Climate**Change**Science

Information Paper

Australian rainfall — past, present and future

A product of the Australian Climate Change Science Program

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- Australia's climate is naturally variable
- Australia's east coast, south-east and south-west have become drier over recent decades, from a wetter period during the mid-twentieth century
- the north-west has become wetter over the past century
- research is helping to explain the factors that influence our rainfall and how they are being affected by human-induced climate change
- relative to the long-term average, Australia is likely to become drier in southern areas during winter, and in southern and eastern areas during spring.

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1. Introduction

Australia has a highly variable climate. It is not uncommon for one region to be in drought while flood waters cause damage elsewhere. Superimposed onto this climatic variability are longer-term changes to rainfall. Large swathes of eastern and south-eastern Australia have experienced a drying trend over recent decades, as has the south-west of Western Australia. Conversely, north-western Australia has become considerably wetter.

Rainfall changes have important policy implications. State and Commonwealth governments have begun to respond to growing populations, rainfall reductions and likely future changes via a number of adaptive measures. These measures include water restrictions, campaigns to lower water consumption, and construction of new infrastructure including pipelines, improvements to stormwater and wastewater management, and desalination plants.

Changes to water management also include the Murray-Darling Basin Plan to provide water for the environment and sustainable irrigation activities.

Climate change presents a threat to Australia's environment and our lifestyle. Higher temperatures are likely to have exacerbated the impact of recent droughts. Global warming may be affecting seasonal patterns of rainfall, leading to decreases in rainfall and runoff in important food producing regions of Australia, such as the Murray-Darling Basin and south-western Western Australia.

This paper summarises what we know about Australian rainfall, including historical trends, regional changes, patterns of climate variability, and projections for the remainder of this century. It draws on extensive data and information collected over the past century by the Bureau of Meteorology, on detailed climate change projections produced by CSIRO and the Bureau, and on peer-reviewed published research from Australia and overseas.

Collecting weather data

The Bureau of Meteorology maintains an extensive network of weather stations throughout Australia. The stations record data including rainfall, temperature, humidity, pressure, sunshine and wind. In addition to stations run by Bureau staff, there is an important volunteer rainfall network with about 6000 observers.

Monitoring of annual to multi-decadal climate variability is facilitated by the construction of high-quality rainfall datasets, developed by selecting high-quality sites, and, where necessary, adjusting long, continuous records to remove artificial shifts caused by changes in station site characteristics, instrumentation and weather exposure.

Most high quality instrumental climate records extend back only to the late 19th century. Researchers can track earlier climate from a variety of sources, such as tree rings, fossils and coral. For example, Lough (2003) used north-east Queensland coral records to determine rainfall variations from 1754 to 1985.

2. Rainfall observations

Australia has the lowest average annual rainfall of all inhabited continents. Half of the country receives an average of less than 300 mm per year. Our rainfall pattern is strongly seasonal, with large year-to-year variations. Much of the continent is dominated by the influence of dry, sinking air of the sub-tropical high pressure belt. When high pressure systems move north during winter, westerly winds drive rain-bearing cold fronts across southern Australia. As a result, much of Victoria, South Australia and Western Australia experiences wet winters and relatively dry summers. More uniform rainfall occurs in southern Tasmania, parts of eastern Victoria and much of New South Wales. In contrast, summers are very wet in tropical northern Australia due to the monsoon. Occasional tropical cyclones bring additional rainfall. Northern Australian winters are typically dry, except for regions near the tropical east coast, leading to the widespread use of the terms ‘wet’ and ‘dry’ season rather than ‘summer’ and ‘winter’ over northern Australia.

The first consistent rainfall observations date back to 1832 and demonstrate great year-to-year variability as well as variability over longer timescales, particularly in southern Australia (Power *et al.*, 1999). During the period of modern observations, there have been three major droughts in the south: the Federation drought of 1895-1905, the World War 2 drought of 1936-1945 and the recent drought that started in 1997 and ended in 2010.

Interspersed with droughts have been relatively 'wet' periods, with 1950-1990 of significance as this was when water was allocated for major irrigation projects in areas such as the Murray-Darling Basin.

The recent 13-year drought in the southern Murray-Darling Basin and Victoria is unprecedented compared with other recorded droughts since 1900 (CSIRO, 2010). (The previous record drought lasted 10 years from 1936 to 1945 (CSIRO, 2010).) The recent drought was largely restricted to southern Australia and was characterised by lower year-to-year rainfall variability and an absence of years with above average rainfall.

Figure 1 shows Australia's average annual rainfall from 1961 to 1990.

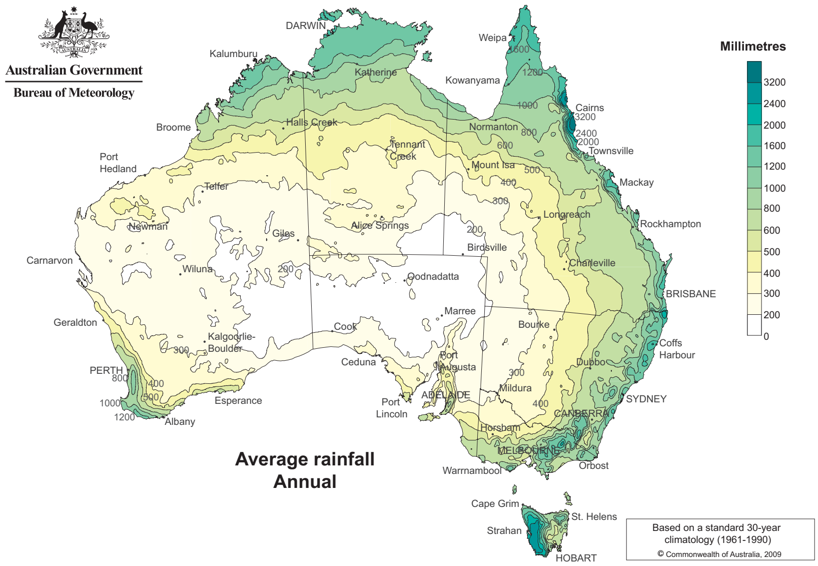


Figure 1. Average annual rainfall from 1961 to 1990. Rainfall generally increases towards the coast, with mountainous areas and the far north receiving higher rainfall. Much of inland Australia is very dry. (1961-1990 represents the World Meteorological Organization standard climatological reference period.) (Source: Bureau of Meteorology)

