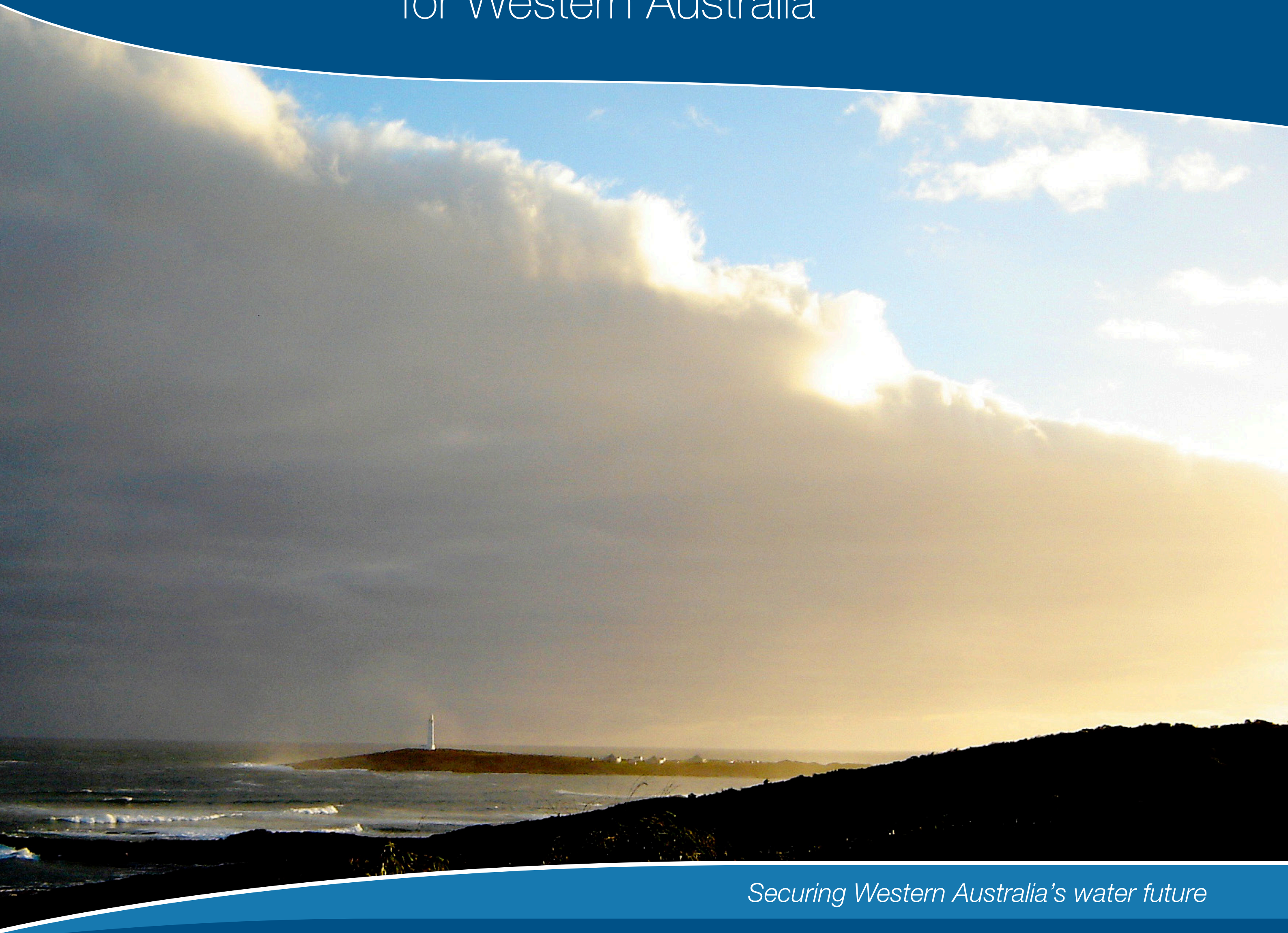
Government of **Western Australia**
Department of **Water**

Selection of future climate projections for Western Australia



Securing Western Australia's water future

Water*Science*
technical series

Report no. WST 72
September 2015

Selection of future climate projections for Western Australia

Department of Water

Water Science Technical Series

Report no. 72

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Summary

It is widely recognised that since the 1970s south-west Western Australia (WA) has experienced declining rainfall. This has resulted in a 60% reduction in stream flow to Perth metropolitan dams pre-1975 compared to post-1975 (Water Corporation 2015) with the lowest flows recorded in the last decade. Declining stream flow has also been observed in many other south-west catchments (CSIRO 2009a). Studies using results from general circulation models (GCMs) suggest that this trend will continue into the 21st century (Charles et al. 2010). In 2013 the Department of Water (the department) developed standard climate scenarios for five broad climatic regions within the state. The aim was to enable consistent application of climate projections; capture the associated range of uncertainty; and provide climate scenarios in a readily accessible and applicable form.

Previous climate change studies have used output from GCMs to estimate the potential for climate change in WA. In many parts of WA, no climate projections are available for the future time horizons necessary for water resource planning or in a format appropriate for hydrological modelling. This study will assist the department to use climate scenarios for the management of water resources with consistency and transparency.

The department has developed climate scenarios for five regions, covering the entire state. The climate scenarios are reported using anomalies– the average change in a climatic variable for a future period compared to the baseline period. Standard monthly climate anomalies were developed for the following regions, variables, scenarios and time horizons:

- **Regions:** South-west, Central-west, Pilbara, Kimberley, Central
- **Variables:** Rainfall, temperature, relative humidity, radiation, FAO56 reference potential evapotranspiration (derived), Penman evaporation (derived)
- **Scenarios:** Wet, median, dry
- **Time horizons:** 2030, 2050, 2070, 2100

The scenarios are based on the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. The dataset archive is associated with the IPCC’s 4th assessment report (IPCC 2007a).

From the CMIP3 data, the department selected 12 GCMs that perform the best at reproducing observed behaviour in the climate system for WA and four emissions scenarios (A1FI, A2, A1B, B2) that describe global carbon dioxide production into the future. This resulted in a range of possible climates for the future time horizons. Three scenarios (wet, median and dry) that capture the range and uncertainty in the GCMs and are practical for modelling and management were then selected. The gridded monthly anomalies for the wet, median and dry scenarios are combined with observed climate data from the World Meteorological baseline period of 1961–90 to develop a scaled climate scenario for the region, time horizon and variable of interest.

Within south-west WA, all 12 GCMs project that average annual rainfall will decline through the 21st century. The projected percentage changes in rainfall by 2030 are consistent with the results of previous studies (CSIRO 2009a), and with recent trends in rainfall for the region.

The regional average change in annual rainfall for the South-west for 2030 relative to the baseline period is –14% for the dry scenario, –5% for the median scenario, and –2% for the wet scenario. Potential evapotranspiration (PET) at 2030 is projected to increase by 2–3%, with a 0.7 °C increase in temperature. Given the trends in temperature and rainfall in south-west WA it is not appropriate to assume that the historical climate is an indicator for the future and therefore climate projections should be used in water resource management.

In all other regions within the state, there is inconsistency among the 12 best performing GCMs in the direction of rainfall trend. For example in the Pilbara, the driest GCM projects a 35% reduction in average annual rainfall for the region by 2100 while the wettest projects a 10% increase. Observations from the region over the last several decades show strong upward rainfall trends in some locations, with downward trends in others. Similarly, the Kimberley region has inconsistencies with the GCM projections ranging from a 22% reduction in average annual rainfall to an 18% increase. At some meteorological stations, the upward rainfall trends over the last 50 years are well above the wettest rainfalls projected by any GCM.

For most locations outside the South-west, the inter-annual and decadal rainfall variability is high. In many cases, this variability exceeds the climate trend of the wet, median and dry scenarios, even by 2100. Therefore it is likely that in the regions outside the South-west the climate projections do not encompass the full range of potential climate variability for the nominated time horizons. So, the long-term rainfall records are more appropriate for scenario modelling than the climate projections. Although considerable uncertainty surrounds the rainfall projections for these regions, the temperature and PET projections may still be appropriate for use, for example in calculating crop water demand or evaporation from open water bodies.

The CSIRO and Bureau of Meteorology (BoM) have recently finalised a project to analyse the next generation of climate modelling (CSIRO & BoM 2015) and "provide projections at varying levels of complexity and in various formats to support NRM requirements" (CSIRO 2012). The project – *Climate change projections for Australia's regional NRM regions* (CSIRO 2012) – is based on the CMIP5 model runs, and IPCC 5th assessment report (IPCC 2013) which have recently been released and supersede the CMIP3 datasets. As formal assessments of the CMIP5 GCM results become available the department will review and may revise the climate scenarios selected here for Western Australia.

1 Introduction and background

1.1 Introduction

The south-west of WA has experienced declining annual rainfall since the middle of the 20th century, accompanied by rising temperatures (BoM 2013a). The downward rainfall trend resulted in substantial reductions of dam inflows (Water Corporation 2015), and increased demand for groundwater and alternative water sources including desalinated water. It is widely recognised that the South-west is experiencing a drying climate (IOCI 2012) that is projected to move into a more water-limited state (Charles et al. 2010). The possibility that the rainfall trends in the south-west of Australia are the result of anthropogenic influence has been recognised by the IPCC (2007b).

There is a clear need to assess the risks to water resources associated with climate change. To achieve this, climate scenarios which can be used for water management are necessary. Several research projects have aimed to quantify the potential impacts of climate change on water resources in WA, including the *South-west Western Australia Sustainable Yields project* (SWWASY (CSIRO 2009a, b), the *Northern Australia Sustainable Yields project* (Li et al. 2009), and the *Pilbara Water Resource Assessment* (CSIRO in prep.). These projects use GCM simulations to develop climate projections for the 21st century and assess possible changes to rainfall and other climate variables. Although this research is comprehensive for some locations, for many parts of WA and for many time horizons, no projections are available in a form suitable for hydrological modelling. The varied availability of projections means that scenario development, modelling and impact assessment has not been systematic.

In response, the Department of Water developed a standard, comprehensive set of climate scenarios for the whole of WA. The aim of the project is to enable a consistent, methodical assessment of climate change for departmental modelling and impact assessment. These scenarios will be used in various aspects of departmental business, including:

- Groundwater modelling to support allocation planning and to assess changes in groundwater recharge, flow and levels under a changing climate.
- Surface water and catchment modelling to support allocation planning.
- Assessment of the impacts of climate change on hydrological and nutrient modelling supporting water quality improvement planning.
- Modelling the impacts of climate change on integrated surface water and groundwater systems.
- Integrated water and land-use planning.
- Supply projections modelling associated with water supply planning.

How to use this document

This document is intended for use by practitioners undertaking surface water and groundwater modelling and assessments. It also serves as supporting scientific information for water planners and managers.

- Chapter 1 provides background information on WA's climate trends and influences by region and the context for why the department needs climate scenarios.
- Chapter 2 considers what aspects of climate science are important for developing climate scenarios for water resource assessments.
- Chapter 3 narrows the climate scenarios to a manageable selection for modelling and planning and describes the scenarios selected.
- Chapter 4 describes how the department should use the climate scenarios selected in Chapters 2 and 3.

1.2 Climatic influences and trends in Western Australia

Climatic regions

Western Australia covers 2.5 million square kilometres, extending from tropical latitudes in the north through the mid-latitudes to the south coast at 35°S. The state comprises regions with diverse climatic influences and varied weather phenomena. One way in which the Bureau of Meteorology (BoM) defines climate zones is using a seasonal rainfall classification, as shown in Figure 1-1. This classification gives some indication of the seasonality of weather systems which are important for generating rainfall in different regions, and forms the foundation for the state subdivisions which were considered for analysis in this study. The region around the Kimberley has summer dominant rainfall; much of the Pilbara and interior is classified as arid; and the South-west is classified as winter or winter dominant rainfall. Average annual rainfall and average daily temperature for WA are shown in Figure 1-2 and Figure 1-3.

For the purposes of this study, the BoM seasonal rainfall classification was used to define subregions (Figure 1-1). Analyses of baseline climate and the projections made by general circulation models were considered for each of these regions. The climate regions/zones are as follows:

- The South-west region, which includes Perth, Geraldton, Esperance and the Wheatbelt, extends inland to Kalgoorlie and north to Shark Bay. This region has winter dominant rainfall (marked wet winter and dry summer), with some summer rainfall in the eastern portion.
- The Central-west region extends north from the South-west region to Coral Bay and inland to Mount Magnet. This region is classified as arid (low rainfall).
- The Pilbara region extends from Exmouth to around 300 km east of Port Hedland and inland to Newman. This region is classified as arid. Summer rainfall contributes most to the annual total though rain may also fall in winter.

- The Kimberley region extends from south of Broome to the state border with the Northern Territory. Summer rainfall is dominant (marked wet summer and dry winter) as a result of monsoonal weather systems.
- The Central region covers the remainder of the state. It is in the arid zone, characterised by infrequent rainfall events and very low annual rainfall.

These regions are defined on the basis of climatic influences and therefore do not correspond directly to administrative boundaries.

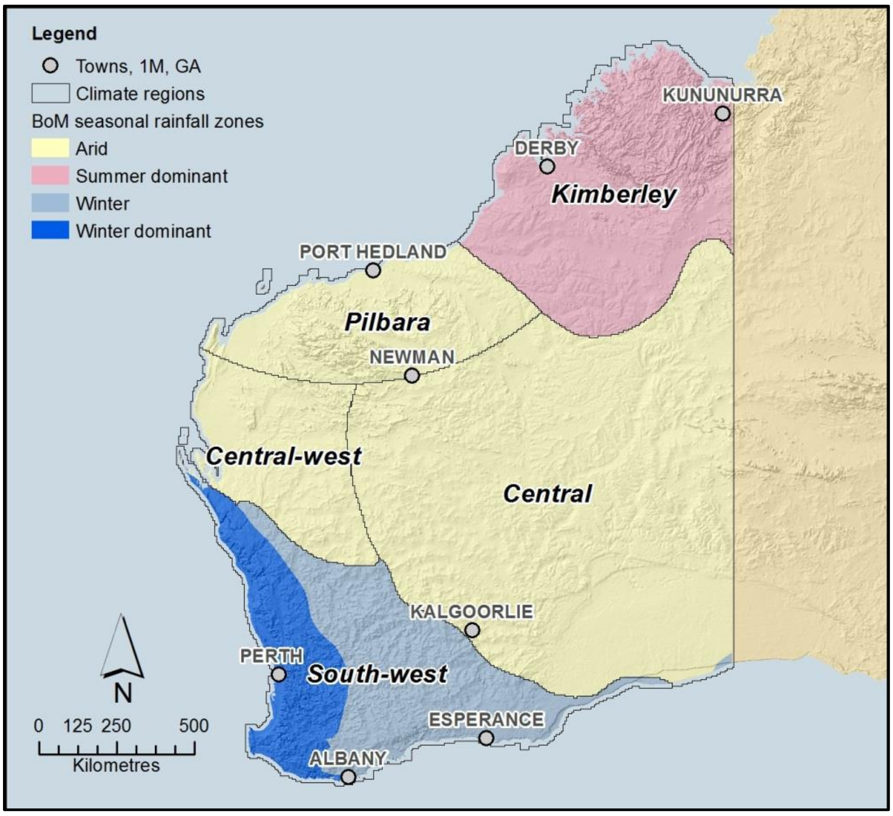


Figure 1-1: Seasonal rainfall zones of Australia (source BoM 1999) with the subdivisions used for this study

