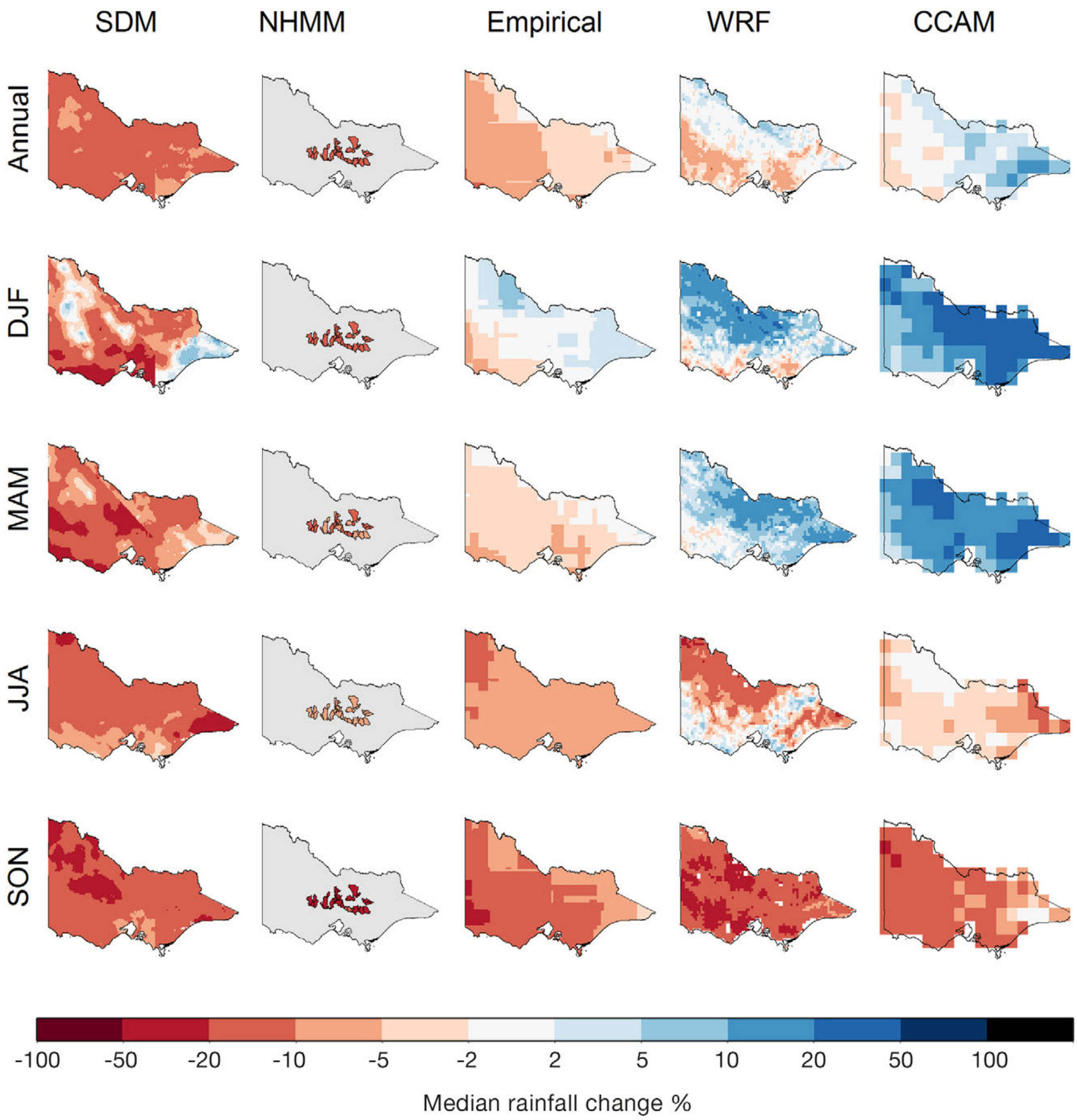


Figure 5.2: Median rainfall changes (%) for available downscaling ensembles for later this century under a high emission scenario (details in Table 5.1): Bureau of Meteorology Statistical Downscaling Model (SDM), statistical downscaling (NHMM; Note that only selected catchments were analysed), empirical downscaling (Empirical), dynamical downscaling from NARCliM ensemble (WRF), and CSIRO dynamical downscaling (CCAM).