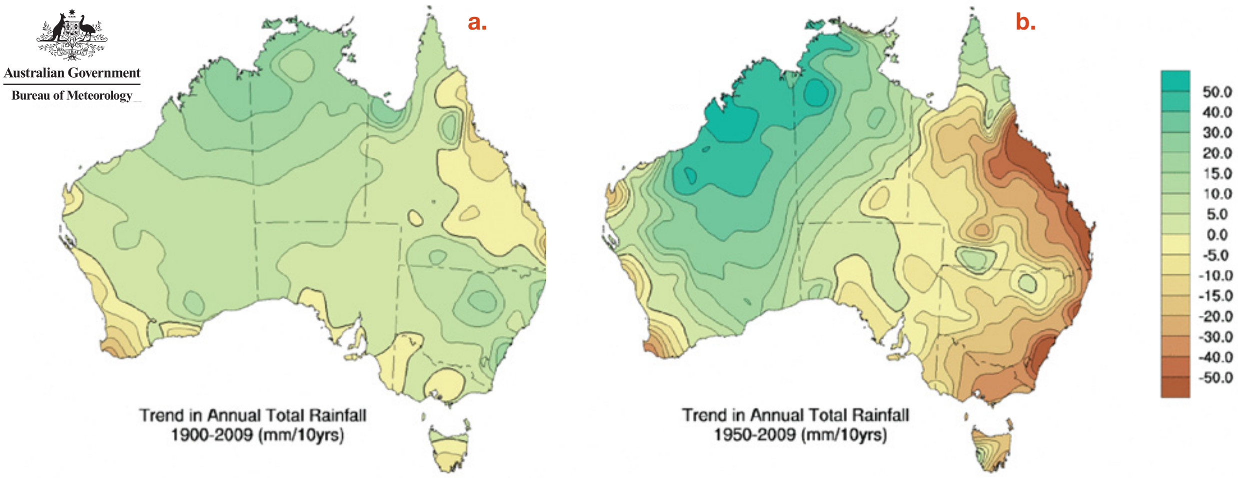


Figure 2. Trends in annual mean rainfall during **a.** 1900-2009 and **b.** 1950-2009. Rainfall changes since 1950 have been significant in many regions. Units are mm per decade. (Source: Bureau of Meteorology)

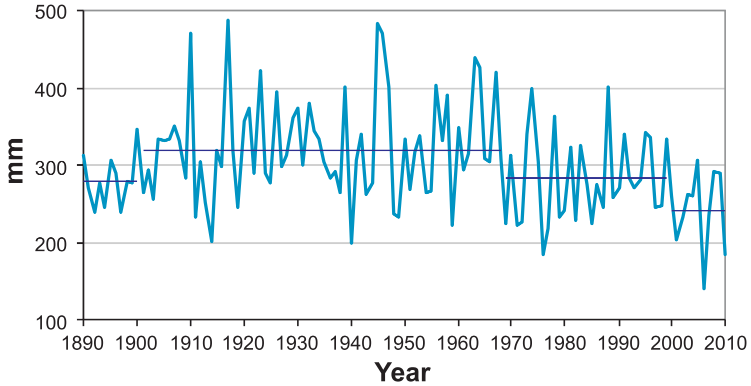


Figure 3 Rainfall from May to July over south-west Western Australia, 1890 – 2006. (Source: Hope and Ganter, 2010)

The rainfall trends across Australia since 1950 have been large, with vast areas experiencing reductions or increases (CSIRO and Bureau of Meteorology, 2007). Most heavily populated regions have experienced reductions in annual rainfall since the mid-1950s (Figure 2).

Regional changes

South-western Western Australia

During the first half of the 20th century, south-west Western Australia experienced a number of wet winters and few extremely dry winters. This changed in the 1970s when winters became drier; translating to a significant reduction of inflows to dams (Power *et al.*, 2005; Cai and Cowan, 2006). The 1970s rainfall reduction has been exacerbated by a further decline since the 1990s (Figure 3). Most of the reductions have been from May to July (Hope *et al.*, 2009).

South-eastern Australia

Rainfall across south-eastern Australia is highly variable on inter-annual and decadal time-scales (Figure 4). The first half of the 20th century was markedly drier than the second half, with a significant increase in the late 1940s (Murphy and Timbal, 2008). In the late 1990s, most of the region entered an extended dry spell. From 1997 to 2009, virtually the entire area experienced rainfall below the long-term average, with some places recording the lowest totals on record. Most of the rainfall decline up to 2006 occurred in autumn, with 2006 through 2008 also experiencing relatively poor rainfall in winter and spring. The rainfall decline affected the southern area of the Murray-Darling Basin and the whole of Victoria, with impacts on the environment, irrigation industries and the cities of Adelaide, Melbourne and Canberra.

Potter *et al.* (2010) show that a 13% reduction in rainfall in the southern Murray-Darling Basin from 1997-2006 led to a streamflow decrease of 44%.