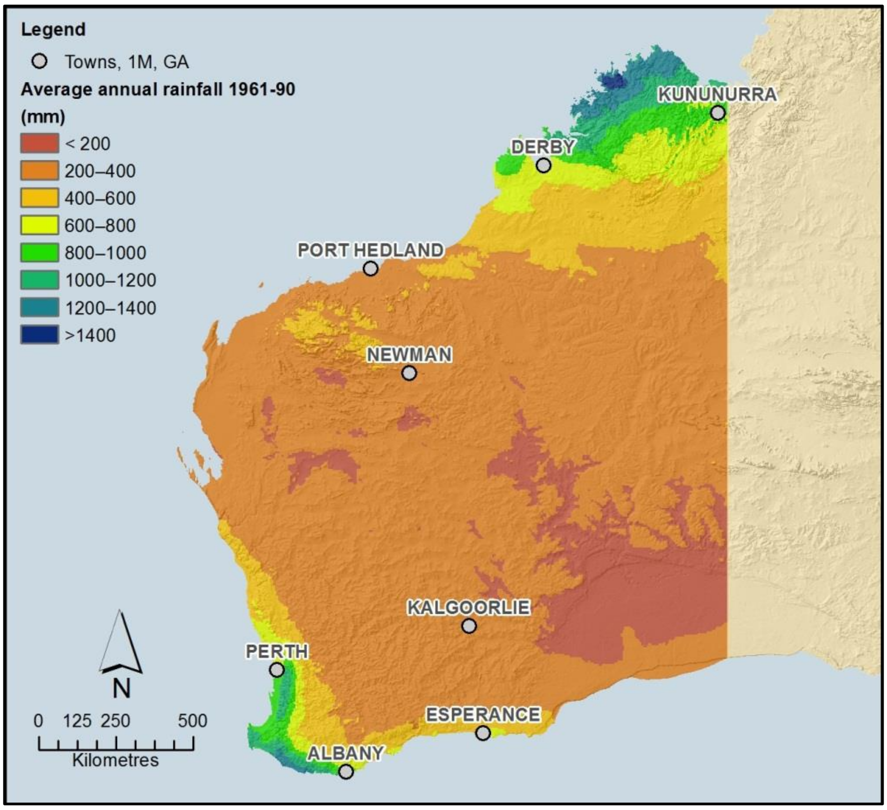


Figure 1-2: Average annual rainfall 1961–90 for Western Australia (source BoM 2013b)

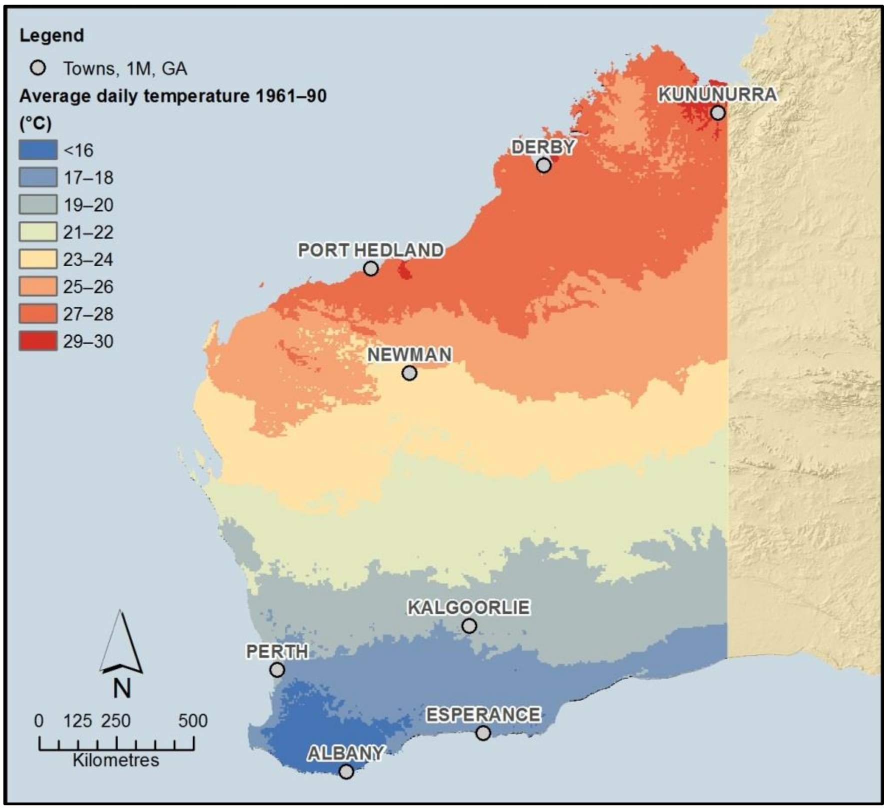


Figure 1-3: Average daily temperature 1961–90 for Western Australia (source BoM 2013b)

Climatic trends and influences

The Australian Bureau of Meteorology provides a summary of the important climatic influences throughout Australia (BoM 2010; Figure 1-4). Generally rainfall in the tropical and subtropical north is influenced by summer monsoonal and cyclone activity; the South-west is influenced by winter frontal systems, troughs and cut-off lows associated with westerlies; and the interior and Central-west are influenced by multiple weather systems, including north-west cloud bands. A brief discussion of the climatic influences and general characteristics of each region is included in the next section.

Statistical analyses of rainfall trends were completed for 32 meteorological stations throughout the state, with at least six stations in each region. The station locations are shown in Figure 1-5. Graphs of rainfall and temperature for all stations are shown in Appendix A. These graphs have different scales due to the wide variation in rainfall throughout the state. A 30-year backward mean is used to represent the trend, as it represents the 'average climate' which could be calculated for a given point in time based on the previous 30 years of data, which is typically the length of record used to calculate average climate conditions.

The student's T test was used to assess the differences in mean annual rainfall for 1961–90 and 1990–2010 relative to the historical period 1900–60. The percentage difference in mean annual rainfall is shown in Table 1-1. The non-parametric Mann-Kendall test was used to assess whether rainfall for 1950–2012 had a trend or not. For both tests, *p*-values of less than 0.1 were assumed significant. SILO patch point data (QDERM 2013) was used for analyses as the in-filled data provide extensive spatial and temporal coverage, and multiple climate variables are available at all stations.

For 1961–90, only two locations (Serpentine and Perth Airport) indicate a statistically significant difference in mean annual rainfall relative to 1900–60. For 1990–2010, 17 of the 32 stations have statistically significant changes in mean annual rainfall relative to 1900–60. Over the western portion of the South-west region, mean annual rainfall decreased in the second half of the 20th century. Over most of the remainder of the state, rainfall has increased, with the largest increases in the north-west and central parts of the state. The Mann-Kendall test indicated statistically-significant downward trends in the South-west, and upward trends over most of the North-west and Central regions.

The trends identified at individual stations are consistent with the gridded rainfall trends for 1950–2012 reported by BoM (2013a) and shown in Figure 1-6; and with the results reported in *Climate Change in Australia* (CSIRO & BoM 2007). Note the data inland is sparse (Figure 1-5) influencing the reliability of the gridded trends in some areas. *Climate change in Australia* highlighted that there is a marked contrast in temperature and rainfall trends between the first and second halves of the 20th century, with the period 1950–2006 defined by large and spatially coherent trends in total annual rainfall in contrast to more stationary climate during 1900–50.

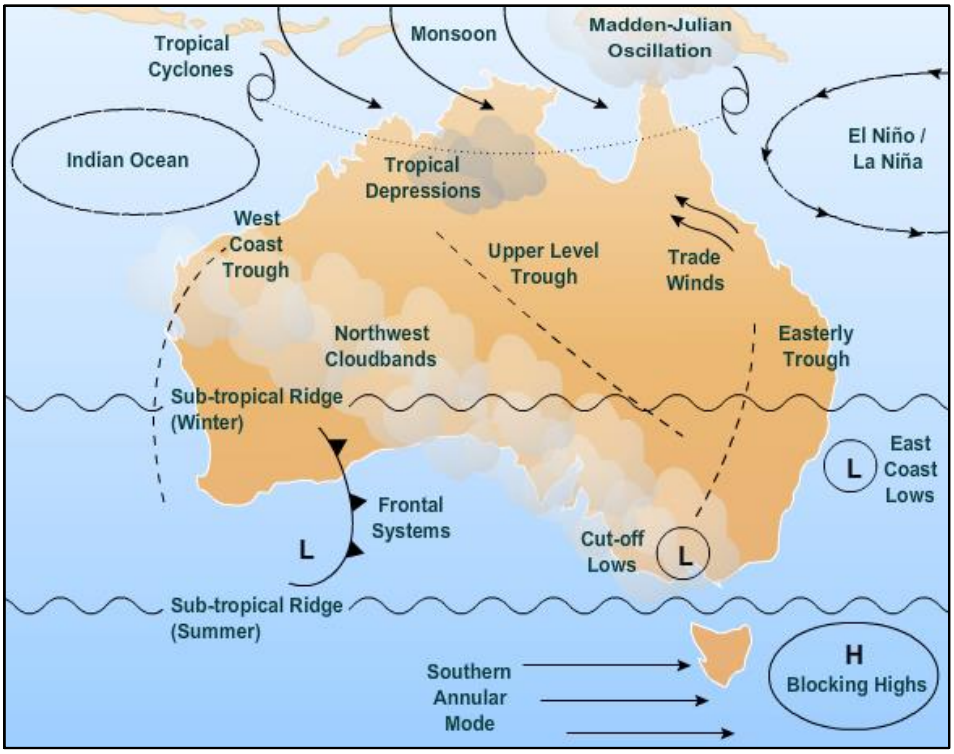


Figure 1-4: Australian climate influences (source BoM 2010)

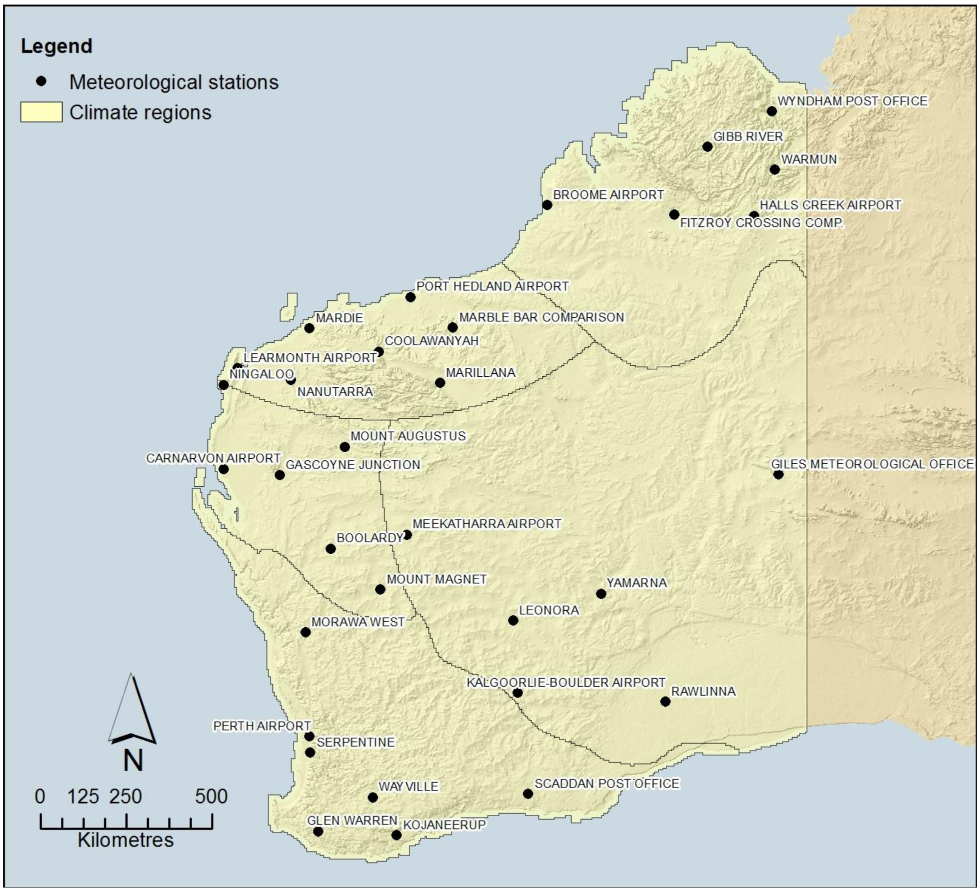


Figure 1-5: Meteorological stations used for analysis of trend and assessment of climate scenarios

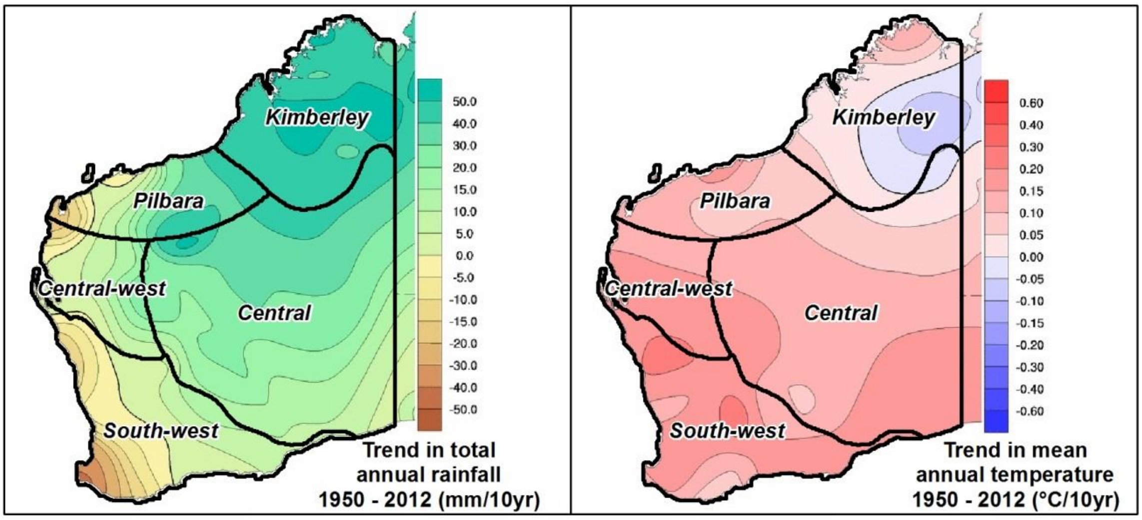


Figure 1-6: Trends in mean temperature and rainfall, 1950–2012 (source BoM 2013a)