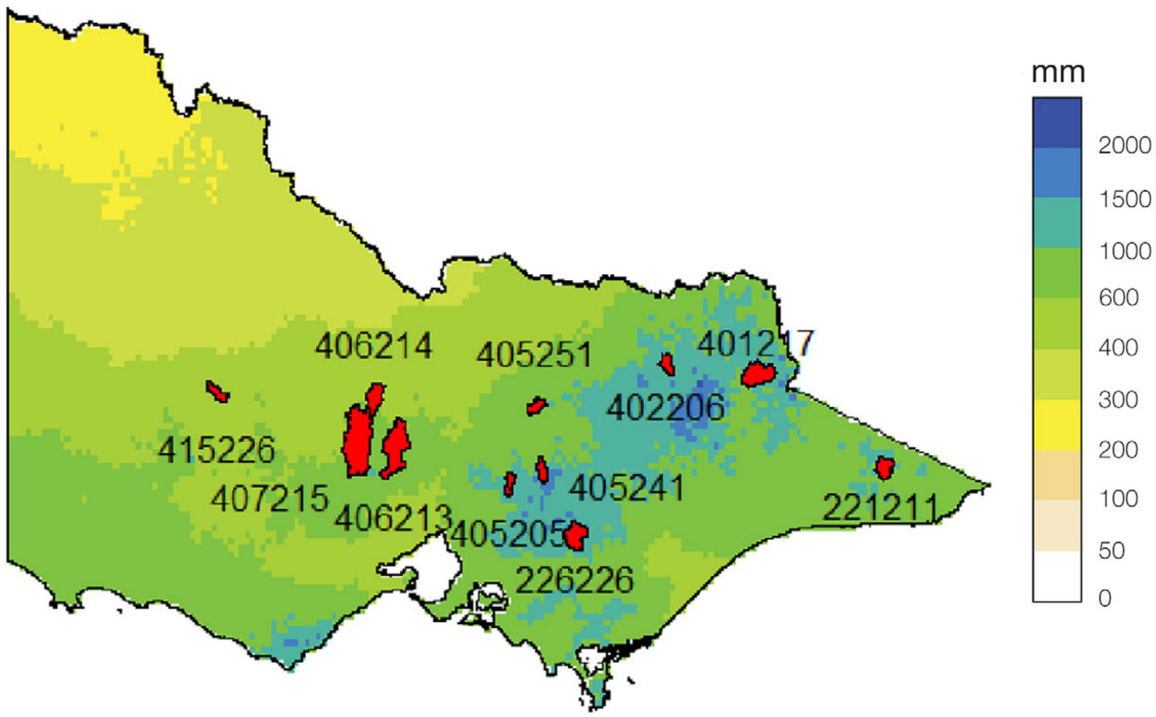


Figure 5.3: The selected 11 catchments (Table 5.2) used for comparison of different downscaled datasets (Figure 5.2, Table 5.1).

ID	Catchment name
221211	Combienbar River @ Combienbar
226226	Tanjil River @ Tanjil Junction
401217	Gibbo River @ Gibbo Park
402206	Running Creek @ Running Creek
405205	Murrindindi River @ Murrindindi above Colwells
405241	Rubicon River @ Rubicon
405251	Brankeet Creek @ Ancona
406213	Campaspe River @ Redesdale
406214	Axe Creek @ Longlea
407215	Loddon River @ Newstead
415226	Richardson River @ Carrs Plains

Table 5.2: List of catchments (Figure 5.3) used for comparison of runoff from different downscaled datasets.