Australian east coast

Rainfall over much of the populous eastern coastal region has declined since the 1950s (Figure 2b). The largest drying exceeds 50 mm per decade (CSIRO and Bureau of Meteorology, 2007). The trend partly reflects a very wet period around the 1950s.

North-western Australia

North-western Australia has seen a substantial increase in annual rainfall since the 1950s (Figure 2b), amounting to more than 30 mm per decade across the north-west third of Australia and exceeding 50 mm per decade over parts of the north-west coast. The wet season has become wetter, with only small rainfall changes occurring during the rest of the year (Shi *et al.*, 2008).

Rainfall extremes

East coast lows, tropical cyclones, monsoon troughs, severe thunderstorms, cut-off lows and mid-latitude fronts can all lead to high rainfall and floods.

Trends in extreme rainfall across much of Australia have been consistent with mean rainfall trends, although trends in the extremes have typically been greater than the mean trend (Alexander *et al.*, 2007). That is, where average rainfall is increasing, the extremes have tended to increase at a faster rate. In some regions, rainfall totals have decreased but extreme rainfall has still increased. There are fewer rainfall days but when it does rain, it tends to be heavier.

Gallant *et al.* (2007) found that the proportion of total rainfall stemming from extreme events has increased since the 1950s in south-western Australia and along the eastern coast, and since the 1970s in the south-east.

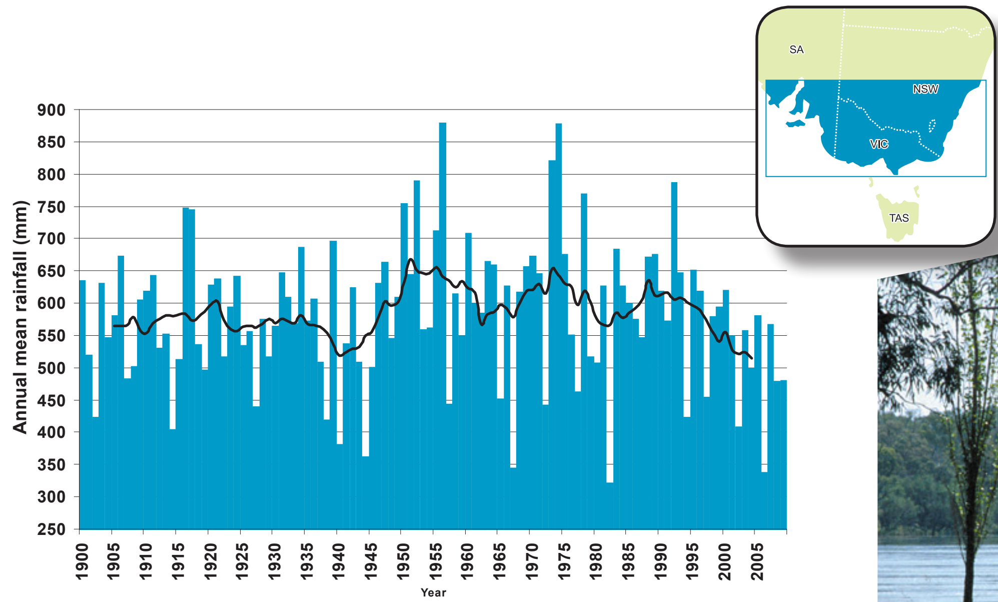
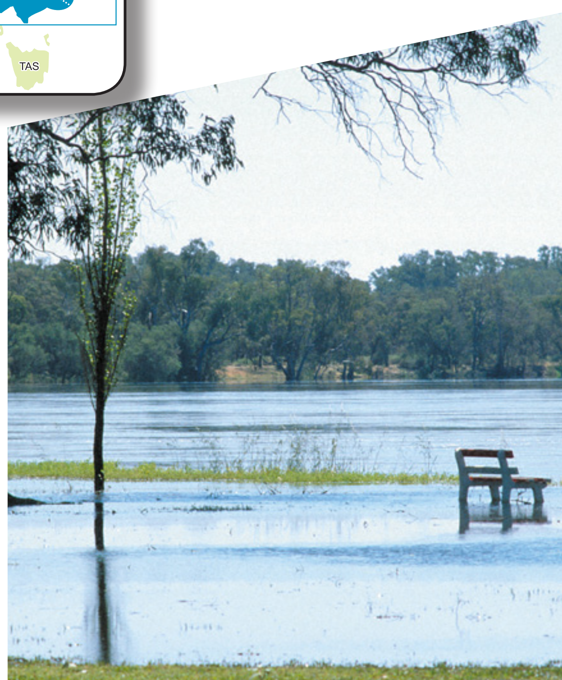


Figure 4. Mean annual rainfall over mainland south-eastern Australia (see inset map) from 1900 to 2009. Also shown is the 11-year running mean (solid black). (Source: Timbal *et al.*, 2010)



3. Factors that influence Australia's rainfall

Researchers have made advances in identifying the factors that influence our climate. Described here are elements that affect Australia's rainfall. Many of these elements fluctuate in strength, timing and impact. None of them acts in isolation.

Blocking: High pressure cells can remain stationary at middle to high latitudes, stopping the normal eastward progression of high- and low-pressure systems. This 'blocking' happens most often in winter near south-eastern Australia. Cold fronts approaching the blocking region from the west often weaken and travel south-east, carrying rain away from the continent. However, small cyclonic components sometimes form on the northern side of the blocking high pressure cell. The resulting 'cut-off' lows (that is, cut off from the mid-latitude westerlies) make a major contribution to south-eastern Australian rainfall. Blocking in the Great Australian Bight induces rainfall in western Australia.