Region	Station	Commence	Cease	T test p-value (1961-1990) & (1900-1960)	Change in mean annual rainfall (1961-1990) & (1900-1960)	T test p-value (1990-2010) & (1900-1960)	Change in mean annualrainfall (1990-2010) & (1900-1960)	Mann-Kendall significance level (1950-2012)	Trend
South West	Serpentine	31/12/1905	-	0.08	-7%	0.00	-19%	0.01	negative
	Perth Airport	30/04/1944	-	0.03	-9%	0.00	-16%	0.01	negative
	Morawa West	31/07/1912	1/01/1997	0.11	-9%	0.03	-14%	not sig.	negative
	Wayville	31/10/1938	31/05/2004	0.40	-4%	0.06	-10%	0.10	negative
	Glen Warren	31/12/1924	30/11/2003	0.16	-6%	0.01	-12%	0.10	negative
	Scaddan Post	31/12/1906	1/01/2000	0.62	-2%	0.54	4%	not sig.	positive
	Kojaneerup	30/04/1926	1/01/1998	0.45	-4%	0.99	0%	not sig.	positive
Pilbara	Mardie	31/03/1885	-	0.14	20%	0.18	22%	not sig.	neutral
	Learmonth Airport	31/03/1945	-	0.62	7%	0.71	-6%	not sig.	negative
	Nanutarra	30/09/1898	-	0.11	18%	0.34	13%	not sig.	positive
	Coolawanyah	31/12/1922	-	0.13	15%	0.00	39%	not sig.	positive
	Marillana	30/11/1936	-	0.31	12%	0.00	51%	0.01	positive
	Port Hedland	31/07/1942	-	0.53	7%	0.53	9%	not sig.	positive
	Marble Bar	31/07/1895	-	0.29	10%	0.01	33%	0.01	positive
Kimberley	Broome	31/07/1939	-	0.40	8%	0.01	31%	0.05	positive
	Fitzroy Crossing	28/02/1893	31/01/2000	0.32	7%	0.00	30%	0.01	positive
	Halls Creek	31/12/1943	-	0.35	8%	0.00	35%	0.01	positive
	Warmun	31/12/1897	-	0.54	-5%	0.00	30%	0.01	positive
	Gibb River	31/12/1921	-	0.69	2%	0.01	21%	0.05	positive
	Wyndham	31/03/1968	-	0.54	4%	0.00	33%	0.05	positive
Central	Meekatharra	31/05/1944	-	0.55	6%	0.12	20%	0.05	positive
	Giles	31/07/1956	-	na	na	na	na	0.05	positive
	Kalgoorlie	28/02/1939	-	0.23	9%	0.14	14%	0.05	positive
	Leonora	31/12/1897	-	0.53	7%	0.01	30%	0.05	positive
	Yamarna	30/11/1967	30/06/1998	0.16	18%	0.00	51%	0.05	positive
	Rawlinna	31/08/1915	30/04/2002	0.49	7%	0.01	30%	not sig.	positive
Central-west	Boolardy	31/12/1890	-	0.42	8%	0.11	18%	not sig.	positive
	Carnarvon	31/12/1944	-	0.67	4%	0.22	13%	not sig.	positive
	Gascoyne	31/03/1907	-	0.82	2%	0.20	16%	not sig.	positive
	Mt Augustus	31/07/1901	-	0.14	17%	0.35	13%	not sig.	positive
	Mt Magnet	31/12/1894	-	0.59	6%	0.14	18%	0.05	positive
	Ningaloo	30/09/1898	-	0.48	8%	0.92	-1%	not sig.	positive

significant at α=0.1

SILO patch point data used for analysis, for entries marked na dataset was insufficent to complete statistical analyses

Table 1-1: Station commence and cease dates; statistical significance of the difference in mean annual rainfall, 1900–60 compared with 1961–90 and 1990–2010; and statistical significance of Mann-Kendall test for trend, 1950–2012

Climatic trends and influences by region

South-west region

The South-west region has a Mediterranean-type climate with long, hot and dry summers, and cool, wet winters. Frontal systems, troughs and cut-off lows are the main rainfall mechanism from late autumn through to spring (Hope et al. 2014; Pook et al. 2014). Summer rainfall is generally associated with tropical cyclone activity which is infrequent and highly variable. Average annual rainfall varies from over 1000 mm on the south coast to less than 400 mm inland, with most rainfall in winter. Summer maximum temperatures average in the low–mid 30s, with winter maxima in the mid-teens (BoM 2008). Annual evaporation is between 1000 mm in the coastal areas of the South-west and 2400 mm inland.

The South-west region has experienced a widely reported decline in rainfall over the last several decades (CSIRO & BoM 2007; IPCC 2007b; CSIRO 2009a; Hope & Ganter 2010; IOCI 2012). The reduced rainfall is a result of weakened and less frequent frontal systems, attributed to large-scale changes in southern hemisphere circulation patterns resulting from changes in global heat distribution (Frederiksen et al. 2012). The trend in rainfall decline is expected to continue, based on the climate projections from GCM results analysed as part of the SWWASY project (CSIRO 2009a).

Figure 1-7 shows the long-term rainfall and temperature records at the Serpentine (9039) meteorological station, south of Perth. The decline in rainfall and the rise in average maximum temperature since the 1950s are apparent. The three lowest rainfall years on record were within the last 20 years and the average maximum daily temperatures for 2010 and 2011 were the two highest on record. Maximum temperature, which better reflects increases in daytime temperatures when most evaporation happens, was used to illustrate rising temperatures in the graphs below. Appendix A shows similar rainfall and temperature trends for other locations in the South-west though some locations along the south coast show no reduction in annual rainfall over the recent period, consistent with the BoM rainfall trend shown in Figure 1-6.

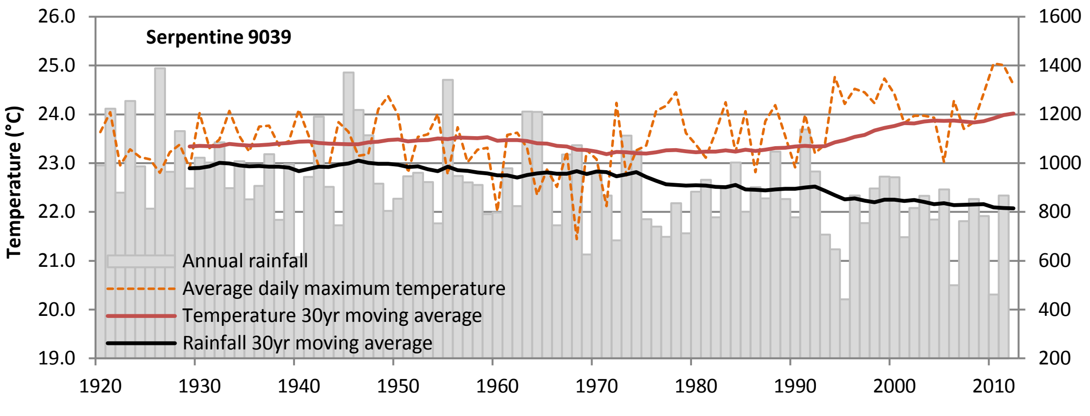


Figure 1-7: Annual rainfall and average daily maximum temperature, 1920–2012 for the Serpentine meteorological station (9039) in the South-west region

Central-west region

This region is a subdivision of the arid area identified in Figure 1-1. Much of the region receives low rainfall, with average annual rainfall of around 300 mm, summer maximum temperatures ranging 30–40 °C, and evaporation 2500–4000 mm per year. In the Central-west, winter fronts, troughs and cut-off lows are the dominant rainfall mechanism though, due to the closer proximity to the tropics, summer rainfall is more common compared with the South-west.

Six meteorological stations were analysed for rainfall trends in the Central-west (Table 1-1 and Appendix A), and none exhibits the drying trend observed in the South-west. The stations show no statistically significant changes in average annual rainfall for the recent (1990–2010) period in comparison with the 1900–60 record. The coastal station at Carnarvon (Figure 1-8) shows an upward trend in average maximum temperature but no trend in annual rainfall.

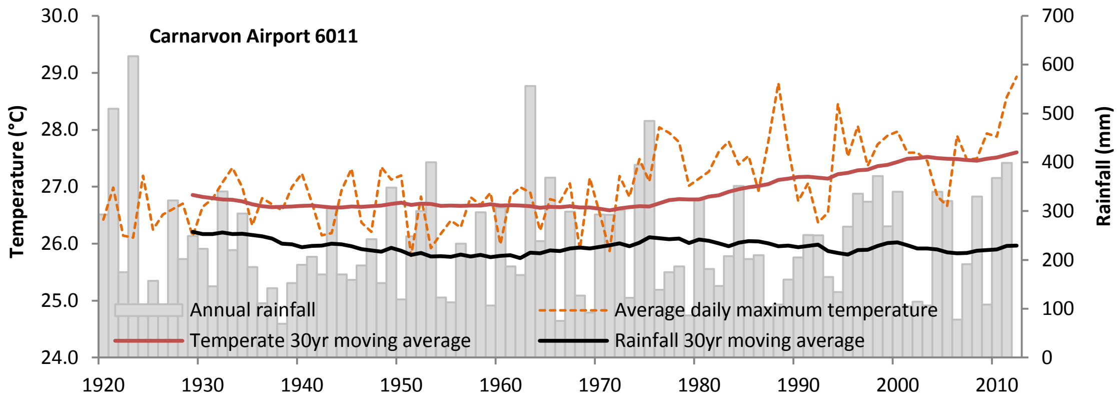


Figure 1-8: Annual rainfall and average daily maximum temperature, 1920–2012 for the Carnarvon Airport meteorological station (6011) in the Central-west region

Pilbara region

The Pilbara region is a subdivision of the arid region located in the subtropics. The region is characterised by dry winters and relatively wet summers, though summer rainfall is sporadic and variable, resulting from tropical cyclone activity. Average annual rainfall is relatively low (200–400 mm), and mostly falls in bursts of intense rainfall over summer (December–March). Summer maximum temperatures range 30–40 °C and annual evaporation varies between 2800 and 3800 mm.

The east of this region has experienced a recent increase in annual rainfall in some locations, as shown in Figure 1-6 and Appendix A. The Indian Ocean Climate Initiative 3 project (Charles et al. 2012) identified an increase in 'wetter weather states' across the region since the1960s. Figure 1-9 illustrates high inter-annual rainfall variability, and the upward trends in rainfall and temperature at Marillana. Similar rainfall trends are present at Port Hedland, Coolwanyah and Marble Bar but are absent or less pronounced at locations further west, for example, at Learmonth Airport (Figure 1-10). Rotstayn et al. (2012) theorised that the recent increases in rainfall could be attributed to increased aerosols derived from south-east Asia; however, this was assessed using only one GCM and was not conclusive.

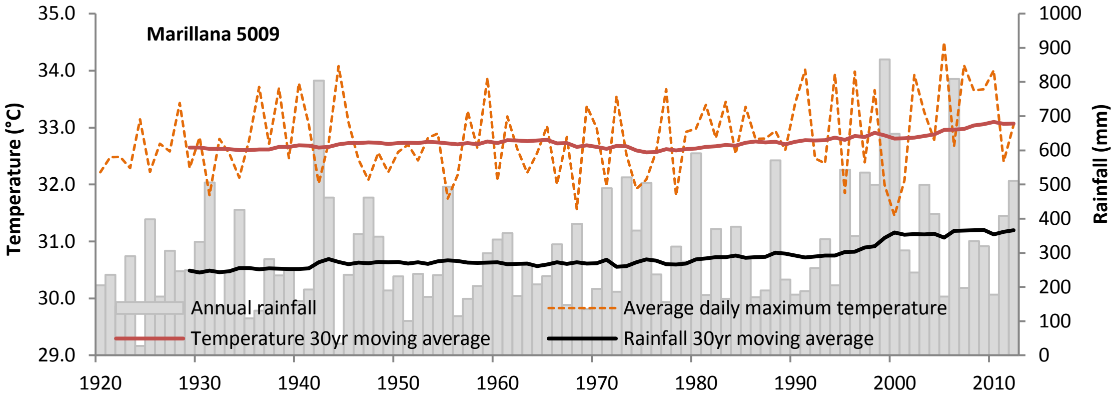


Figure 1-9: Annual rainfall and average daily maximum temperature, 1920–2012 for the Marillana meteorological station (5009) in the Pilbara region

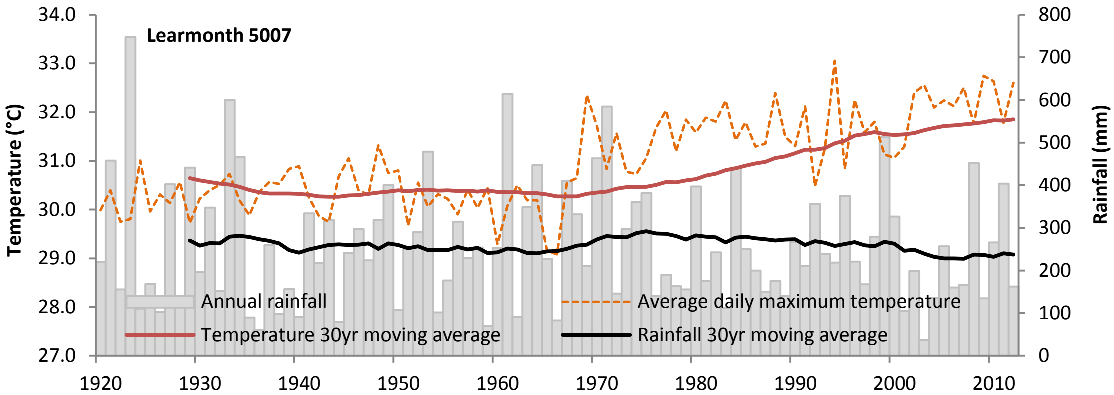


Figure 1-10: Annual rainfall and average daily maximum temperature, 1920–2012 for the Learmonth Airport meteorological station (5007) in Pilbara region

Kimberley region

The Kimberley region has a tropical monsoonal climate and covers the Western Australian portion of the summer dominant rainfall zone. Most of the rainfall in this region results from the summer monsoon season and tropical cyclones. The region has a steep rainfall gradient, with average annual rainfall of more than 2000 mm in the far north down to 400 mm in the interior.

As with the Pilbara, statistically significant rainfall trends have been observed throughout the Kimberley. Figure 1-11 shows increasing rainfall at Fitzroy Crossing but with no temperature trend. Similar trends are apparent at all assessed weather stations within the region (Appendix A & Figure 1-6). Analysis of weather patterns (atmospheric conditions) in this region indicate that the two wettest patterns have increased in frequency over the last 50 years (IOCI 2012). The *Northern Australia Sustainable Yields project* (Li et al. 2009) also demonstrated a statistically significant increase in annual rainfall for the recent period (1996–2007).

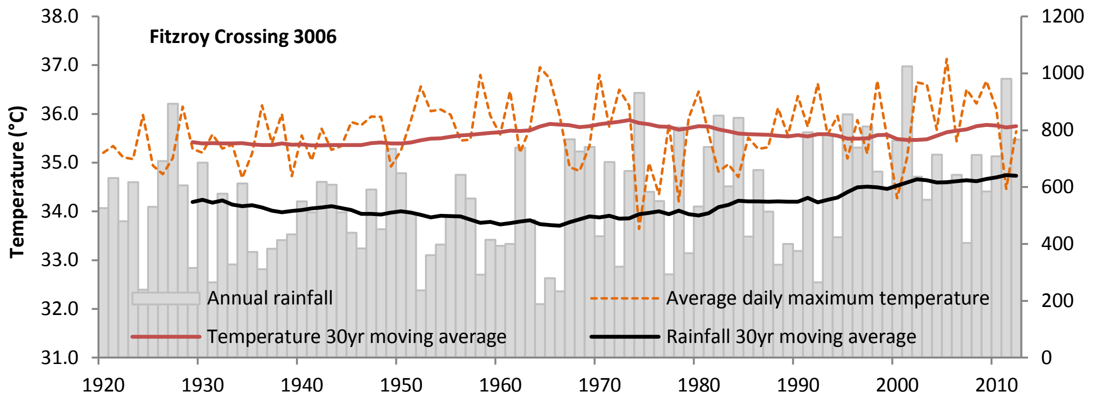


Figure 1-11: Annual rainfall and average daily maximum temperature, 1920–2012 for the Fitzroy Crossing meteorological station (3006) in Kimberley region

Central region

The Central region encompasses the remainder of the arid zone, with average annual rainfall generally less than 300 mm. This area is large and experiences multiple weather influences, including frontal systems in the south near Kalgoorlie, with rainfall from monsoonal and tropical cyclones more common in the northern half of the region. North-west cloud bands can also result in rainfall in late autumn and early winter (BoM 2008). Evaporation throughout the region is very high, averaging 3000–4000 mm per year. Maximum summer temperatures average 30–40 °C.