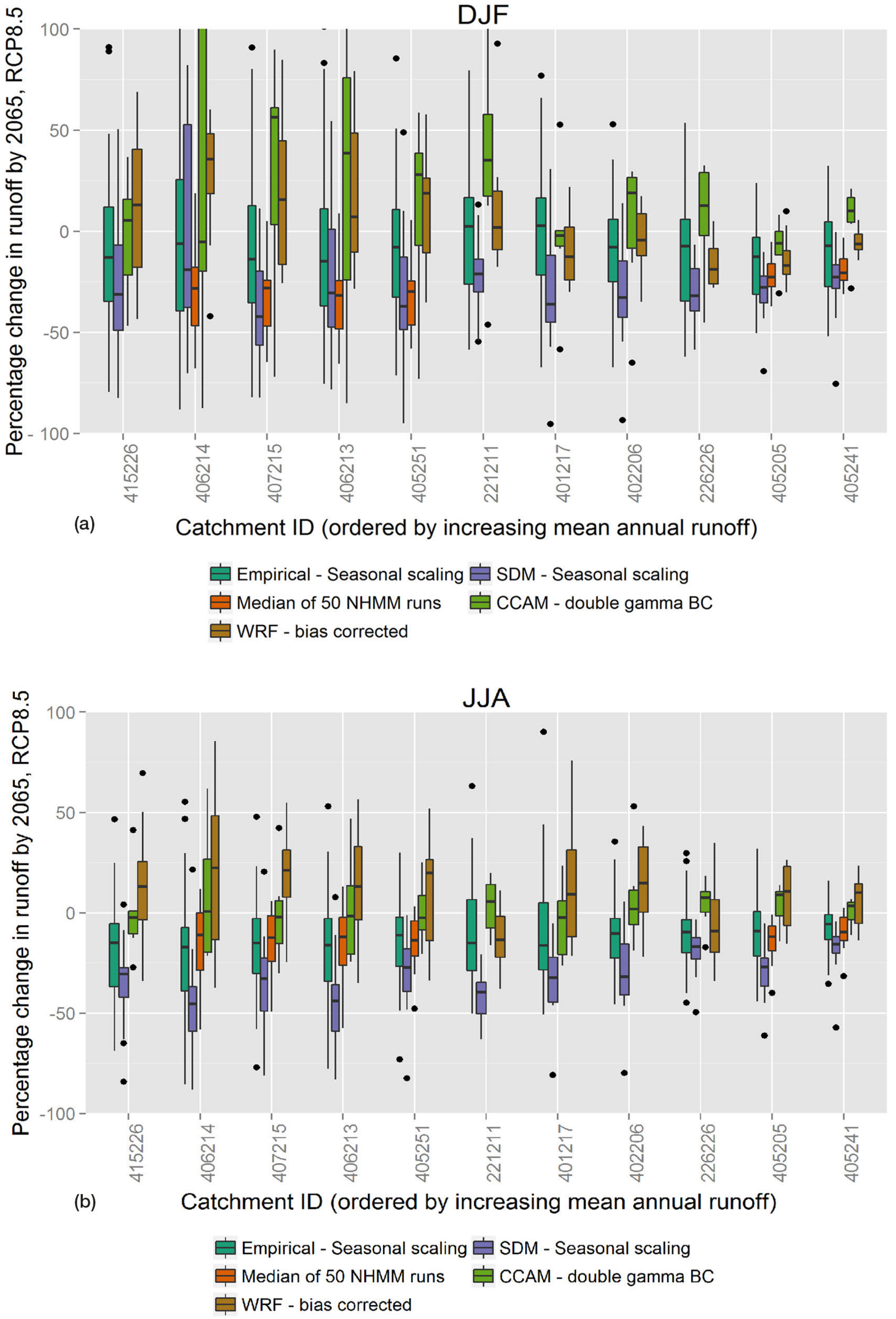


Figure 5.4: Regional projections of runoff for 11 catchments (Table 5.2, Figure 5.3) for summer (a) and winter (b). Projections follow a high emissions scenario and represent change for a far-future time period relative to the current climate (see Table 5.1 for details). Note the range for the y-axes here are set at –100% to +100%; summer runoff is very low in the drier catchments and the larger (>100%) increases for CCAM are relatively small in absolute magnitude. The shading indicates the 25-75 percentile range of climate model results. Dots are results from outlier models.