El Niño – Southern Oscillation (ENSO): There are large-scale atmospheric changes driven by ocean surface temperature differences between waters in the western and eastern Pacific Ocean. The irregular see-sawing of warmer and cooler water across the Pacific gives rise to the cycle of El Niño and La Niña events. El Niños usually reduce rainfall over eastern Australia; La Niñas usually increase rainfall over most of Australia.

The Hadley Cell: The process by which heat is transported in the atmosphere from equatorial zones to higher latitudes. Due to the rotation of the Earth, the Hadley Cell does not extend to the poles. Rather, the downward return flow occurs along the sub-tropical ridge around 30°S and 30°N.

Indian Ocean Dipole (IOD): An irregular see-sawing of surface water temperatures across the Indian Ocean. When the dipole is in a positive phase, sea water off the Sumatra-Java coast north-west of Australia tends to be cooler than normal, and there are fewer rain-bearing systems that extend to central and southern Australia. A negative phase of the dipole produces the opposite effect, with warmer than normal waters bringing increased rain.

Interdecadal Pacific Oscillation/ Pacific Decadal Oscillation: El-Niño-like variability that occurs on decadal and longer time scales, linked to decadal changes in ENSO and Australian climate.

Influences on Australia's rainfall

Numerous factors affect Australia's climate (Figure 5). There is the mid-latitude jet stream (strong upper-atmosphere westerlies) and the succession of high and low pressure systems that move across southern Australia from west to east, bringing fronts, troughs, warm northerlies, cold southerlies, rain, and fine weather.

Add a host of regional and global oceanic and atmospheric influences, and it's little surprise that climate — especially rainfall — changes, from year to year, decade to decade and over the centuries. Australia's climate is naturally variable.

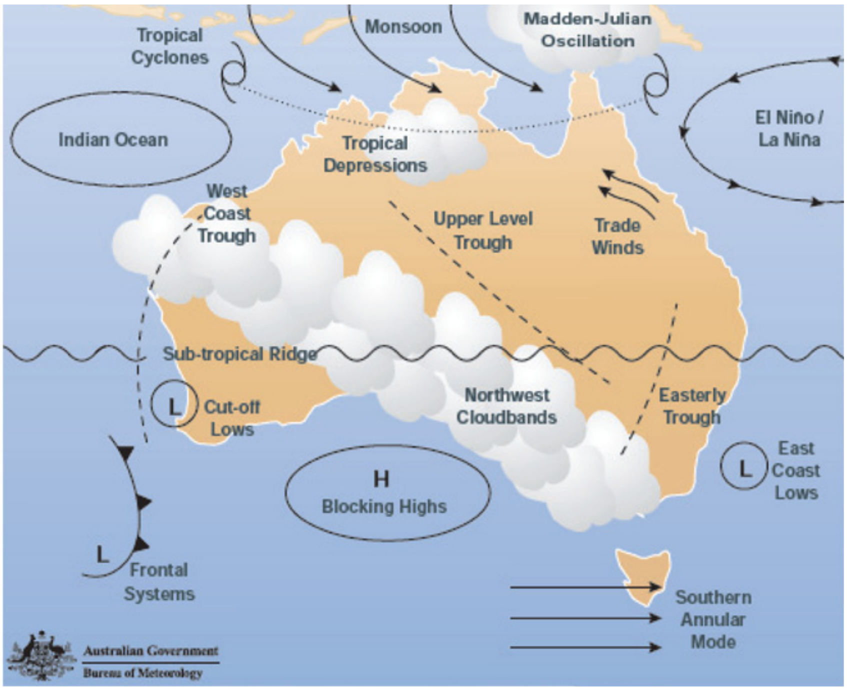


Figure 5. Large-scale features that affect Australia's rainfall (Source: Bureau of Meteorology)

Detection and attribution of climate change

Identifying a trend in rainfall in a region is one thing; establishing the reason for the trend is more difficult. Climatic variability causes changes on decadal time scales. There are changes caused by variations in atmospheric aerosols, through stratospheric ozone depletion, and changes in land use. Rising concentrations of greenhouse gases may cause long-term changes. There is a strong motivation for understanding why climate is changing as this information will help planners and water managers know what to expect in future to avoid surprises and to respond adequately.

An important objective of climate science programs such as the Australian Climate Change Science Program (ACCSP), the Indian Ocean Climate Initiative (IOCI) and the South-Eastern Australian Climate Initiative (SEACI) is to determine the extent to which changes can be attributed to natural climatic variability or other natural causes, and to greenhouse gas increases and other human-induced changes.

Madden-Julian Oscillation (MJO): A band of low atmospheric pressure originating off the east coast of central Africa travelling eastward across the Indian Ocean and northern Australia every 30 to 60 days. The state of the MJO can help establish the timing of rainfall across much of tropical Australia. In summer, the MJO can intensify and even establish the monsoon as well as help trigger tropical cyclones.

Southern Annular Mode (SAM): A ring of atmospheric pressure variations that encircles Antarctica and extends to Australian latitudes. There are alternating changes in windiness and storm activity between the middle latitudes (40-50°S) and higher latitudes, over the southern oceans and Antarctic sea ice zone (50-70°S). In its positive phase, the SAM brings light winds and settled weather to far southern Australia.

Sub-tropical ridge: A belt of high pressure around 30°S (roughly straddling a line running through Adelaide and Canberra) that separates the trade winds of the tropics from the westerlies of the mid-latitudes. The ridge is characterised by light winds, fine and sunny weather and an absence of storms. It moves southwards as summer approaches, bringing fine weather and sunshine to southern Australia.

Tropical cyclones: These intense tropical low-pressure systems generally hold large amounts of moisture. When tropical cyclones hit the coast, they often bring extensive rainfall. Rainfall can extend inland, including to southern latitudes, as the cyclone weakens to become a tropical depression.