The historical rainfall record from Kalgoorlie (Figure 1-12) shows relatively small upward trends in rainfall and temperature. At other locations, for example Yamarna (Figure 1-13), large positive trends in rainfall are evident. In Yamarna rain falls predominantly in summer and autumn, and it is likely that trends in annual rainfall here are influenced by weather systems different from those in Kalgoorlie in the south-west of the Central region. The BoM trend maps (Figure 1-6) indicate general rises in temperature and rainfall across central Australia.

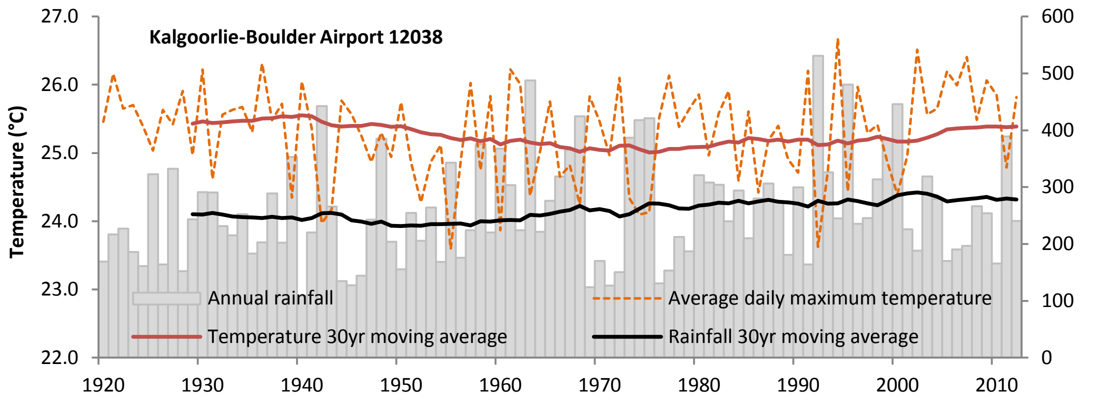


Figure 1-12: Annual rainfall and average daily maximum temperature, 1920–2012 for the Kalgoorlie meteorological station (12038) in the Central region

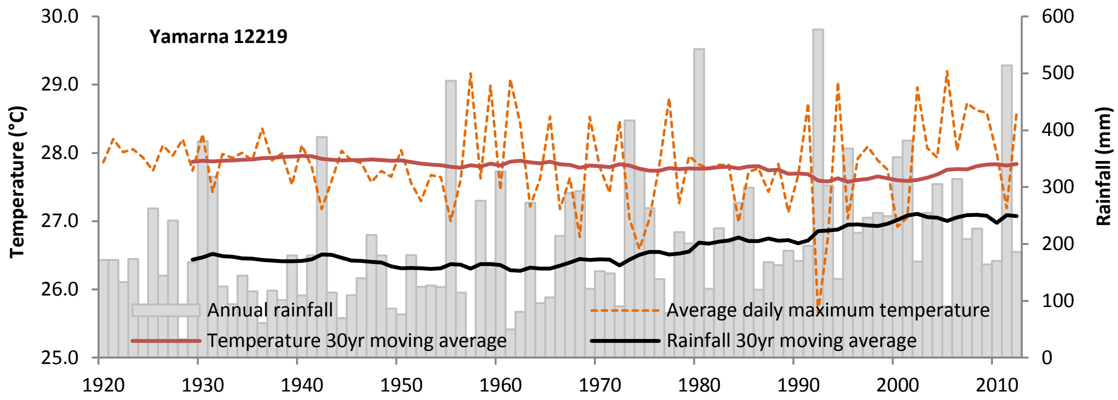


Figure 1-13: Annual rainfall and average daily maximum temperature, 1920–2012 for the Yamarna meteorological station (12219) in the Central region

1.3 The need for standard climate projections

Climate change will affect water availability in Western Australia, particularly in the South-west. To usefully inform estimates of future water availability and reduce uncertainty in climate projections, methods used for scenario development, modelling and impact assessment need to be systematic and recognise the likely future climates in different parts of the state. Many recent groundwater and surface water studies completed by the department have considered climate change. However, the approach to defining the future climate has varied between studies. Depending on the choice of baseline period, emissions scenario, general circulation model and time horizon selected, it is possible to draw quite different conclusions about the impacts of climate change. Many locations in WA have no climate projections developed for local-scale hydrological modelling or analysed for their applicability to water resource management.

Inconsistencies in climate projections between studies

Some recent department publications that considered the potential consequences of climate change on water resources, both surface water and groundwater, are listed in Table 1-2. The table illustrates the various methods used to develop climate scenarios for the south-west of WA. Generally, surface water assessments have utilised project specific statistically downscaled climate data provided by CSIRO, sometimes for only one general circulation model and emissions scenario. The scenarios developed by CSIRO for the SWWASY project have also frequently been used for surface water studies and integrated groundwater and surface water modelling. Groundwater modelling has typically taken a simpler approach to climate scenarios, using either historical dry or wet periods of record or annual scaling techniques to adjust rainfall or recharge. In other studies, the ensemble mean results reported for *Climate Change in Australia* (CSIRO & BoM 2007) have been used in annual or seasonal scaling.

In an internal discussion paper (DoW 2012), the issue of choice of baseline was identified as causing confusion amongst different management plans – for example the Perth-Peel Regional Water Plan Background Paper (DoW 2009) said:

> *"The Perth-Peel 15 per cent decline scenario is equivalent to the Gnangara Sustainability Strategy 'dry' climate scenario of an 11 per cent decrease in the 1976–2006 rainfall, since the 30-year-rainfall average is 4 per cent drier than the 20-year-rainfall average (1980–1999)".*

This illustrates how helpful it would be to use consistent baseline periods since different baseline periods result in different relative changes.

Table 1-2: Different approaches used to define climate scenarios for selected departmental studies

Author & year	Study	Baseline	GCM	Scenario	Downscaling	Source
Bari et al. 2005	Modelling of streamflow reduction due to climate change in Western Australia – A case study	1975–2004	CSIRO Mk3	A2	Statistical	CSIRO, project specific
Kitsios et al. 2009	Projected impacts of climate change on the Serpentine catchment Downscaling from multiple General Circulation Models	1960–89 1975–2004	CSIRO Mk3 CCAM HadAM3P ECHAM4	A2	Dynamic Statistical	CSIRO, project specific
DoW 2009a	Climate change, water demand and water availability scenarios to 2030 Perth-Peel regional water plan background paper	1980–1999	Ensemble	Ensemble	Annual scaling	Climate Change in Australia 2007
De Silva 2009	PRAMS scenario modelling for the Gnangara Sustainability Strategy	1976–2006	n/a	n/a	n/a	Historic data
Smith et al. 2009	The impact of climate change on rainfall and streamflow in the Denmark River catchment, Western Australia	1975–2006	CSIRO Mk3.5	A2 A1B B1	Statistical	CSIRO, project specific
Varma 2009	Southern Perth Basin groundwater-resource assessment: Application of SWAMS and ESCP Models	1971–2003	n/a	n/a	Annual scaling	IOCI 2001 Whetton 2002
CSIRO 2009	Surface water yields in south-west Western Australia	1975–2007	Multiple	0.7 °C 1.0 °C 1.3 °C increase	Monthly & daily percentile scaling	Original
Boniecka 2010	The effects of climate change on streamflow in south-west Western Australia Projections for 2050	1975–2004	CSIRO Mk3.5	A2	Statistical	CSIRO, project specific
Marillier 2010	WaterCAST nutrient modelling of the Leschenault catchment	1998–2007	CSIRO Mk3 CSIRO Mk3.5	A2 B1	Statistical Monthly scaling	Cleary 2008
Hall et al. 2010	Murray hydrological studies: surface water, groundwater and environmental water	1975–2007	MRI NCAR PCM	+0.7 °C +1.0 °C +1.3 °C	Monthly & daily percentile scaling	CSIRO 2009

Availability and accessibility of climate projections

Climate Change in Australia (CSIRO & BoM 2007), the SWWASY (CSIRO 2009a) and the *Northern Australia Sustainable Yields* (Li et al. 2009) projects are three high-profile studies that have analysed the results of climate modelling released with the IPCC's AR4 report (IPCC 2007a). These studies provide information about the potential effects of climate change in WA but the climate projections provided have limited use for modelling applications at the Department of Water.

Climate Change in Australia provides Australia-wide information on observed climate change and its likely causes, and projections of future climate change and sea level rise. Gridded climate projection datasets are available for temperature and rainfall for various seasons, emissions scenarios and time horizons. To generate the climate projections, results from multiple GCMs were combined, and the 10^{th}, 50^{th} and 90^{th} percentile changes in temperature and rainfall were calculated from the combined results. Using this method, it is possible to identify the likely range of climate variability projected by the many different GCMs and emissions scenarios. However, when modelling with climate scenarios at a local scale, there is a limitation to this method. By combining results from multiple GCMs, it is possible to generate variable sets that are no longer internally consistent, and are therefore not appropriate in hydrological modelling. For this reason Hennessy et al. (2012) commented that the methods used in *Climate Change in Australia* are suitable for general communication, but may be unsuitable for detailed risk assessments involving multiple variables. The recommendation is that a single GCM is used to simulate climate anomalies so that correlation between variables is accounted for.

The SWWASY project (CSIRO 2009a; CSIRO 2009b; Charles et al. 2010) developed scenarios to assess the potential influences of climate change on surface water and groundwater availability in south-west WA. The scenarios are for the year 2030, relative to the historical period 1975–2007. The methods used addressed the limitations of *Climate Change in Australia* in that wet, median and dry scenarios based on a single GCM were identified by considering the range of climate variables projected by 15 GCMs. The GCMs were selected based on availability of daily data rather than those that performed best for WA. The project provided climate time-series datasets for 0.05° grid-cells throughout the study area for rainfall, temperature, relative humidity and solar radiation, as well as derived Morton's wet areal evapotranspiration. The time-series were used in groundwater and surface water modelling to calculate changes in yield.

The SWWASY datasets are appropriate for use at the local scale but the SWWASY project only provides climate scenarios for a small part of the south-west, the fresh water resources (Figure 1-14). The department also assesses water resources outside these areas for a range of purposes, such as land-use planning and fit-for-purpose water. The *Northern Australia Sustainable Yields Project* (Li et al. 2009) and upcoming *Pilbara Water Resource Assessment* (CSIRO in prep.) provide some additional coverage. However, for much of WA there are no climate projections available for use in hydrological modelling or analysed for their applicability to water resource management. In addition, these projects produced

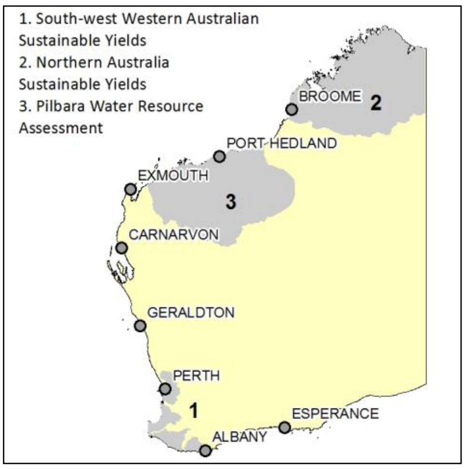


Figure 1-14: Spatial extent of the South-west, northern and Pilbara climate projection datasets

climate projections for a time horizon of 2030 (and 2050 for the Pilbara assessment), so it is not possible to model the impacts of climate change for the middle and latter half of the 21st century which is required for long-term water supply planning.

1.4 Project scope

A comprehensive set of standard climate projections for modelling of climate change in WA was developed to:

- Ensure consistency in the application of climate within the Department of Water.
- Incorporate the most recent climate science and recommendations from leading climate research organisations as they are updated.
- Capture uncertainty and variability in climate predictions.
- Present climate advice in a user-friendly and readily accessible and applicable manner.
- Provide a method for making scientifically rigorous and defensible planning decisions.

This project builds on existing policy and research, and provides a platform to develop future departmental policy and guidance.

This report addresses five issues related to selecting a consistent and comprehensive set of climate scenarios for WA: selection of emissions scenarios; selection of GCMs for application to WA; selection of a standard climate baseline period; capturing uncertainty; and provision of climate datasets and advice.

1.5 Project outputs

The climate scenarios are reported as anomalies – the average change in a variable for a future period compared to the baseline period. Standard monthly climate anomalies were developed at a 0.05° grid cell resolution for the following variables, scenarios, time horizons, and regions:

- **Regions:** South-west, Central-west, Pilbara, Kimberley, Central.
- **Variables:** Rainfall, temperature, relative humidity, radiation, FAO56 reference potential evapotranspiration (derived), Penman evaporation (derived).
- **Scenarios:** Wet, median, dry.
- **Time horizons:** 2030, 2050, 2070, 2100.

Gridded datasets are available in ESRI grid format, but can be converted to other formats as required.

1.6 National projects

Climate science is continually developing, and the draft IPCC 5th assessment report was recently released (IPCC 2013). The report updates the climate science and the technical and socio-economic components of climate change. New general circulation model results are already available in the Coupled Model Intercomparison Project 5 (CMIP5) archives, and results from many of these models have been analysed and published.

The CSIRO and BoM have recently finalised a project to analyse the next generation of climate modelling and “provide projections at varying levels of complexity and in various formats to support NRM requirements” (CSIRO 2012). The project – *Climate Change Projections for Australia’s regional NRM regions* (CSIRO 2012) – is based on the CMIP5 model runs and IPCC 5th assessment report (IPCC 2013). The report associated with this work has recently been released (CSIRO & BoM 2015) and it discusses the latest global emission scenarios and their influence on Australian climate. As the datasets associated with this work become available the department will review and may revise the scenarios developed here for Western Australia.

2 Selection of emissions scenarios, general circulation models, baseline and downscaling method

There are four main considerations in generating climate scenarios for rainfall, temperature and potential evapotranspiration (PET): selection of emissions scenarios, GCMs, climate baseline period and downscaling method.

1. The emissions scenarios that best describe global CO_2 production for the 21st century must be used. The Special Report on Emission Scenarios (SRES) produced by the IPCC (IPCC 2000) lists six potential emissions scenarios that describe possible global CO_2 production ‘storylines’. Originally these six scenarios were considered to be equally likely; more recent publications indicate that the fossil fuel emissions growth rate over the last decade is higher than for the most fossil-fuel intensive scenarios (Raupach et al. 2007).
2. It is important to use the GCMs that perform well at reproducing observed behaviour in the WA’s climate system. Climate projections reported in the IPCC AR4 report (IPCC 2007a) were based on results from 23 different general circulation models (GCMs) maintained by various research institutions. The GCM results are freely available through the Coupled Model Intercomparison Project 3 archives (CMIP3). Results from the models vary so the most appropriate models should be used in selecting climate scenarios.
3. A climate scenario must adopt a suitable reference baseline period: a period which serves as the base on which the datasets that represent climate change are constructed (IPCC 2007a). The baseline period is selected to ensure adequate variability of climate within the period, the availability of historical data, and to avoid the presence of major trends in climate within the baseline period.
4. A downscaling method is selected to relate the modelled future climate at a global scale to changes in local scale phenomena, by scaling of a baseline dataset.