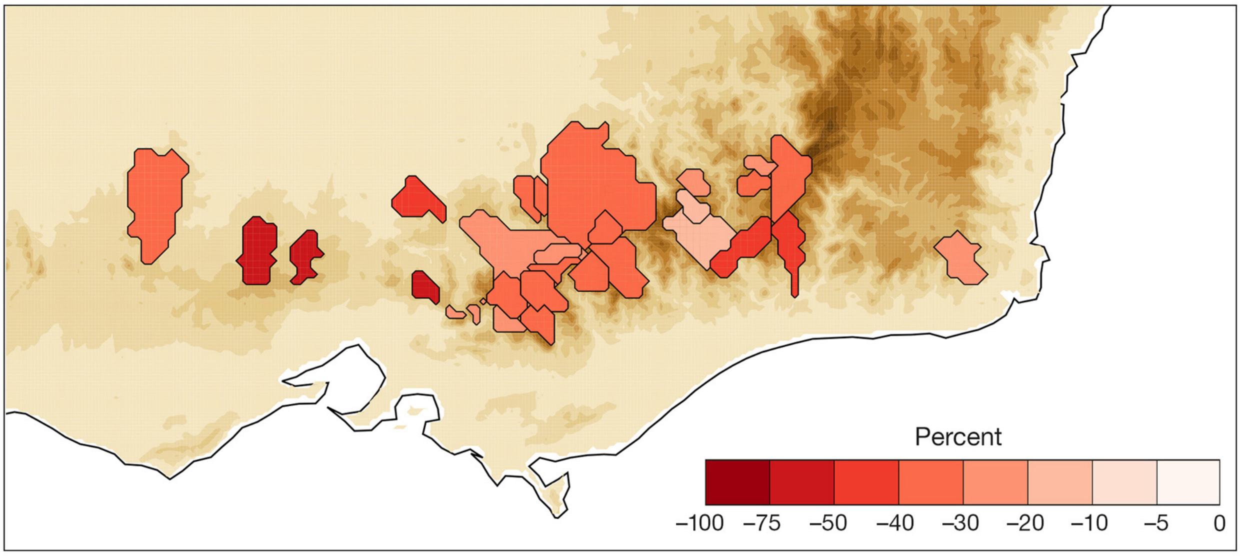


Figure 5.5: Projected streamflow change for regional cool season (May to November) using a regression relationship between streamflow and the output from SDM downscaling for a selection of catchments in Victoria. Map shows relative change between projected streamflow for 2056–2076 under RCP8.5 relative to the 1975–2005 reconstructed mean. Map background shows topography.

Runoff

Using the change signal based on empirical scaling of CMIP5 models, future runoff in summer is most likely decreasing, noting that an increase in runoff is still possible in most catchments (Figure 5.4a). The change signal from the two statistical downscaling methods (SDM and NHMM) also point to a decrease in runoff across most catchments. Results from the dynamical downscaling outputs (CCAM and WRF) look rather different, indicating an increase in the western drier catchments. A clear explanation for why the different downscaling techniques give such great differences in projected rainfall is an obvious subject for further research.

There is somewhat greater agreement amongst methods in winter, though differences in the sign of change still exist in most catchments (Figure 5.4b). Empirical scaling of global climate models suggests that a decrease is most likely, particularly in the west. Statistical downscaling methods (NHMM and SDM) agree with a drying change signal, which is particularly strong in SDM. The dynamical downscaling outputs again tend towards a wetter future in many catchments.

The wide range of projected runoff results is due to the range of downscaled rainfall projections (Figure 5.2). The differences in projected rainfall change, particularly for individual seasons, are profound, with agreement among datasets found only in spring. Because Victorian catchments are largely water-limited, differences in rainfall projections are further magnified in the runoff projections. In this region, any change in rainfall typically results in a two to three times change in runoff[46].

Uncertainty can also come from the hydrological models and/or approaches used[47,48], particularly in the process of conceptualisation and model parameterisation for extreme hydrologic conditions (e.g. the Millennium Drought) and when extrapolating the models to predict a future under warmer, higher carbon dioxide and altered precipitation conditions. For example, results from rainfall-runoff regression modelling in VicCI (which captured the rainfall-runoff relationship through the Millennium Drought) with SDM rainfall projections show drier projections of future runoff (Figure 5.5)[49,50], most likely because the SDM rainfall projections are drier than the global climate model projections (as discussed above).

Making use of Victorian runoff projections

DELWP has produced guidelines and recommendations to support water managers in their future planning[51] based on the outcomes of VicCI research and one of the methods available to produce runoff projections[5].

The projected runoff changes presented in Figure 5.6 are for the high-level emission scenario RCP8.5 and for two different time periods centred on 2040 and 2065. The range shown in Figure 5.6 is based on the range in outputs from 42 CMIP5 climate models. The lower percentile case illustrates the ‘wet’ low impact end of model responses, and the high percentile case shows the ‘dry’ high impact end of model responses; the median gives the central model response in the 42-model range. A fourth scenario that represents a step climate change based on recent (post-1997) historical drying trends in the regional climate is not shown here, but is also presented in the guidelines[51].

The climate change signal is given by scaling factors based on the modelled difference between recent years (1986-2005) and 20-year periods around 2040 and 2065 from 42 CMIP5 global climate model simulations. These scaling factors (which have global climate model spatial resolution) are applied to 5 km resolution gridded observed rainfall and potential evapotranspiration (PET) data to give inputs for hydrological rainfall-runoff modelling. Rainfall changes in the different seasons are scaled differently with magnitude-dependent scaling factors.

Averaging across the CMIP5 model ensemble will smooth out any natural variability during these 20-year periods, leaving only the forced climate change signal. To include a sufficient level of natural variability, the scaling factors are applied to 40-year time windows of observed rainfall and PET (1975–2014). Choosing a shorter time period to scale would not be meaningful for hydrological planning due to the large natural variability of rainfall in Victoria, as discussed in Chapter 1.