Changes to climatic influences

Since the Industrial Revolution, the atmospheric concentrations of greenhouse gases such as carbon dioxide, methane and nitrous oxide have risen. The increase is contributing to temperature increases in the troposphere (the approximately 10km deep lower atmosphere where weather occurs) and to changes in other climatic components including rainfall. There have also been increases in human-generated aerosols and tropospheric ozone, depletion of stratospheric ozone, and substantial changes in land use. All of these factors have the potential to affect regional climate and rainfall.

El Niño events have become more frequent and La Niña events less frequent since the late 1970s (Power and Smith, 2007). This change is linked to a weakening of the trade winds and a slowing of the Walker Circulation.

However, in 2010-11, one of the strongest recorded La Niña events led to record high rainfall across much of northern and eastern Australia. This caused widespread flooding. Australia experienced its wettest September on record, the wettest winter on record in northern and central Australia, and the wettest summer on record in Victoria (Bureau of Meteorology, 2011).

The SAM has exhibited a pronounced positive trend during summer over the past 30 years, corresponding to a decrease in surface pressure over the Antarctic and Southern Ocean and a pressure increase over mid-latitudes, including southern Australia (Nicholls, 2007).

Since 1975, there has been a weakening of the intensity of winter storms (low pressure systems) in southern Australian latitudes. This is related to a drop in the strength of upper tropospheric jet stream winds across mid-latitudes of the Southern Hemisphere (Frederiksen *et al.*, 2010). These 'storm track' changes are consistent with the observed reduction in rainfall over southern Australia, and in particular, south-west Western Australia. They are also consistent with findings that the recent decline in rainfall in south-western Western Australia is strongly associated with a decrease in the number of low pressure systems (Hope *et al.*, 2006) and increased persistence of high pressure systems (Hope and Ganter, 2010).

4. Attribution of observed changes

South-western Western Australia

Hope *et al.* (2006) found that the decline in rainfall in south-western Western Australia from the period 1958–1975 to 1976–2003 was strongly associated with a reduction in the number of low pressure systems crossing the region. More recent changes, including an apparent further drop in rainfall in the 1990s, are associated with the persistence of high pressure systems. For example, 2006 was a record breaking year, with very low rainfall totals and mean sea-level pressure values well above normal across southern Australia (Hope and Ganter, 2010).

Since the 1970s, upper level winds have weakened, reducing storm development (Frederiksen and Frederiksen, 2007).

IOCI has concluded that it is likely that the serious rainfall decline in south-west Western Australia is, in part, due to the enhanced greenhouse effect (Timbal *et al.*, 2006), and unlikely to be a result of natural climatic variations alone (Ryan and Hope, 2006). Regional land cover changes are a possible additional contributor to the rainfall reduction (Pitman *et al.*, 2004). Individual contributions of the different drivers are difficult to quantify, but one modelling study concluded that increasing concentrations of greenhouse gases have caused half of the winter rainfall reduction (Cai and Cowan, 2006). The study also concluded that ozone-depletion plays no role in the winter rainfall reduction, and that other factors, such as multi-decadal variability or land-use changes, must be invoked to fully account for the observed winter rainfall reduction.

A negative value of SAM can have a drought-breaking influence on south-western Western Australia. However, 2010 marked the highest positive winter SAM value on record (Cai *et al.*, in press). The positive phase of SAM is associated with above-average surface pressure in the vicinity of southern Australia. Climate models project an increasing SAM trend as warming continues, meaning that the long-drying trend is expected to continue through the 21st century (Cai *et al*,. in press).

South-eastern Australia

Numerous studies have examined recent rainfall changes across south-eastern Australia. Launched in 2006, SEACI has provided a strong focus for this work. There are many potential causes of the autumn-winter rainfall decline that commenced in the late 1990s, including changes in the frequency of El Niño and La Niña events (Cai and Cowan 2008) and in the Indian Ocean Dipole (Ummenhofer *et al.*, 2009). The Indian Ocean Dipole in spring has been trending upwards (Cai *et al.*, 2009a), at least in part due to human-induced climate change (Cai *et al.*, 2009b) so it may account for some of the decline of rainfall in spring across south-eastern Australia. However, the Indian Ocean Dipole is unlikely to explain the autumn-winter rainfall decline because then it has little impact in the region (Timbal and Murphy, 2007; Nicholls 2009).

Recent work by Watterson (2010) indicates that sea-surface temperature anomalies to the north and west of Australia are also unlikely to be contributing to the autumn rainfall decline as they have limited influence on south-east Australian rainfall during autumn-winter. In addition, much of the observed relationship between south-eastern Australia rainfall and these sea-surface temperatures results from the large-scale atmospheric circulation that is both driving the rainfall and driving the sea-surface temperature. Nicholls (2009) states that sea surface temperatures around northern Australia are tending upwards and so should have led to *increased* rainfall rather than the observed overall decline. That was confirmed by Smith and Timbal (2010) and quantified by Timbal and Hendon (in press), who found that the influence of the tropics during the recent rainfall deficiency across south-eastern Australia has been positive overall (hence reducing the magnitude of the deficit) with a small negative contribution in spring. Despite positive sea-surface temperature trends, the influence of El Niño and La Niña variations is also limited because there is not a pathway for these phenomena to affect rainfall in autumn and winter (Cai *et al.*, 2011).

The autumn rainfall decline has been associated with increasing intensity of the subtropical ridge over eastern Australia (CSIRO, 2010). Nicholls (2009) accounts for a similar proportion of the rainfall decline through the increase in surface pressure, which he ascribes to the upward trend in the SAM.