The following sections describe the selection process for SRES scenarios, GCMs, the climate baseline for use in WA and the downscaling method used.

2.1 Emissions scenarios

Four SRES scenarios (A1FI, A2, A1B, B2) that describe future potential global CO_2 production have been selected. A moderate level of climate sensitivity is used to calculate the degree of global warming associated with each emissions scenario (IPCC 2000).

The SRES (IPCC 2000) described six emissions scenarios that explore various development pathways. Each pathway considers demographic, economic and technological driving forces resulting in greenhouse gas emissions. The projected emissions outlined by the SRES scenarios are used to force GCMs, and develop climate projections for the next century.

The IPCC AR4 synthesis report (IPCC 2007a) summarises the SRES scenarios:

- *The A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. A1 is divided into three groups that describe alternative directions of technological change:*
    - *fossil intensive (A1FI)*
    - *non-fossil energy resources (A1T)*
    - *a balance across all sources (A1B).*
- *B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy.*
- *B2 describes a world with intermediate population and economic growth, emphasising local solutions to economic, social, and environmental sustainability.*
- *A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change.*

Projected global warming is influenced by both the emissions released into the atmosphere (and therefore the choice in SRES scenario), and the sensitivity of the climate system to the elevated emissions.

Climate sensitivity is a measure of the climate response to sustained radiative forcing (IPCC 2007a). Feedback cycles can amplify or dampen the response to the forcing, for example, through changes in water vapour, cloud formation and albedo. How the choice in emissions scenario and climate sensitivity influence global surface warming is illustrated in Figure 2-1. The solid lines illustrate surface warming for each emissions scenario with median climate sensitivity, and the dashed lines show the possible range of warming for each scenario based on high and low climate sensitivity. The range in climate sensitivity is determined by considering the output of multiple climate models for the different emissions scenarios. The department adopted a moderate level of climate sensitivity (the solid lines in Figure 2-1) to calculate the global warming associated with each emissions scenario.

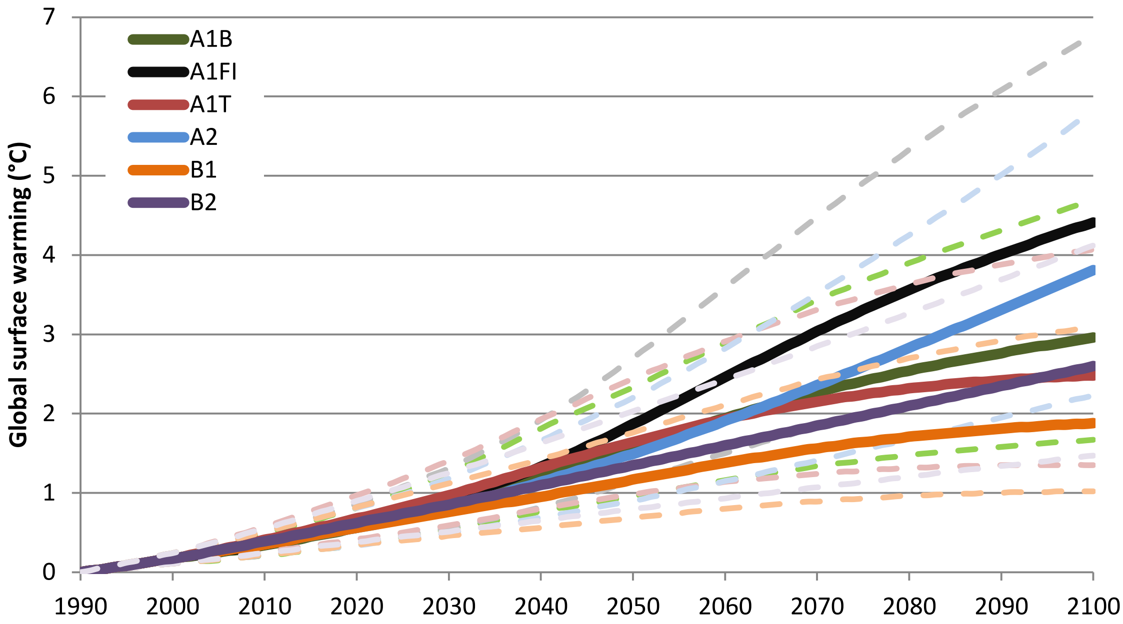


Figure 2-1: Global surface warming for the six SRES scenarios. Warming is relative to 1961–1990. Data sourced from SimCLIM (2012). Solid lines show median sensitivity and dashed lines show low and high sensitivity range.

At the time of publication of the *Special Report on Emissions* (IPCC 2000), no likelihood was attributed to any of the emissions scenarios. Recent studies have examined our current trajectory in relation to greenhouse gas emissions. Raupach et al. (2007) assessed the growth rate in CO_2 emissions from fossil-fuel burning and industry between 1990–99 and 2000–04, and found it to be higher than for any of the SRES scenarios developed by the IPCC, and that no region is decarbonising its energy supply. Le Quéré (2009) identified a 29% increase in fossil fuel emissions between 2000 and 2008. It is impossible to know whether this trend will continue later in the century, but it is reflective of recent global efforts to control emissions.

Atmospheric CO_2 concentration is monitored by the NOAA earth system research laboratory at the Mauna Loa Observatory in Hawaii. Observations from 1958 onwards are available and these are compared with the atmospheric CO_2 concentration projected by several SRES scenarios from 1990 onwards (Figure 2-2). The graph shows that the current concentration is consistent with the emissions scenarios identified by the IPCC. Although the various emissions scenarios do not diverge significantly until the latter half of the century, the data shows the ongoing increase in CO_2 concentration and that the mean growth rate in CO_2 has also increased since observations began (Figure 2-3).

Based on the current trajectory of emissions growth, it is appropriate to remove the A1T and the B1 scenarios from further analysis. The remaining four SRES scenarios (B2, A1B, A2, A1FI) capture a large range of potential global warming, sufficient to account for the uncertainty associated with the emissions scenarios.

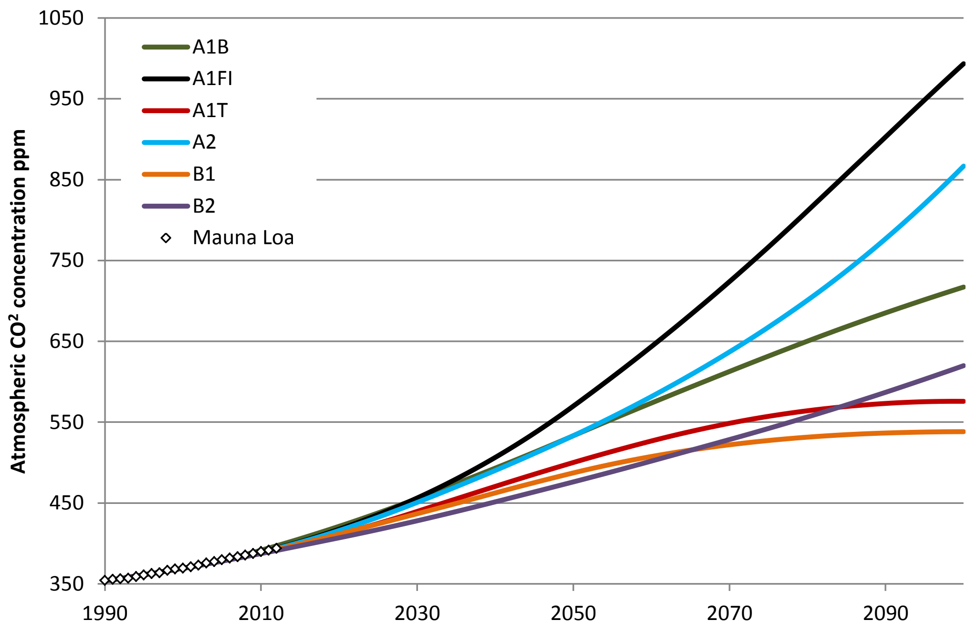


Figure 2-2: Atmospheric CO_2 concentrations at Mauna Loa and projected emissions for SRES scenarios 1990–2100 (sources NOAA/ESRL 2013 and SimCLIM 2012)

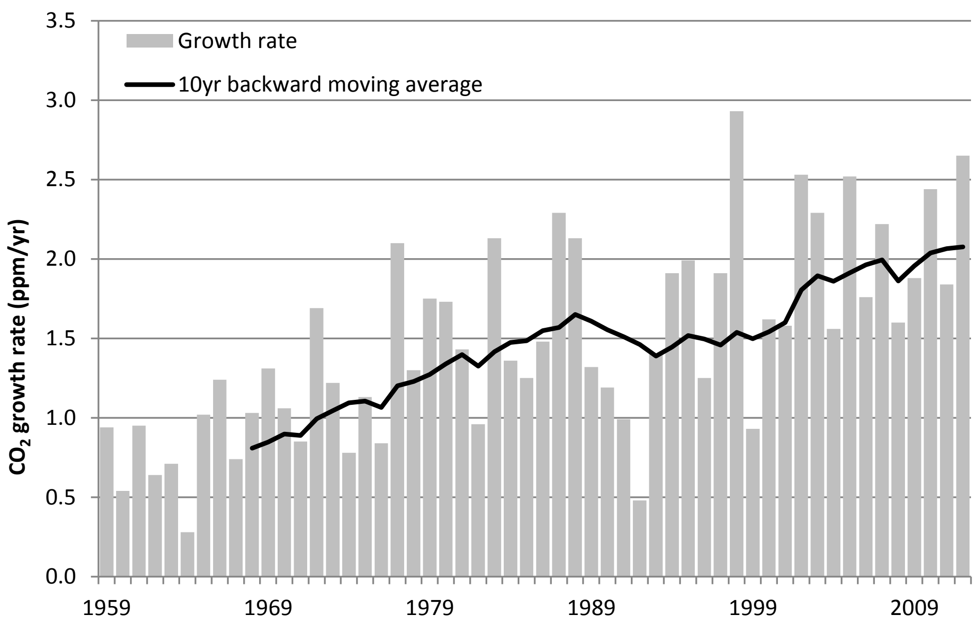


Figure 2-3: Annual mean CO_2 growth rate measured at Mauna Loa (source NOAA/ESRL 2013)

2.2 General circulation models (GCMs)

Results from 23 GCMs (IPCC 2007a) were assessed. Each model responds differently to the emissions scenarios, creating a range of potential climates. A sufficient range in GCMs should be included to account for the uncertainty in climate projections, but it is reasonable to exclude GCMs which do not perform well in the region of interest.

The twelve GCMs that perform well at reproducing observed behaviour in the climate system for WA have been selected and eleven GCMs that reproduced observed climatic conditions poorly were eliminated from further analysis. This also leaves a reasonable number of GCMs and emissions scenarios to use in water resource projects.

Some studies have selected GCMs based on data availability in the CMIP3 archives. For example, the SWWASY (Charles et al. 2010) required GCM reporting at a daily timestep in order to complete daily scaling, and this meant including many of the GCMs which exhibit low skill and excluding some of the best performing models. The South Australian Department for Water used a local analysis of skill (Suppiah et al. 2006) to exclude certain GCMs, and also required that the GCMs reported PET as a standard output (Gibbs et al. 2011). This resulted in only four GCMs being used in their final analysis, which could be considered too few to capture uncertainty in the climate projections. As this study uses simple monthly scaling (see section 2.4), and derives PET anomalies from other variables, it is possible to use some GCMs which demonstrate better than average skill.

The GCMs were selected for WA using published information about their ‘skill’. GCM ‘skill’ is a measure of a particular model’s ability to reproduce observed behaviour in the climate system. It can be reported using various metrics. Commonly, observed data for a historical period are compared with modelled data for the same period to report pattern correlation, where the spatial patterns of temperature, mean sea level pressure or some other variable are compared to measure the closeness of fit. Smith and Chiew (2009) produced a summary of eleven studies which measure GCM skill at regional, national and/or global scale. Of these, two national level studies were selected for assessment in this study: Suppiah et al. (2007) and Watterson (2008). Two additional studies by Chiew et al. (2009a) and Frederickson et al. (2012) were added to the assessment as they included data specific to WA. A description of each study and measure of skill for the GCMs follows:

- **Chiew et al. (2009a)** calculated the root mean square (RMS) error and difference in coefficient of variation (CV) for observed and modelled rainfall for the period 1961–2000. Results were calculated for south-western, northern, and south-eastern Australia. For this study, the RMS error and difference in coefficient of variation for south-western and northern Australia were considered. A lower RMS error and smaller difference in CV implies better model performance.
- **Suppiah et al. (2007)** assessed how well each of the 23 GCMs reproduced average (1961–90) patterns of mean sea level pressure, temperature and rainfall over the Australian region. The measure reported is ‘demerit points’ where 1 demerit point is assigned where pattern correlation is less than 0.8 in any season, and an additional demerit point is added for any model with a root mean square (RMS) error greater

than four, or pattern correlation below 0.6. A score of less than 8 was considered acceptable.

- **Watterson (2008)** used the ‘M statistic’ to report the ability of GCMs to reproduce the observed climate (1961–90) across three climatological fields: temperature, sea level pressure and rainfall. This measure of skill was used in weighting model results in *Climate Change in Australia* (CSIRO 2007). A higher M statistic implies better model performance.
- **Frederiksen et al. (2012)** identified that changes in large-scale circulation in the southern hemisphere has resulted in the observed decline in rainfall in south-west WA. Wind speeds of the subtropical jetstream over the southern Indian Ocean influence the potential energy available for storm formation, and the observed reduction in wind speed between 1949–68 and 1975–94 was identified as a likely cause of reduced storm formation for the latter period. The linear trend in atmospheric stability between 1948 and 2006 was reported to be highly statistically significant (*p*-value of 0.05). The authors assessed the ability of GCMs to reproduce the trend in atmospheric stability, and reported this in the metric ‘anomaly pattern correlation’ (APC), where 1 indicates a perfect match between modelled and observed atmospheric instability, and –1 indicates a perfect mismatch. This metric is useful in the south of the state.

To select the GCMs to include in this study, a standardised score was produced, giving even weight to each of the four studies. Generally, GCMs which achieve better scores for one metric performed better across all the metrics. The GCMs were ranked according to overall performance. The GCM ranking and skill metrics for individual studies are shown in Table 2-1.

The top 12 GCMs were selected and the bottom 11 GCMs were eliminated from further analysis. Of the 12 selected GCMs, nine achieved a positive anomaly pattern correlation (an important measure of GCM skill for the south-west as it is related to trends in storm formation in the region) compared with a simple comparison of rainfall or mean sea level pressure. Twelve GCMs were considered a usable number for use in water resource modelling while still encompassing the range in uncertainty in climate projections.

Table 2-1: GCM rankings and skill scores. For Anomaly Pattern Correlation (APC), the average of the best two scores was used.