Because of the typically long residence time of greenhouse gases in the atmosphere, the impact of climate change increases with time so a greater change in runoff is expected for the latter of these two periods. The change signal for different percentile thresholds varies across Victoria with differing impacts on runoff (Figure 5.6). The low impact (wet) maps show increases of runoff of around 2–10% by 2040 over most of Victoria, and slightly larger than this to the north and eastern part of Victoria. In the later period (2065), most of southern Victoria is likely to see little to no increase in runoff, with decreases in runoff in the south-western part of the region and the main runoff producing areas along the Great Dividing Range. The high impact (dry) response shows a 20–50% decrease in runoff over Victoria by 2040, which is enhanced, particularly in the west, by 2065 (Figure 5.6). The median response indicates runoff decreases of 5–15% over most of Victoria by 2040 and 10–30% by 2065, with larger reductions in the south-west. The small to moderate increases (2–10%) in runoff projected for the north of Victoria by 2040 lie mostly in low runoff producing areas (Figure 5.1).

The current projections[5] show overall broad agreement with previous projections[52] in terms of the projected range of change for Victorian river basins[3]. Some differences exist such as a less dry ensemble median change and a drier ‘driest’ change (90th percentile) and a wetter ‘wettest’ change (10th percentile). These changes reflect the range in the global climate model rainfall projections used by the previous and current hydrological modelling, the latter global climate model ensemble (CMIP5) having a broader range in rainfall projections and somewhat less dry projections compared to the previous generation global climate models (CMIP3).

Selecting global climate models based on set criteria can result in a range of change that is different to that when using all available global climate models. For example, in Chapter 3 we note that global climate models that better simulate the seasonal characteristics of rainfall in Victoria will give a somewhat drier future compared

to when using all global climate models. Different results could also be achieved by combining the selected global climate models with the predominantly wet downscaled projections of CCAM, or drier results from SDM.

The projections in the DELWP guidelines[51] represent plausible pathways for future runoff given information based on global climate models as well as historical trends. No scenario is deemed to represent a 'most likely' future. Rather, the intent is for water resource planners to explore the full range of scenarios to identify system sensitivities to climate change impacts on surface water availability and groundwater resources through examining expected system performance under alternative demand scenarios, and different options for drought response, system operations and water supply augmentation.