A climate modelling study showed that the observed intensification of the high pressure ridge could only be achieved when anthropogenic greenhouse gases are included (CSIRO, 2010) consistent with the notion that enhanced greenhouse gases force the SAM into its high phase (e.g. Cai and Cowan, 2006).

These changes do not fully account for the lengthy drought and it remains likely that natural variability was also a contributing factor (CSIRO, 2010). Nicholls (2008) suggests the possibility that climate change is increasing the severity of Australian droughts, by raising temperatures and increasing evaporation. Cai and Cowan (2008) similarly suggest that rising temperatures have dramatically reduced runoff in the Murray-Darling Basin. However, these findings are not supported by the rainfall-run-off modelling studies by Potter *et al.* (2010), who showed that only a small fraction of the decreased run-off response to reduced rainfall is linked to increased temperature.

East coast

The general drying trend over eastern Queensland since 1950 (Figure 2b) is consistent with increased frequency and severity of El Niño events since the 1970s (Gallant *et al.*, 2007). There have been more than twice as many El Niño events as La Niña events in this period and El Niño has been more dominant in recent decades than in any other period on record (Power and Smith, 2007).

Kang *et al.* (2011) found that including polar ozone depletion in climate models led to a poleward displacement of the Southern Hemisphere westerly jet, accompanied by a poleward shift of mid-to high-latitude precipitation. The most noticeable consequences in Australia is a precipitation increase across eastern Australia in summer, therefore suggesting that the observed decline has been somewhat mitigated by a tendency toward the positive phase of SAM.

The extent to which global warming is responsible is being investigated through the ACCSP. The record wet conditions in 2010-11 highlights the importance of La Niña events in balancing the impact of El Niño 'droughts'. An imbalance between La Niña and El Niño events in recent decades is a part explanation for the apparent drying trends.

As noted earlier, a particularly strong La Niña event led to record high rainfall across much of eastern Australia, causing widespread flooding.

North-western Australia

There remains substantial uncertainty about the cause of the large rainfall increases in north-west Australia. Climate model simulations driven only by increased greenhouse gases do not reproduce well the rainfall increase over north-western and central Australia (Cai *et al.*, 2011). Rotstayn *et al.* (2007) report that inclusion of human-induced aerosol changes in model simulations results in a better match with the increasing rainfall observed over north-western Australia.

Aerosol from Asia largely stays in the Northern Hemisphere; they are not transported over Australia. The Asian haze may alter the north-south temperature and pressure gradients over the tropical Indian Ocean, thereby increasing the tendency of monsoonal winds to flow toward Australia, bringing rainfall to the north-west. Thus, researchers have suggested that human-generated aerosols from Asia may have contributed to the observed rainfall increases in the northwest. However, due to the complexity of the underlying processes, limitations of the model and the effects of natural variability, it is difficult to draw firm conclusions (Rotstayn *et al.*, 2007; Shi *et al.*, 2008).

Wardle and Smith (2004) have argued that warming of the Australian continent might have strengthened the monsoon, resulting in increased rainfall. However, they left open the question of whether recent increases in greenhouse gases are sufficient to have caused the necessary amount of warming.

5. How will rainfall change in future?

Climate Change in Australia (CSIRO and Bureau of Meteorology, 2007) presents extensive information about likely future rainfall changes.

Reliability of projections

Regional precipitation variations are sensitive to small differences in atmospheric circulation and other processes, as is evident from Australia's large natural rainfall variability. It is difficult to make definitive statements about likely future rainfall changes for particular places. CSIRO and Bureau of Meteorology (2007) acknowledge that projections of global and regional climate change contain a number of uncertainties. Predictability is limited by factors such as human behaviour and the uncertainties inherent in complex systems. However, global climate models continue to improve in their ability to represent current global and regional patterns of temperature, precipitation and other variables.

Global rainfall patterns strongly reflect the general atmospheric circulation. Climate models represent overall features well, including subtropical dry zones and the position of mid-latitude storm tracks (CSIRO and Bureau of Meteorology, 2007). There are, however, some systematic errors that are important to Australian projections, including in temperature and precipitation patterns that affect model representation of the seasonal cycle and ENSO. Cai and Cowan (2006) report that models simulate well the seasonality in the relationship between SAM and rainfall in south-western Western Australia. However, Cai *et al.* (2010) state that most models perform poorly in simulating the relationship between ENSO and the rainfall decline in south-eastern Queensland.

Models generally simulate too much light rain, and underestimate the contribution and frequency of heavy rain (CSIRO and Bureau of Meteorology, 2007). CSIRO (2010) reports that the seasonal pattern of rainfall deficits for 1997-2006 across south-eastern Australia did not resemble the patterns of rainfall changes under global warming projected by climate models. However, the seasonal pattern of rainfall deficits across the region for 2006-2009 does more closely resemble the projected seasonal patterns of change (CSIRO, 2010).

Likely future changes

CSIRO and Bureau of Meteorology (2007) project a reduction in rainfall for southern areas of Australia, especially in winter, and in southern and eastern areas in spring (based on the median and the majority of individual model results, (Figure 6), caused by the contraction in the rainfall belt towards the higher (more southern) latitudes. Future changes in summer tropical rainfall in Northern Australia were uncertain. Figure 7 shows the probability of annual rainfall change exceeding various thresholds.

It is likely that the most intense rainfall events in most locations will become more extreme, driven by a warmer, wetter atmosphere. The combination of drying and increased evaporation means soil moisture is likely to decline over much of southern Australia.

CSIRO has undertaken high-resolution climate change projections for Tasmania (Grose *et al.*, 2010), revealing a pattern of increased rainfall over the coastal regions, and reduced rainfall over central Tasmania and in the north-west.