GCM	RMSE of mean south-west WA rainfall (mm)[1]	RMSE of mean northern Australian rainfall (mm)[1]	Difference in CV of rainfall for south-west WA[1]	Difference in CV of rainfall for northern Australia[1]	Demerit points[2]	M-statistic[3]	APC[4]	Rank
CCSM--30	155	263	0.00	0.14	2	677	0.66	1
UKHADGEM	138	201	0.08	0.00	2	674	0.46	2
FGOALS1G	142	308	0.09	0.10	2	639	0.51	3
MIROC-HI	104	327	0.01	0.08	7	608	0.52	4
MPIECH-5	231	329	0.01	0.12	1	700	–0.24	5
MIROCMED	127	413	0.06	0.14	7	608	0.62	6
ECHO--G	246	290	0.06	0.19	4	632	0.37	7
MRI-232A	386	378	0.02	0.12	3	601	0.44	8
BCCRBCM2	127	811	0.00	0.14	5	590	0.41	9
GFDLCM21	182	320	0.16	0.09	2	672	–0.36	10
GISS--ER	86	444	0.08	0.19	8	515	0.71	11
GFDLCM20	199	255	0.10	0.19	4	671	–0.22	12
CCCMA T47	117	401	0.00	0.00	8	518	0.26	13
CSIRO-30	185	302	0.08	0.01	7	601	–0.03	14
UKHADCM3	241	296	0.10	0.01	6	608	–0.18	15
CSIRO-35	298	284	0.22	0.14	-	-	0.26	16
CCCMA T63	101	382	0.01	0.02	10	478	0.37	17
CNRM-CM3	165	416	0.09	0.06	4	542	–0.24	18
NCARPCM1	192	474	0.03	0.11	11	506	0.37	19
GISS-AOM	183	612	0.05	0.03	8	564	–0.16	20
INMCM-30	265	438	0.16	0.05	7	627	–0.31	21
IPSL_CM4	282	660	0.14	0.18	14	505	0.31	22
GISS--EH	124	954	0.10	0.21	14	304	-	23

GCM included in analysis
GCM excluded from analysis

1) Chiew et al. (2009a), 2) Suppiah et al. (2007), 3) Watterson (2008), 4) Frederiksen et al. (2012)

2.3 Climate historical baseline period

Given the size of WA, it is difficult to select a single baseline period which satisfies all criteria and is suitable for all locations. Consideration was given to previous climate change studies and the variability and trend of the rainfall records at various locations in the state (Table 1-1). The World Meteorological Organisation (WMO) normal period of 1961–90 was selected as the most suitable baseline period for WA. This period captures significant dry and wet years in most locations within the state, but excludes the more recent period where the South-west has been significantly drier and parts of the North-west have been significantly wetter (as discussed in section 1.2). This baseline is recent enough to include a large amount of observational data across the state. A 30-year baseline period is an appropriate length of record for use in computationally intensive modelling (for example, integrated surface water and groundwater models).

The baseline period is the historical period relative to which future climate projections are made. The baseline period is used in two ways, to:

1. calculate local-scale climate anomalies from global scale GCM results (anomalies are the average changes in a variable for a future period compared to the baseline period; see section 2.4)
2. construct the climate scenarios by scaling the baseline dataset using the calculated climate anomalies (see chapter 4).

The baseline period of 1961–90 was selected for WA with consideration of the following:

- stationarity in rainfall
- consistency with baseline periods used in other studies
- sufficient variability within the period
- the availability of measured climate variables for that period.

The IPCC (2001a) recommended that there should be no significant trend in climatic variables during the baseline period. This is difficult to achieve using a single baseline across all of WA. In the South-west there was an observable trend in rainfall during most of the last century (see Section 1), and it is impossible to select a baseline that includes a period of stationary rainfall and an adequate historical rainfall record.

Trends in rainfall have been identified throughout WA over various time periods during the last century. In the South-west, reduced rainfall between (1949–68) and (1975–94) is linked to reduced storm formation over the Indian Ocean (Frederiksen et al. 2012). In northern Australia, Li et al. (2009) identified a statistically significant wetting by comparing a recent period (1996–2007) with a historical period (1930–96), with a *p*-value of less than 0.01 for most of study area. The IOCI technical synthesis report identified a marked increase in total rainfall in north-west WA since 1950 (IOCI 2012).

Trend analyses for climatic sites across WA are shown in Table 1-1. There are two locations with a statistically significant difference in mean annual rainfall for 1961–90 relative to 1900–60. For 1990–2010, 17 of 32 stations have a statistically significant change in mean annual rainfall relative to 1900-60. The long-term rainfall records at various locations throughout the state are shown in Appendix A, with most sites fairly stable during 1961–90. Despite a change in climate in 1975, the trend in the recent period is still stronger than that observed in the 1961–90 period.

Various baselines have been used in previous studies, depending on the intended purpose of the climate analysis, and the local variability in climate. The IPCC commonly report climate and sea level projections relative to a 1980–99 baseline (IPCC 2007a). They also provide some guidelines for baseline period selection; in particular, to use a period that represents '*present-day or recent average climate in the study region and of a sufficient duration to encompass a range of climatic variations, including several significant weather anomalies'* (IPCC 2001b). The World Meteorological Organisation (WMO) normal period of 1961–1990 is frequently used in climate impact studies (IPCC 2001b). The SRES emissions scenarios are projected from 1990. If a later baseline period is selected then a degree of warming is already seen in the observed data.

Within Australia, various baselines have been used in previous climate change studies. Chiew et al. (2009b) recommend that the entire record of historical climate records (1895–2008) should be considered when selecting a baseline. Availability of measured climate anomalies is an issue for the longer-term period as there were few meteorological stations in the early 1900s in WA. In *Climate Change in Australia* (CSIRO & BoM 2007) the IPCC 1980–99 period was adopted, and all projections were reported relative to this period. In the SWWASY project (CSIRO 2009a), a baseline period 1975–2007 was adopted in order to exclude the pre-1970s period which was wetter relative to the recent climate of the South-west. In South Australia, the Department for Water (2011) adopted a 50 year baseline from 1961–2010 to capture more variability in the record. The *Northern Australia sustainable yields project* (Li et al. 2009) used a baseline of 77 years from 1930 to 2007.

2.4 Downscaling methodology

A variety of methods can be used to downscale the outputs of GCMs from a global resolution to those suitable for local analysis. These include dynamical downscaling, statistical downscaling and constant scaling. There are advantages and disadvantages for all three methods (Table 2-2). Constant scaling has been selected for this study.

- Dynamical downscaling involves the use of a regional climate model (RCM) to increase the spatial resolution of the outputs. The RCM is driven by the boundary conditions of the GCM to derive smaller-scale information.
- Statistical downscaling involves creating relationships between the large-scale climate variables (predictors) to the regional and local variables (predictands). Various techniques are used in statistical downscaling including regression, weather typing, and stochastic weather generators.
- Simple scaling methods such as constant scaling, daily scaling and daily translation method are also used. Constant scaling is also referred to as the delta or perturbation method (Mpelasoka and Chiew 2009) or the use of change factors (Fowler et al. 2007). It involves the scaling of daily or monthly rainfall by a constant factor – the ratio of future to historical GCM rainfall.

Constant monthly scaling has been used in this study and involves applying a different scaling factor to each month of the year, for each climate variable. This was the most appropriate method considering the size of the study area (being the state of WA) and the advantages of the small time and computational costs, simplicity and practicality for large regions. These advantages are why most similar large-scale projects have opted for a form of constant scaling (Charles et al. 2010; CSIRO in prep.; CSIRO 2012).

Table 2-2: Advantages and disadvantages of dynamical downscaling, statistical downscaling and constant scaling

	Advantages	Disadvantages
Constant Scaling	• Practical[5] • Can be applied across large regions[2,5] • Quick application[1,5] • Simple[1,2,5,6] • Less uncertainty as not calibrated to GCM[2] • Accounts for large uncertainties related to local climate change projections[5]	• Changes to event frequency not considered • GCM simulations of large-scale atmospheric circulation are better than those of rainfall[5] • Temporal sequence of wet days is unchanged[1] • Assumes the spatial pattern of climate remains constant[1] • Future rainfall has same sequence but scaled amounts [2]
Statistical Downscaling	• Low computational cost[4,9] • Produces point rainfall that can be used in rainfall/runoff applications[2] • Accounts for greater range of rainfall characteristics by considering the daily weather types[2]	• Atmospheric variables need to be chosen carefully[1] • Requires expert judgement[5] • Subjective expert judgement required to calibrate the downscaling relationships and bias correct the GCM predictors[2] • Poorly represents extreme events[1] • Underestimate variance[1] • Assumes constancy of empirical relationships in the future[3,9] • Requires definition of weather types conditioned on large-scale predictors[2]
Dynamical Downscaling	• High resolution[1,9] and can directly produce gridded rainfall required for hydrological applications[2] • Multi-decadal simulations[9] • Realistically simulate regional climate features[1]	• Long computer run times[2] • Computationally demanding[9] and expensive[1,3,5,8] • Dependent on use of complex models[8] • Constrained by spatial resolution[5] • Can introduce additional biases[7] • Rainfall parameterisation requires many modelling experiments to capture the drivers of rainfall in the region[2] • Lack of two-way interactions between regional and global climate[9] • Variability within internal parameterisation provides uncertainty[1]

1) Fowler et al. 2007 2) Chiew et al. 2010 3) IPCC 2001b 4) Timbal 2004 5) Mpelasoka and Chiew 2009 6) Santoso et al. 2008 7) Kurylyk and MacQuarrie 2013 8) University of British Columbia 2008 9) IPCC 2001a

Constant (pattern) scaling using SimCLIM

To calculate the monthly scaling factors, the software SimCLIM (2012) was used to extract the spatial and temporal patterns of climate change projected by the 48 scenarios. Although GCM results are freely available through the CMIP3 archives, SimCLIM provides post-processed GCM results in a user-friendly environment, making it an efficient tool for analysis.

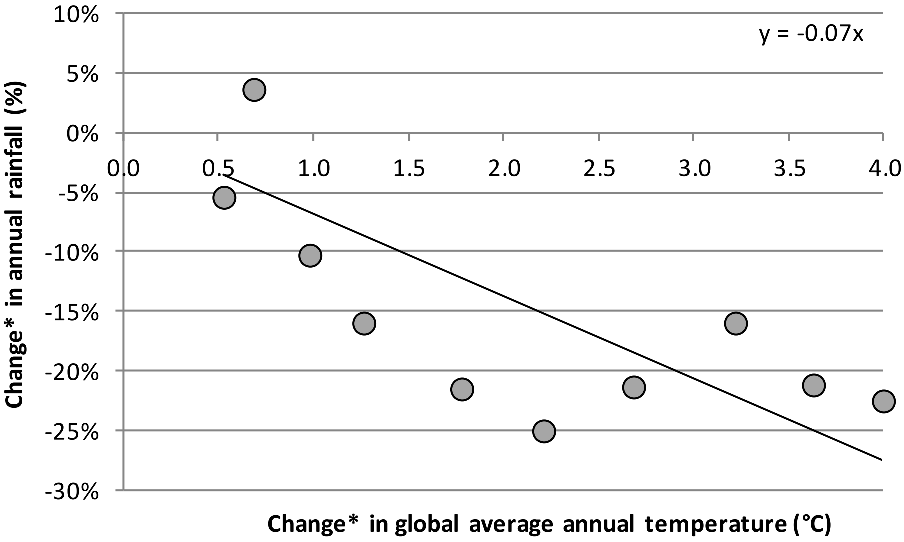
SimCLIM uses the pattern scaling method (Santer et al. 1990) to extract climatic trends from raw GCM results. Pattern scaling relates global changes in temperature to a local change in a specific variable; for example, rainfall or temperature. This is also referred to as a GCM pattern. The assumption is that for a given increase in global temperature there will be a local response in the given variable.

To calculate patterns for each GCM the global mean temperature is calculated for the baseline period (1961–90) using a GCM simulation of the 20th century. The local variable of interest (e.g. June mean rainfall or radiation) is averaged for this baseline period. For the same GCM, a 21st century model run (generally the A1B scenario due to availability of results) is used to calculate the change in global mean temperature and the change in the variable of interest for each decade of the 21st century, relative to the baseline – this change is termed the climate anomaly. The GCM pattern is calculated using linear regression with the global temperature anomaly as the independent variable and the local variable anomaly the dependent variable. For every grid-cell of the GCM, this relationship will be slightly different. This means that for the same GCM, some areas of WA might show increasing rainfall with decreases in other areas.

The linear regression used in the pattern scaling process is illustrated in Figure 2-4. In this example the grey circles represent a single decade from the 21st century GCM simulation. Nine out of ten decades in the 21st century project lower rainfall relative to the 1961–90 baseline period and all project higher global temperatures. The slope of the linear regression is –0.07, which indicates that for every 1 °C of global warming, this location will experience a 7% reduction in average annual rainfall.

Using a GCM pattern the change in rainfall, or other variable, is estimated for a given increase in global temperature. The pattern scaling technique is useful in that changes in climate variables can be related to any specified increase in temperature for any given time horizon. It is also less sensitive to short-term variations in climate within the GCM results compared with extracting GCM results for specific future time periods from the simulation.

The constant linear relationship between the global mean temperature and the local variable means that pattern scaling results in a ‘smoothly’ increasing or decreasing average climate trend from the end of the baseline period through to 2100 in this case. In reality, there will be wet periods and dry periods in the future, causing the moving average to increase or decrease throughout the century (as seen in the historical rainfall moving average). It is a limitation that the climate variability and extremes from the raw GCM results are not captured using pattern scaling. Instead, variability is included in the future scenarios by applying the anomalies to the observed baseline climatology. This is comparatively simple to communicate and a practical and defensible technique.



**Calculated for each decade from 2000–2100, relative to the 1961–1990 baseline period*

Figure 2-4: Pattern scaling example showing declining average annual rainfall with increasing temperature

SimCLIM uses GCM patterns to generate climate projections for future time horizons, based on an increase in global mean temperature expected for a particular emissions scenario. For this study, the time horizons (2030, 2050, 2070 and 2100 selected) are consistent with previous studies (CSIRO & BoM 2007; IPCC 2007a). The increases in global temperature for each of the four emissions scenarios and time horizons, with a moderate level of climate sensitivity, are shown in Table 2-3, as sourced from SimCLIM. The projected change in a given variable is calculated by multiplying the slope of the GCM pattern by the global mean temperature change for the specified time horizon.

Table 2-3: Global mean temperature change for selected time horizons

Year	Increase in temperature °C			
	B2	A1B	A2	A1FI
2030	0.9	0.9	0.8	0.9
2050	1.4	1.6	1.5	1.9
2070	1.9	2.3	2.4	3.0
2100	2.6	3.0	3.8	4.4

3 Selection of wet, median and dry climate scenarios

The previous chapter discussed the selection of four emissions scenarios (B2, A1B, A2, A1FI) and 12 GCMs for determination of climate projections in WA. This gave a total of 48 potential scenarios which could be used for each climatic region. The historical baseline period selected is the WMO normal period of 1961–90, and the downscaling method is constant monthly scaling.

Analysing the 48 scenarios for each region shows:

- the range of uncertainty between GCMs
- the level of agreement between the different GCMs.

This allows selection of wet, median and dry climate scenarios for use in water planning and modelling.

The gridded GCM results sourced from SimCLIM were analysed within ArcGIS to select wet, median and dry scenarios for each region, using the methods described in this chapter.

3.1 Analysis of GCM results and selection of the wet, median and dry scenarios

GCM results were analysed to select three scenarios – the wet, median, and dry – that are representative of the likely range of climate changes for each region as a whole, and that capture the range of uncertainties associated with the climate projections. This reduced the potential scenario from 48 to three, which is more manageable for use in modelling and planning. The selection process involved extracting GCM projections for temperature and rainfall from SimCLIM for all 48 scenarios. The results were then analysed to select a wet, median and dry scenario for each of the five defined regions: the South-west, the Central-west, Pilbara, Kimberley and Central.