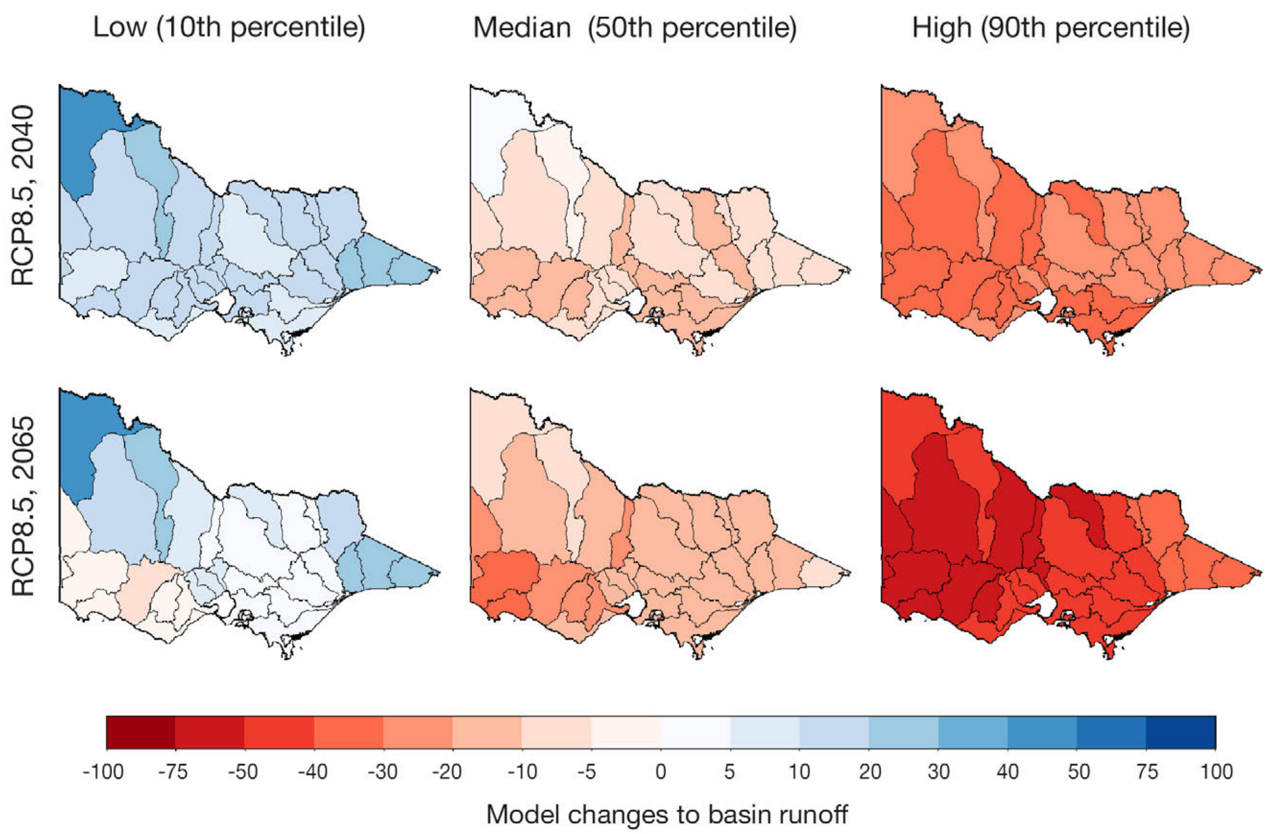


Figure 5.6: Low, median and high model percentage changes to basin runoff by 2031–2050 or 2056–2076 relative to 1986–2005 following RCP8.5.

6. Directions for future research

VicCI research was guided by the need to better understand recent changes in climate and to improve climate prediction and projection methods for use in water resources management and planning.

Although substantial progress was made across the key research themes of understanding of the current climate, its predictability and its influence on Victoria's hydrology, and understanding of future climate change and its impact on water availability, new questions have emerged and some questions need additional attention.

Any future research should consider a focus on:

1. Improved understanding of recent climate variability and change and its impact on water resources
2. Improved seasonal to interannual predictions of climate and their uptake by resource managers
3. Improved projections of future climate and runoff, focusing on understanding the cause for model uncertainties and their plausible ranges, as well as discriminating between different types of operational vulnerabilities in water resource management (in terms of size of potential impact and when increased risks may emerge in a future time horizon).

Improved understanding of current climate

The wintertime subtropical jet is a strong modulator of the connections between Victorian rainfall and tropical influences from the north and mid-latitude influences from the south. Little work has been done on diagnosing variations in the subtropical jet and associated impacts on Victorian climate. Diagnosing the causes and nature of variability of the subtropical jet could provide insight into how variations of the Hadley circulation impact on Victoria's climate and additional sources of climate variability suggested by VicCI research. This focus on the subtropical jet could help better diagnose modelling capability to depict the full range of Victorian climate, which could be used to help better constrain climate model projections of future climate.

VicCI research highlighted that we need to better understand the effect of changes in the mean meridional circulation, especially changes in the Hadley circulation, on changes in Victorian climate, such as those associated with the ongoing cool season rainfall decline. Although local expansion of the Hadley circulation, driven primarily by the recent cold phase of the IPO, would appear to be promoting increased rainfall rather than the observed declines, results obtained at the end of VicCI suggest that the Hadley circulation has been intensifying as well as expanding. This intensification is not anticipated by basic theories for the response of the mean meridional circulation to climate change, but it could explain why winter time surface pressure has been increasing and Victoria's wintertime rainfall has been decreasing. A concerted effort to understand how and why the Hadley circulation appears to be getting stronger is required. A combination of observationally based studies using the new tools developed in VicCI and modelling studies could be used to clarify the mechanisms of Hadley circulation intensification, why it is occurring and the impact on Victoria's climate.

Several important impacts of the IPO on Victorian climate, including causing variations in seasonal climate predictability and teleconnections, were highlighted in VicCI research; however, the IPO is still a very poorly understood and simulated phenomenon. There is no widely accepted theory to explain the physical mechanisms of the IPO and its lack of predictability is a concern. Hence, it is not really clear what the IPO truly represents, how it responds to increasing greenhouse gases or ozone depletion and whether the changes as seen since the late 20th century will apply in the future. The switch from warm to cold phase in the late 1990s is the first occurrence that has been captured by the modern space based global observing system, and this one instance has provided important insights. However, more high-quality observations (available only as opportunities arise)

Left: Stream in Melbourne catchment area. Paul Feikema

combined with well-designed modelling studies are needed to fully understand the IPO and its impacts. An especially important, yet challenging, avenue of research is to quantify the mechanism of any two-way feedback between ENSO, the IOD, and the SAM with the IPO, which could help promote persistence of the IPO as well as swings in phase.

A significant source of uncertainty in future projections of Victoria's climate is the baseline from which change occurs, so there is scope for improved definition of the 'baseline' climate. There is extensive literature on 'optimal climate normals', developed as an aid to making long lead seasonal predictions that could be brought to bear to better guide what the optimal sampling period is for best depiction of the current climate. This work could include a literature review and experimentation with simple methods of defining new normals. The possibility could also be explored of combining the previous few years of observed climate with a few years of predicted climate (e.g. from CMIP5 decadal prediction hindcasts) to make a best estimate of the current climate normal (or baseline).