Models show an increase in daily rainfall intensity and in the number of dry days. Thus, we will need to wait longer for rain, but when it does fall, it will be heavier. Extreme daily rainfall tends to increase in many areas but not in the south in winter and spring when there is a strong decrease in mean rainfall.

There is no consensus among climate models used for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment on how global warming

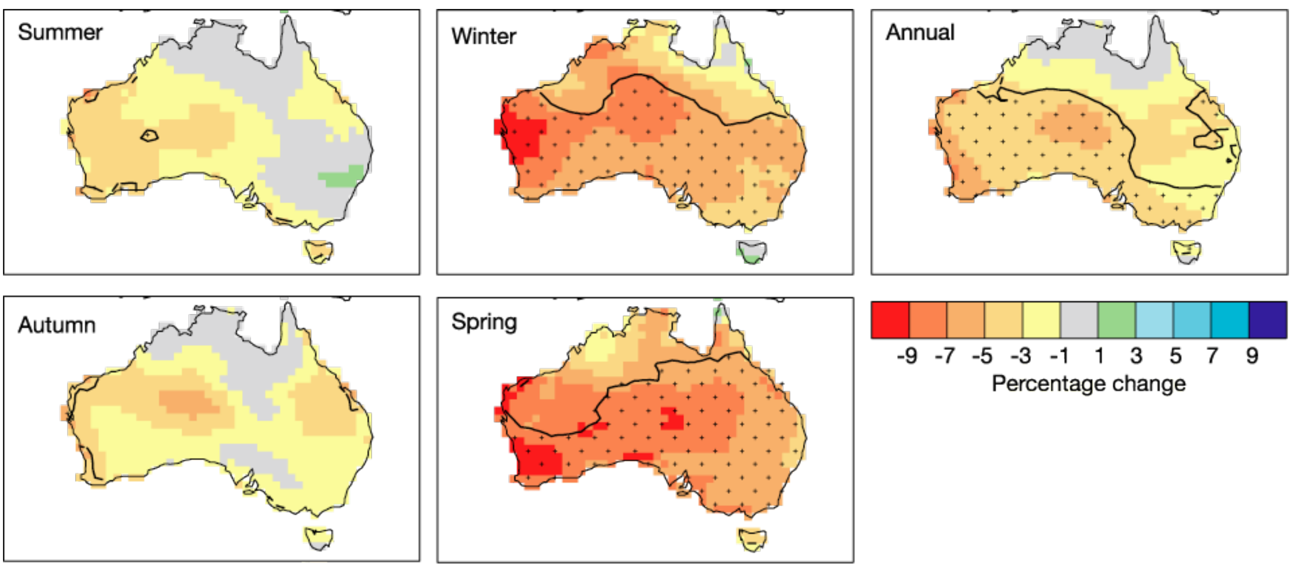


Figure 6. Best estimate of projected percentage rainfall change for 2030 relative to 1990 under a mid-range emissions (A1B) scenario. Stippling indicates where a decrease is likely. (Source: CSIRO and Bureau of Meteorology, 2007)

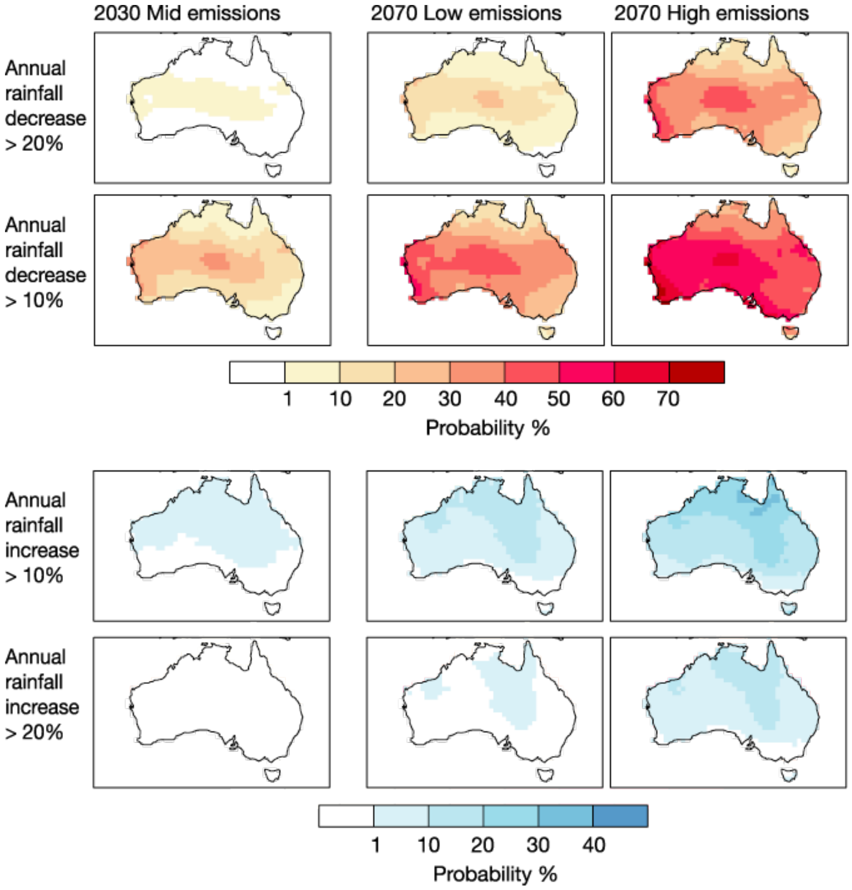


Figure 7. Probability (%) of annual rainfall change, relative to 1990, exceeding various thresholds based on the spread of climate model results. The mid, low and high emission scenarios are A1B, B1 and A1FI (IPCC, 2000). (Source: CSIRO & Bureau of Meteorology, 2007)

will influence ENSO variability in the Pacific Ocean, except that ENSO will remain a major cause of climatic variability over much of Australia and beyond. Rainfall over southern Australia is projected to decline in response to global warming, even if ENSO variability in the Pacific does not change. If this rainfall decline is evenly spread throughout the ENSO cycle then rainfall deficiencies during El Niño events over the coming century are likely to intensify, and replenishing rainfall that often occurs during La Niña years to be somewhat reduced. Furthermore, rainfall deficiencies during El Niño years will be accompanied by higher temperatures, which may exacerbate water shortages in some places.