To select the three representative scenarios the following method was used for each region:

1. For each grid cell, calculate the change in mean annual rainfall and mean annual temperature at 2100 relative to the baseline using the GCM pattern and change in global temperature provided by the SimCLIM software.
2. Calculate the zonal mean change in annual rainfall and mean annual temperature for each region.
3. Rank the results by change in mean annual rainfall and identify the GCM and emissions scenario associated with the 10^{th}, 50^{th} and 90^{th} percentiles.
4. Select from all of the GCM results:
    a. A drier-hotter scenario (future dry) which is close to the 10^{th} percentile change in rainfall and has a relatively large increase in temperature.
    b. A mid-range scenario (future median) which is close to the 50^{th} percentile change in rainfall and has a moderate increase in temperature.

c. A wetter-cooler scenario (future wet) which is close to the 90th percentile change in rainfall with a relatively smaller increase in temperature.

Results from a single emissions scenario – GCM combination are used for each region and scenario (wet, median, dry). This ensures that the climate anomalies, particularly rainfall, are consistent throughout the region. That is, the climate anomalies vary gradually across the grid cells of the region and there are no large differences in the anomalies between adjacent grid cells.

Additionally, scenarios were selected in order to have a larger temperature anomaly associated with the dry scenario than with the median and wet scenarios. This is to ensure that the 'worst case' scenario for water resources ('future dry') has both larger temperature and rainfall anomalies than the 'future median' and 'future wet' scenarios. So instead of selecting the emissions scenario–GCM combination specified by the exact 10th, 50th and 90th percentile ranking, adjacent emissions scenario–GCM combinations were considered within a few rankings of the 10th, 50th and 90th percentiles to enable selection of an emissions scenario–GCM combination that satisfies these additional criteria.

5. For each of the selected scenarios, the monthly gridded anomaly was calculated at each time horizon for rainfall, temperature, relative humidity, radiation, FAO56 reference potential evapotranspiration and Penman evaporation.
6. The monthly anomalies were then used to scale baseline climate data from BoM weather stations. This step was used to examine the individual monthly anomalies at specific locations, including the physical plausibility of the anomaly values for monthly rainfall, and to identify any potential issues with extreme monthly anomalies or inconsistencies between the three representative scenarios (see Appendix C for more detail).

As the scenarios were selected on a regional scale, it was important to confirm that an appropriate range in uncertainty was captured by the three scenarios at a local scale. Figure 1-5 shows the location of the weather stations used for this assessment throughout the state. If one of the selected scenarios was inappropriate, then an alternative scenario was used, and the process was repeated from step 4.

Note that depending on the location, the 'future wet' scenario may still result in a decrease in rainfall. This will be the case where all, or most, of the GCMs agree that a drying trend is present, for example, in WA's south-west.

Climate variables analysed

Climate anomalies for each month of the year were developed for the following variables:

- **Maximum, minimum and mean daily temperatures**: Reported as change in temperature °C for a given time horizon. Note that the same anomaly is used for maximum, minimum and mean temperatures due to GCM data availability. It is likely that minimum temperatures will increase more quickly than mean or maximum temperature.

- **Rainfall:** Reported as per cent change in total monthly rainfall for a given time horizon.
- **Relative humidity:** Reported as per cent change in daily average relative humidity for a given time horizon. Note that relative humidity for minimum and maximum temperatures is not available.
- **Solar radiation:** Reported as per cent change in net daily incoming short-wave solar radiation for a given time horizon.

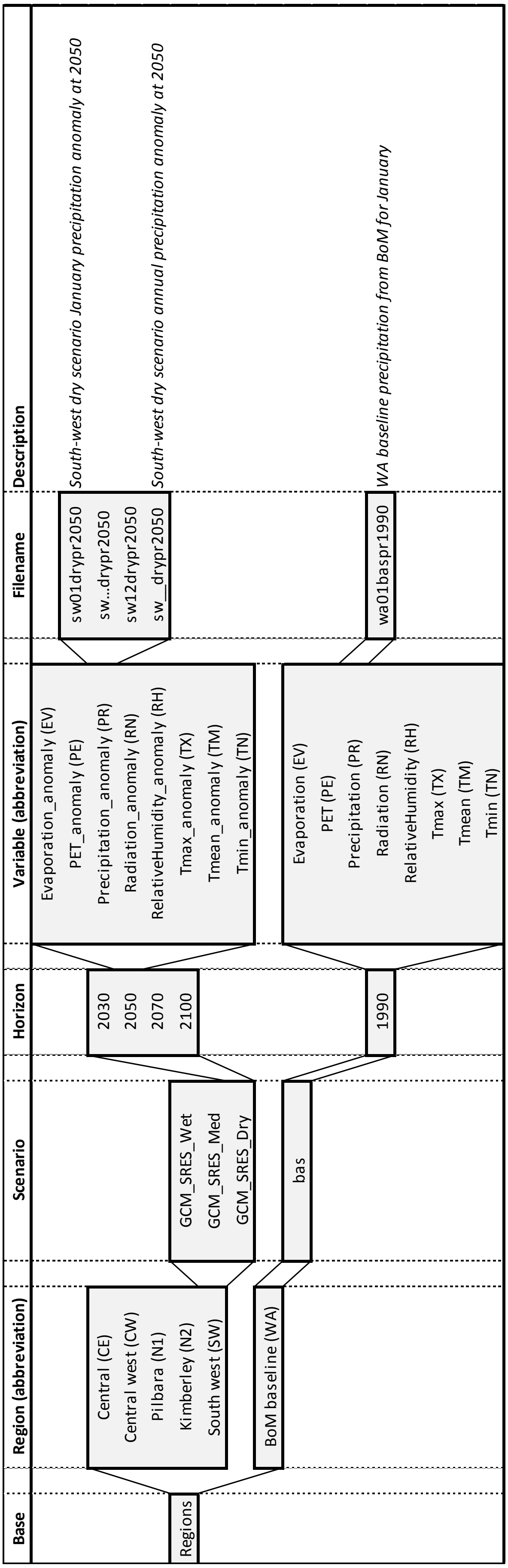
Evaporation and PET are not available from SimCLIM as they are not commonly available variables in the CMIP3 archives. So these variables were calculated using the solar radiation, temperature and humidity data for the baseline and future time horizons. Penman's equation (Penman 1948) was used to calculate evaporation and the FAO56 Penman-Monteith method (Allen et al.1998) was used to calculate reference PET. The results for the baseline period and time horizons were used to calculate anomalies for these two variables. The full calculations are described in Appendix B.

Spatial extent and output format

Spatially distributed gridded climate anomalies were calculated in SimCLIM, and were resampled to a 0.05° cell size across WA using bilinear interpolation. Each of the climatic regions was defined using a standard grid extent. Subsequent grid analysis was performed using these extents, and all grids were stored in ESRI grid format.

The analyses resulted in three scenarios – wet, median and dry– for each of the five regions, for eight variables, at four time horizons for each month of the year. This is a total of 5760 grid files which are stored with a standard naming convention and directory structure (Figure 3-1).

Figure 3-1: Directory structure and naming conventions for grid files



3.2 Climate scenarios for Western Australia

The following section describes the selected wet, median and dry scenarios for each of the regions. The level of agreement in the rainfall trends projected by the GCMs for summer, winter and annually is mapped in Appendix D. The highest levels of agreement between GCMs are for declining winter rainfall in the South-west region.

In the ranked GCM results, the true 10^{th}, 50^{th} and 90^{th} percentile scenarios would be averages between two different scenarios (e.g. the 50^{th} percentile scenario would be the average of the 24^{th} and 25^{th} ranked scenario). The figures for each region show the 5^{th} ranked scenario labelled as the 10^{th} percentile, the 25^{th} ranked scenario labelled as the 50^{th} percentile, and the 44^{th} ranked scenario labelled as the 90^{th} percentile. The selected representative scenarios for each region are highlighted in grey for all figures in this section.

In the South-west region it is appropriate to apply the scenarios to support water plans and strategies; however, in regions outside the South-west these scenarios are not applicable. Before a scenario is applied, the data needs to be analysed and the following criteria satisfied:

1) There is general agreement in the direction of change (i.e. drying or wetting) amongst the GCM results.
2) The projected trend in average rainfall is consistent with decadal trends in observed data.
3) The inter-annual variability associated with the climate scenario is consistent with the variability in the observed data.

If these criteria are not satisfied, it is likely that either the GCMs are not capturing the local rainfall processes adequately, the observed trend in rainfall at this location is not related to global warming or the constant downscaling technique used to generate scenarios in this report is not appropriate for the location (or a combination of the above). In these instances it is more appropriate to use long-term historical climate sequences in water resource projects and planning, as this is likely to provide a better estimation of the future climate than the scenarios outlined in this report.

In the South-west region all scenarios show consistent drying and warming trends in annual rainfall and temperature. Given the trends in rainfall and temperature in south-west WA it is inappropriate to assume that the historical climate is an indicator for the future and that the climate projections should be used for water resource management.

In the Central-west region the majority of the scenarios show drying and warming trends in annual rainfall and temperature. In the other regions, GCM results indicate that both warmer wetter and warmer drier climates are possible, and the selected scenarios reflect this. The inconsistency in the direction of the rainfall trend for the future indicates that the long-term rainfall records are more appropriate for scenario modelling than the climate projections. Although considerable uncertainty surrounds the rainfall scenarios for these regions, the projections for temperature and PET may still be appropriate for use; for example, in calculating crop water demand or evaporation from open water bodies.

South-west region

The message in the South-west is clear. All models and the selected scenarios show decreases in rainfall and increases in temperature that are consistent with already observed climate trends. This means that climate projections are useful and critical for precision around projections of our future climate and water availability.

Percentile ranking of GCM results

Table 3-1 shows the percentile rankings from the South-west region. The 48 potential scenarios were ranked by the percentage change in rainfall by 2100, with change in temperature listed as a secondary variable. All the GCMs project decreases in average annual rainfall: 5–67% reductions. By identifying the 10^{th}, 50^{th} and 90^{th} percentile scenarios, it is possible to capture a reasonable range of uncertainty without including the most extreme scenarios.

A scenario one ranks below the 10^{th} percentile was used for the dry scenario. The selected median scenario corresponds to the 50^{th} percentile, as it represents a moderate rainfall reduction, with a moderate temperature rise. For the wet scenario, a GCM other than the identified 90^{th} percentile GCM was used as it resulted in better spatial consistency in rainfall reduction across the region.

South-west WA is widely reported as a region of the globe which is particularly sensitive to climate change. The drying trend projected by the GCMs is consistent with the results of previous studies and the trends observed in the region (CSIRO & BoM 2007; Charles et al. 2010; IOCI 2012).

Regional patterns of change

The gridded change in average annual rainfall for the South-west region is shown in Figure 3-2. The results indicate drying trends for all scenarios though the western part of the region shows greater rainfall reductions than the interior and southern coastline. Table 3-2 lists the annual rainfall, daily temperature and annual PET anomalies at multiple time horizons, and shows the climate trajectories for the region as a whole for the selected wet, median and dry scenarios. These changes are relative to a 1961–90 baseline.

The dry scenario indicates, for the region as a whole, a 14% decline in rainfall, a 0.7 °C temperature rise and a 3% increase in PET by 2030. The drying trend continues in the latter half of the century, with rainfall projected to be 25% less by 2050, and 47% less by 2100. The median scenario indicates a less pronounced drying trend, with a 5% reduction in rainfall by 2030 and 17% by 2100. Temperature is projected to rise by 2.4 °C by 2100. The wet scenario results in only a 7% reduction in rainfall by 2100, and a 2.0 °C temperature rise. The wet scenario compared to the median scenario is associated with a larger reduction in relative humidity which results in a slightly larger rise in PET. In the west of the region, drying trends are more pronounced relative to the regional averages.

The annual rainfall anomalies for the South-west are comparable with those identified in the SWWASY project (CSIRO 2009a) for the equivalent spatial extent in terms of percentage change. For this study the 2030 projected annual rainfall for the dry scenario is similar to the observed average annual rainfall from the last decade in the Perth region.

Table 3-1: GCM results ranked by change in zonal rainfall at 2100 relative to 1961–90 for the South-west region

Scenario		Mean annual rainfall		Mean annual temp.	
		Anomaly	Anomaly	Anomaly	Anomaly
SRES	GCM	(mm)	(%)	(°C)	(%)
A1FI	GFDLCM21	-284	-67.0%	3.68	21.0%
A2	GFDLCM21	-255	-60.0%	3.18	18.2%
A1FI	GFDLCM20	-207	-48.8%	3.69	21.1%
A1B	GFDLCM21	-201	-47.4%	2.47	14.1%
A2	GFDLCM20	-179	-42.2%	3.19	18.2%
B2	GFDLCM21	-177	-41.7%	2.17	12.4%
A1FI	ECHO--G	-140	-32.9%	3.82	21.8%
A1B	GFDLCM20	-139	-32.8%	2.48	14.1%
A1FI	FGOALS1G	-129	-30.4%	3.38	19.3%
B2	GFDLCM20	-122	-28.8%	2.18	12.4%
A2	ECHO--G	-121	-28.5%	3.30	18.8%
A2	FGOALS1G	-111	-26.3%	2.92	16.7%
A1FI	MPIECH-5	-106	-24.9%	3.52	20.1%
A1FI	GISS--ER	-105	-24.7%	4.79	27.3%
A1FI	UKHADGEM	-100	-23.6%	2.18	12.4%
A1B	ECHO--G	-94	-22.1%	2.57	14.6%
A2	MPIECH-5	-91	-21.5%	3.04	17.3%
A1FI	MIROCMED	-91	-21.4%	3.05	17.4%
A2	GISS--ER	-91	-21.4%	4.14	23.6%
A2	UKHADGEM	-87	-20.4%	1.88	10.7%
A1B	FGOALS1G	-87	-20.4%	2.27	12.9%
B2	ECHO--G	-82	-19.4%	2.25	12.9%
A2	MIROCMED	-79	-18.5%	2.63	15.0%
B2	FGOALS1G	-76	-17.9%	1.99	11.4%
A1B	MPIECH-5	-71	-16.7%	2.36	13.5%
A1B	GISS--ER	-70	-16.6%	3.22	18.3%
A1FI	BCCRBCM2	-70	-16.4%	3.60	20.5%
A1B	UKHADGEM	-67	-15.9%	1.46	8.3%
B2	MPIECH-5	-62	-14.7%	2.07	11.8%
B2	GISS--ER	-62	-14.6%	2.83	16.1%
A1B	MIROCMED	-61	-14.4%	2.05	11.7%
A2	BCCRBCM2	-60	-14.3%	3.11	17.7%
B2	UKHADGEM	-59	-13.9%	1.29	7.3%
A1FI	CCSM--30	-54	-12.8%	3.46	19.7%
B2	MIROCMED	-54	-12.6%	1.80	10.3%
A1FI	MIROC-HI	-52	-12.3%	3.39	19.3%
A1B	BCCRBCM2	-47	-11.1%	2.42	13.8%
A2	CCSM--30	-47	-11.1%	2.99	17.1%
A2	MIROC-HI	-45	-10.7%	2.93	16.7%
B2	BCCRBCM2	-41	-9.7%	2.12	12.1%
A1B	CCSM--30	-37	-8.6%	2.32	13.3%
A1B	MIROC-HI	-35	-8.3%	2.27	13.0%
A1FI	MRI-232A	-34	-8.1%	4.10	23.4%
B2	CCSM--30	-32	-7.6%	2.04	11.6%
A2	MRI-232A	-32	-7.4%	3.54	20.2%
B2	MIROC-HI	-31	-7.3%	2.00	11.4%
A1B	MRI-232A	-25	-5.9%	2.75	15.7%
B2	MRI-232A	-22	-5.2%	2.42	13.8%