Seasonal climate prediction

Although significant progress has been made for prediction of Victoria's seasonal climate at regional scales using the ACCESS-S model, there is still large scope for improvement, especially from the perspective of reducing key systematic model errors that limit the predictive skill of the model. Future research to improve forecast skill for rainfall and temperature over Victoria should address the sources of these systematic forecast biases. One area for improvement is the depiction of the teleconnection of the IOD to Victorian climate and the interaction of the IOD and ENSO. Assessing the realism of the simulated large-scale atmospheric wave source over the tropical Indian Ocean and interaction of that wave with the subtropical jet will be a good starting point to understand the model's IOD teleconnection bias. More detailed investigation into the degree that convective variations in the tropical Indian Ocean limits the predictability of south-eastern Australia's climate can also be pursued, with the aim to both better quantify uncertainty of seasonal climate forecasts for Victoria and to help guide model improvements of key processes that control Indian Ocean convective variations. Another improvement could be gained from better land surface initialisation, which provides a longer-term 'memory' for regional climate. Future research as to how best to initialise the land surface state for seasonal climate prediction could have substantial payoff for improved prediction of Victoria's climate.

Improvements in seasonal prediction are only useful if they are put to use, so ongoing consultation and communication with stakeholders and users of seasonal predictions would need to form a key part of this research. For instance, if improvements in the skill of forecasts across the 'autumn predictability barrier' are realised, resource managers must be informed of this new skill and encouraged to have confidence in using predictions that were previously less reliable.

Future projections

Looking at future climate, impacts of ENSO and the IOD on south-eastern Australia climate will depend upon any changes in the behaviour of ENSO and the IOD. Although a consensus has not emerged as to how ENSO and IOD variability might change in a warmer world, recent research reveals that ENSO variability is projected to increase more in those models that simulate the most warming in the central equatorial Pacific. The relationship between those models that warm the most in the central Pacific and those models that best simulate the seasonal variation of Victorian rainfall can also be investigated. This finding could be used to better quantify uncertainty in the expected changes of Victorian climate depending on the expected change in ENSO variability. Future work following VicCI should also focus on understanding the sensitivity of the teleconnection

mechanisms revealed here to the projected changes in the subtropical jet, the behaviour of the IOD and the relationship of the IOD with ENSO.

Immediate needs from the community for updated long-term runoff projections were addressed in VicCI through the development of new regional runoff projections and guidance. However, while global climate models can simulate large-scale processes, the region's climate is also influenced by regional scale processes that are not well resolved by these models. Downscaling can address some of these limitations, but the current downscaled information is incomplete. Better understanding of the change signal in existing downscaled products, improvements of current techniques and additional datasets produced by independent methods are required to better understand how the climate may change on scales that matter to water resource managers.

VicCI research also pointed to the need to better represent the dynamics of the landscape in individual catchments. Catchment properties such as vegetation, terrain, soils and surface-groundwater connection are important to better represent hydrological regimes. Many of these processes are implicitly represented in current hydrological modelling through calibration of the model to observed rainfall, potential evapotranspiration (PET) and streamflow. However, under climate change such calibration or parametrisation may no longer be representative as physical relationships may change in a warmer and higher carbon dioxide concentration world.

Accounting for non-linear relationships between the climate and runoff response presents big challenges to the scientific community with different possible pathways for improvement: for example, adapting hydrological models to represent dominant processes under changed climate, improving the land surface component of climate models, or modifying the parameter schemes and calibration strategies when applying hydrological models to predict climate change impacts on water availability characteristics and relevant hydrological metrics.

Resolving processes that are important for regional hydrology is becoming increasingly feasible with developments in convection-permitting modelling, where simulations down to 1.5 km resolution are conducted for limited geographical regions[53,54]. Not only are convective processes explicitly resolved but so too is fine scale topography that can play a primary role for determining local rainfall. The analysis of the benefit of these very fine resolution dynamical models to simulating regional rainfall climatologies[55] and variability is also important. However, the current utility of these simulations for hydrological purposes is not well studied and recent work indicates that much effort is still needed to reduce model biases in regional rainfall[56]. Known limitations exist around the representation of soil moisture fluxes in the land surface model, surface-groundwater connectivity, parameterisations of shallow convection, and the model representation of dynamic vegetation. Further, a major limitation for model development at these resolutions is the availability of verification datasets with high spatial (horizontal and vertical direction) and temporal (preferably sub-hourly) resolution. Given current limitations, perhaps the greatest value of these experiments, from a hydrological perspective, is the opportunity they provide to study the impact of climate change on rainfall with weak synoptic forcing (but strong land-surface coupling), rainfall in complex terrain, or rainfall intensity dependency on temperature[57,58,59].