SAM is likely to shift towards its positive phase (weaker westerly winds over southern Australia and stronger westerly winds at higher latitudes). All climate models exhibit a trend in the SAM towards its positive phase as greenhouse gas concentrations rise (CSIRO and Bureau of Meteorology, 2007). Positive values of SAM are associated with decreased winter rainfall over south-east and south-west Australia (Hendon *et al.*, 2007).

In recent years, south-eastern Australia and south-western Western Australia have suffered rainfall declines more severe than those projected by climate models. These declines may be in part due to natural climate variability. If this is the case, rainfall may return to levels closer to those experienced before the current dry periods. In regions where rainfall reductions are projected, such reductions may be from a base level that is *higher* than recently experienced. Thus, it may be some decades before the impact of human-induced climate change overcomes natural variability and long-term drier conditions are experienced.

The fact that in many places rainfall from 1961-1990 was markedly above the long-term average is a reminder that using rainfall trends starting within this period is unwise. This anomalous wet period exaggerates the magnitude of the subsequent rainfall decline (Timbal, 2010).

6. Gaps in our knowledge

The ACCSP has made strong contributions to understanding and better modelling of factors responsible for rainfall variability and trends. Research topics have included ENSO, the influence of the Indian Ocean, aerosols, the monsoon and tropical cyclones.

Since 1998, IOCI has been providing information about the climate of Australia's south-west. It has yielded insights into the nature and causes of the rainfall decline experienced during the past decades. Building on the experience gained, SEACI was launched in 2006. This program explores climate, and climate variability and change in the south-east of Australia, including the Murray Darling Basin, and the whole of Victoria. There is still much to be learned on both sides of the continent about how rainfall is likely to change in future.

There are strong arguments for similar investigations of rainfall on the eastern seaboard, where east-coast lows and the trade winds have a considerable impact, and also in tropical Australia. There are important questions to be answered for Australia's north, such as on the timing and strength of the monsoon, and on the likely future frequency and strength of tropical cyclones.

Fundamental to any assessment of climatic trends is the quality and distribution of observations. These observations must continue, and in some cases, be expanded if we are to comprehend the precise nature and impacts of changing climate. Increasingly, these data are supplied publicly via web sites. Developments in database and web technology will permit more sophisticated data products to be made available for research and to support decision making.

Already we are witnessing decreases in surface atmospheric pressure at high latitudes and increases in the sub-tropics. These and other large-scale changes are bound to affect Australia's rainfall.

Identifying and quantifying the extent of human impact on climate change is important. Nicholls (2007) listed the following priority research areas that are relevant to rainfall in Australia:

- influence of aerosol in north-western Australia;
- impact of stratospheric ozone declines and greenhouse gas increases on summer rainfall over parts of Queensland and autumn-winter rainfall across New South Wales and Victoria;
- circulation changes such as ENSO, SAM and the position of the sub-tropical ridge;
- changes to seasonal cycles such as the onset of the monsoon;
- tropical cyclone intensity and frequency; and
- extreme rainfall events.

Climatic extremes are a regular feature of the Australian climate, often causing considerable disruption, loss of life and expense. Climate change is likely to alter the frequency and intensity of extreme events including tropical cyclones, storms, drought, heatwaves, bushfire and floods and may increase their impact. Nicholls (2008) has identified research needs involving improvements to data and modelling, as well as improved understanding of the causes of climatic extremes.

Regional climate modelling and downscaling regional-scale atmospheric variables to local scales will help to determine the likely local impacts of climate and climate change, especially those associated with climatic extremes. Outputs from these downscaling techniques are dependent on the quality of the larger-scale global climate model simulations.

Climate science has progressed dramatically in the past few decades. However, there is still much to learn about atmospheric and oceanic influences on Australia's climate, and the changes to these influences caused by rising atmospheric concentrations of greenhouse gases. Researchers need to better quantify, understand and evaluate climate change feedbacks, such as those due to water vapour, clouds, lapse rate and surface albedo, and establish the impacts of aerosol on climate. The benefits will include better climate models, narrowing the range of climate change projections where possible, and helping quantify projection uncertainties.

7. Conclusions

Australia's rainfall is highly variable. We experience this variability in many ways — through dry spells, downpours, drought and flood. Superimposed upon this variability are longer-term trends, with large increases in tropical Australia and below-average rainfall experienced for more than 30 years in the south-west, and for more than a decade in the east and south-east.

Extrapolation of recent trends is not a reliable way to predict the future. Australia's climate will continue to be variable. Overlaid upon this variability is human-induced climate change caused by rising concentrations of greenhouse gases.

Effective planning demands the best available information about rainfall changes, trends and projections. Research is helping understand the factors that influence our rainfall and the variations that climate change is likely to bring.

8. Credits

This paper has been prepared by Paul Holper on behalf of the ACCSP, funded jointly by the Department of Climate Change and Energy Efficiency, the Bureau of Meteorology and CSIRO. Trends in Australian rainfall and their causes and likely future changes represent an area of great importance and some uncertainty. The Australian Climate Change Science National Framework and the ARC Centre for Climate System Science will provide valuable opportunities for further collaboration and advances in this field.

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