Complementing the need to better resolve the physical aspects of simulating future runoff is the need to improve the practice of translating the impact analysis to useful information for adaptation planning and implementation in the water resource management sector. This should include improving understanding around the rainfall characteristics that are important for streamflow and other hydrological metrics, and the ability to project changes in these characteristics and hydrological responses. It must also involve working together with stakeholders to better understand the nature of vulnerabilities in different operational procedures, supporting decision making around what constitutes high impact events, and establishing the time frame for addressing those challenges.

Glossary

CMIP3
CMIP3 refers to the 3rd Coupled Model Intercomparison Project, or more typically, the global climate models involved in that project. They are also the models used in the IPCC Fourth Assessment Report.

CMIP5
CMIP5 refers to the 5th Coupled Model Intercomparison Project, or more typically, the global climate models involved in that project. They are also the models used in the IPCC Fifth Assessment Report. Note that to make the numbers line up with the IPCC Assessment Reports, there was no CMIP4.

Downscaling
Downscaling methods are used to derive local scale climate data from large scale GCM data. These methods are typically classed as either statistical or dynamical, where the former includes regression or weather pattern based relationships between large and local scale variables and the latter refers to the use of a fine-scale regional climate model (often only the atmosphere component).

DMI
The Dipole Mode Index (DMI) is an index representing the state of the Indian Ocean Dipole. It is the difference in sea surface temperature between the western equatorial Indian Ocean (50°E-70°E and 10°S-10°N) and the south eastern equatorial Indian Ocean (90°E-110°E and 10°S-0°N). Sustained negative DMI indicates negative IOD, with warmer waters near Australia, and is usually associated with wet conditions across Victoria.

El Niño
El Niño refers to extensive warming of the central and eastern tropical Pacific Ocean and a weaker Walker circulation. This occurs every three to eight years and is often associated with drier than usual conditions in eastern Australia.

GCM
Global climate models (GCMs) (previously known as general circulation models) are computer-based representations of the motion and physical interactions of the atmosphere, land and ocean.

Hadley cell
The name given to each cell of the Hadley circulation, typically the southern hemisphere cell as used in this report.

Hadley circulation
The Hadley circulation is the large-scale atmospheric circulation that transports heat from the tropics to the sub-tropics.

IOD
The Indian Ocean Dipole (IOD) is one measure of the difference in sea surface temperatures between the eastern and western Indian Ocean. DMI is an index of the IOD. The IOD influences Victorian climate through spring, ending in December.

Mean meridional circulation
The mean meridional circulation refers to the overall atmospheric circulation of the Earth, transporting heat and moisture from the tropics towards the poles. It includes the Hadley circulation.

Left: Weather station on top of Mt Hotham. Pandora Hope

NINO3

The NINO3 index is used to describe the state of ENSO. It is defined as the average of sea surface temperature anomalies over the region 90°W-150°W and 5°S- 5°N. Sustained values greater than 0.8°C indicate an El Niño; while sustained values less than -0.8°C indicate La Niña.

Reanalysis product

Reanalysis products are synthesised historical data sets that describe that state of the atmosphere-ocean system in a consistent manner.

SAM

The Southern Annular Mode (SAM) is the major mode of variability at high latitudes. A common index of SAM is the difference between surface pressure at 40°S and 65°S. High SAM (higher pressures over southern Australia, and anomalous easterly winds) generally brings dry conditions to Victoria in winter, but wet in other seasons. Low SAM is often associated with wet conditions across Victoria in winter, but dry conditions in spring and summer.

SOI

The Southern Oscillation Index is used to indicate if ENSO is in an El Niño, La Niña, or neutral state. It is based on the difference between Darwin and Tahiti atmospheric pressure. Sustained values less than -7.0 indicate an El Niño, while sustained values greater than +7.0 indicate La Niña.

Subtropical ridge

The subtropical ridge (STR) refers to the region of high pressure that exists across the mid-latitudes co-located with the descending branch of the Hadley circulation. It shifts equatorward during winter and poleward in summer.

Tripole index

The tripole index is an indicator of the variability in tropical ocean temperatures of relevance to Victoria's climate. It is based on the difference between the mean sea surface temperatures (SST) north of Australia minus the average of the SST over the central western Indian Ocean and the central Pacific Ocean. High values tend to be associated with high rainfall for Victoria.

Walker circulation

The Walker circulation is the east-west atmospheric circulation that occurs across the tropical Pacific Ocean.

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