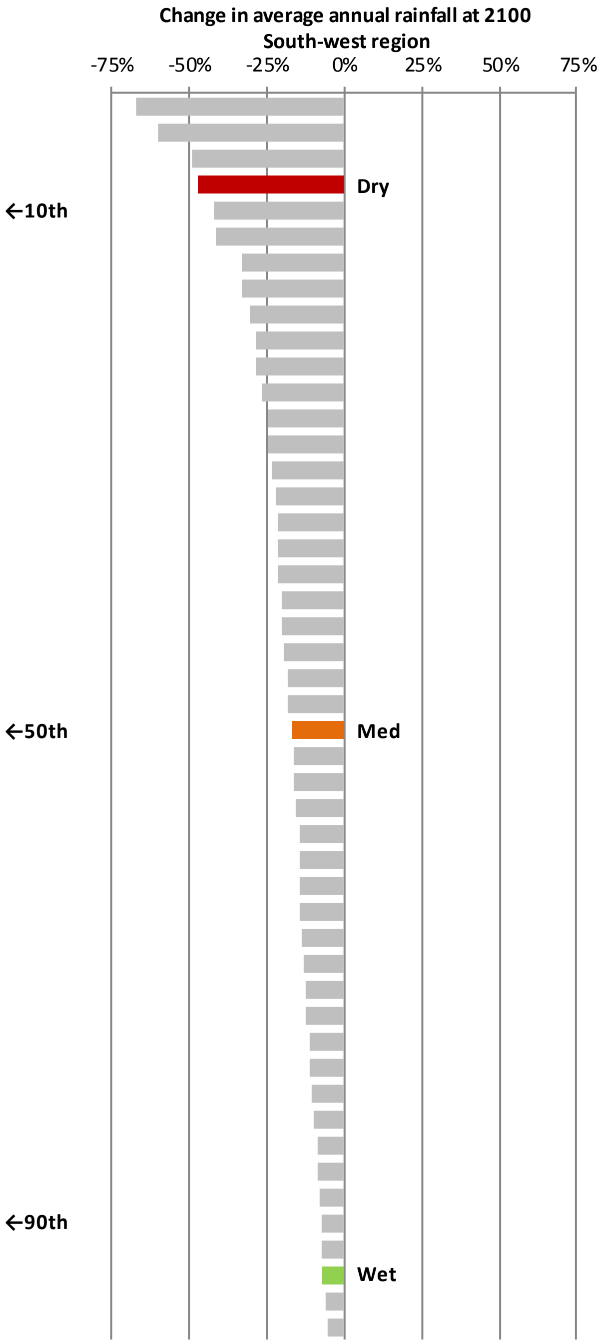
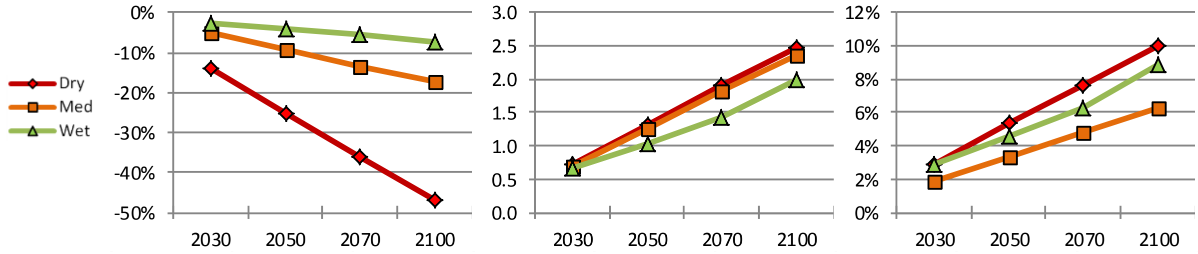


Table 3-2: Regional rainfall, temperature and PET anomalies for the South-west region at 2030, 2050, 2070 and 2100 relative to 1961–90 baseline

	Mean annual rainfall anomaly (%)			Mean daily temp. anomaly (°C)			Mean annual PET anomaly (%)		
Year	**Dry**	**Med**	**Wet**	**Dry**	**Med**	**Wet**	**Dry**	**Med**	**Wet**
2030	-14%	-5%	-2%	0.7	0.7	0.7	3%	2%	3%
2050	-25%	-9%	-4%	1.3	1.3	1.0	5%	3%	5%
2070	-36%	-13%	-5%	1.9	1.8	1.4	8%	5%	6%
2100	-47%	-17%	-7%	2.5	2.4	2.0	10%	6%	9%



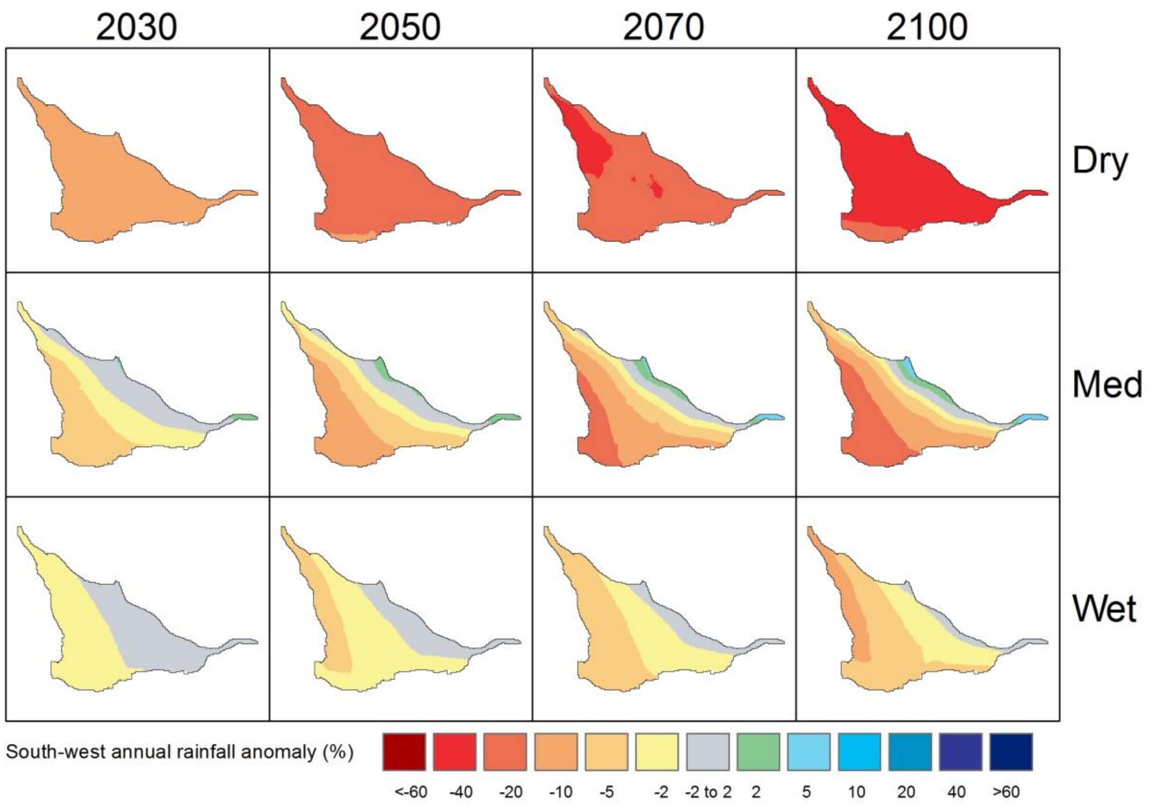


Figure 3-2: Change in average annual rainfall relative to the baseline period for South-west region for representative wet, median and dry scenarios at future time horizons

Central-west region

In the Central-west region the majority of the 48 scenarios project a decrease in rainfall and an increase in temperature. The scenarios are similar to the recent observed trends only along parts of the coastline, whereas the interior stations all show an increasing or steady rainfall trend over recent decades. Over most of the Central-west, the observed trends are the opposite of the drying trend indicated by the climate scenarios (see Appendix F). Therefore, use the long-term historical climate in water resource planning rather the scenarios as they might not be representative of what happens in the future. Although considerable uncertainty surrounds the rainfall anomalies for this region, the temperature and PET anomalies may still be appropriate for use; for example, in calculating crop water demand or evaporation from open water bodies.

Percentile ranking of GCM results

The percentile ranking for the Central-west region is shown in Table 3-3. All but one of the GCMs project a drying trend in the Central-west region. Results are similar to those from the South-west though with smaller rainfall reductions by 2100: mean annual rainfall –50 to 14% with a median of –12%.

For the Central-west region, the selected scenarios do not correspond directly to the 10th, 50th and 90th percentile scenarios. The scenarios selected had consistent rainfall and temperature changes across the region (as per the method described in section 3-2).

Regional patterns of change

Figure 3-3 shows the patterns of change in annual rainfall across the Central-west region for the three scenarios. The region shows an even drying trend for the dry and median scenarios. While the wet scenario shows no trend in the northern half of the region and a drying trend in the south.

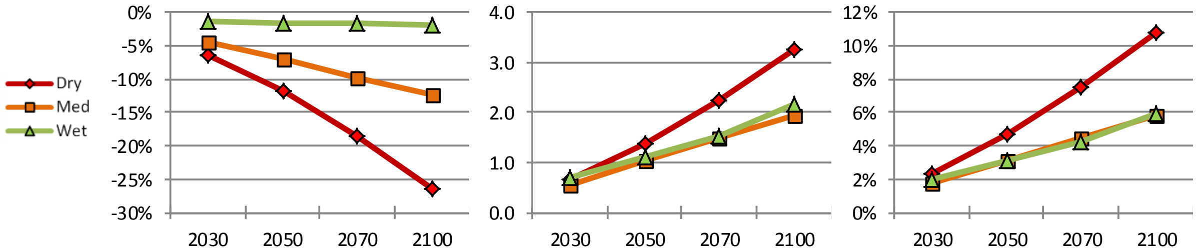
Table 3-4 shows the overall regional trends in rainfall, temperature and PET. The future dry scenario shows a 26% reduction in annual average rainfall by the end of the 21st century, with a temperature rise of 3.3 °C, and PET increasing by 11%. The reduced annual average rainfall is mostly a result of lower rainfall in winter and spring. The future median scenario shows a 12% decrease in rainfall, with a temperature rise of 1.9 °C by 2100. Similarly, the rainfall reduction is mostly in the winter and spring months. The future wet scenario shows only a 1% reduction in annual average rainfall by the end of the century. Average annual temperature is projected to rise 2.2 °C by 2100 for the wet scenario, with a 6% increase in PET.

Table 3-3: GCM results ranked by change in zonal rainfall at 2100 relative to 1961–90 for the Central-west region

Scenario		Mean annual rainfall		Mean annual temp.	
		Anomaly	Anomaly	Anomaly	Anomaly
SRES	GCM	(mm)	(%)	(°C)	(%)
A1FI	GFDLCM21	-109	-49.6%	5.41	23.7%
A2	GFDLCM21	-101	-45.9%	4.68	20.4%
A1B	GFDLCM21	-84	-38.3%	3.63	15.9%
B2	GFDLCM21	-75	-34.1%	3.19	13.9%
A1FI	GISS--ER	-58	-26.3%	6.26	27.3%
A1FI	FGOALS1G	-56	-25.6%	3.28	14.3%
A2	GISS--ER	-50	-22.7%	5.41	23.6%
A2	FGOALS1G	-49	-22.2%	2.84	12.4%
A1FI	BCCRBCM2	-39	-17.8%	4.02	17.6%
A1B	GISS--ER	-39	-17.7%	4.20	18.3%
A1FI	UKHADGEM	-38	-17.3%	2.87	12.5%
A1B	FGOALS1G	-38	-17.2%	2.20	9.6%
A2	BCCRBCM2	-37	-16.9%	3.48	15.2%
A1FI	GFDLCM20	-37	-16.8%	5.01	21.9%
A1FI	ECHO---G	-36	-16.4%	4.15	18.1%
B2	GISS--ER	-34	-15.5%	3.69	16.1%
B2	FGOALS1G	-33	-15.1%	1.94	8.5%
A2	UKHADGEM	-33	-15.0%	2.48	10.8%
A2	GFDLCM20	-32	-14.5%	4.33	18.9%
A2	ECHO---G	-32	-14.4%	3.59	15.7%
A1B	BCCRBCM2	-30	-13.7%	2.70	11.8%
B2	BCCRBCM2	-27	-12.0%	2.37	10.4%
A1B	UKHADGEM	-26	-11.6%	1.93	8.4%
A1B	GFDLCM20	-25	-11.3%	3.36	14.7%
A1B	ECHO---G	-25	-11.2%	2.79	12.2%
B2	UKHADGEM	-23	-10.2%	1.69	7.4%
B2	GFDLCM20	-22	-9.9%	2.95	12.9%
B2	ECHO---G	-22	-9.9%	2.45	10.7%
A1FI	MRI-232A	-9	-4.3%	4.70	20.5%
A2	MRI-232A	-9	-4.1%	4.06	17.7%
A1FI	MIROC-HI	-8	-3.6%	3.97	17.4%
A1B	MRI-232A	-7	-3.4%	3.15	13.8%
A2	MIROC-HI	-7	-3.2%	3.43	15.0%
B2	MRI-232A	-7	-3.0%	2.77	12.1%
A1B	MIROC-HI	-5	-2.4%	2.67	11.7%
B2	MIROC-HI	-5	-2.2%	2.34	10.2%
A1FI	MIROCMED	-4	-2.0%	3.66	16.0%
A2	MIROCMED	-4	-1.7%	3.16	13.8%
A1FI	MPIECH-5	-4	-1.6%	4.54	19.8%
A2	MPIECH-5	-3	-1.4%	3.92	17.1%
A1B	MIROCMED	-3	-1.3%	2.45	10.7%
B2	MIROCMED	-3	-1.2%	2.16	9.4%
A1B	MPIECH-5	-2	-1.1%	3.05	13.3%
B2	MPIECH-5	-2	-1.0%	2.68	11.7%
B2	CCSM--30	19	8.7%	2.37	10.4%
A1B	CCSM--30	22	9.9%	2.70	11.8%
A2	CCSM--30	28	12.7%	3.47	15.2%
A1FI	CCSM--30	32	14.7%	4.02	17.6%

Table 3-4: Regional rainfall, temperature and PET anomalies for the Central-west region at 2030, 2050, 2070 and 2100 relative to the 1961–90 baseline

	Mean annual rainfall anomaly (%)			Mean daily temp. anomaly (°C)			Mean annual PET anomaly (%)		
Year	**Dry**	**Med**	**Wet**	**Dry**	**Med**	**Wet**	**Dry**	**Med**	**Wet**
2030	-6%	-4%	-1%	0.7	0.6	0.7	2%	2%	2%
2050	-12%	-7%	-1%	1.4	1.0	1.1	5%	3%	3%
2070	-18%	-10%	-2%	2.3	1.5	1.5	8%	5%	4%
2100	-26%	-12%	-2%	3.3	1.9	2.2	11%	6%	6%



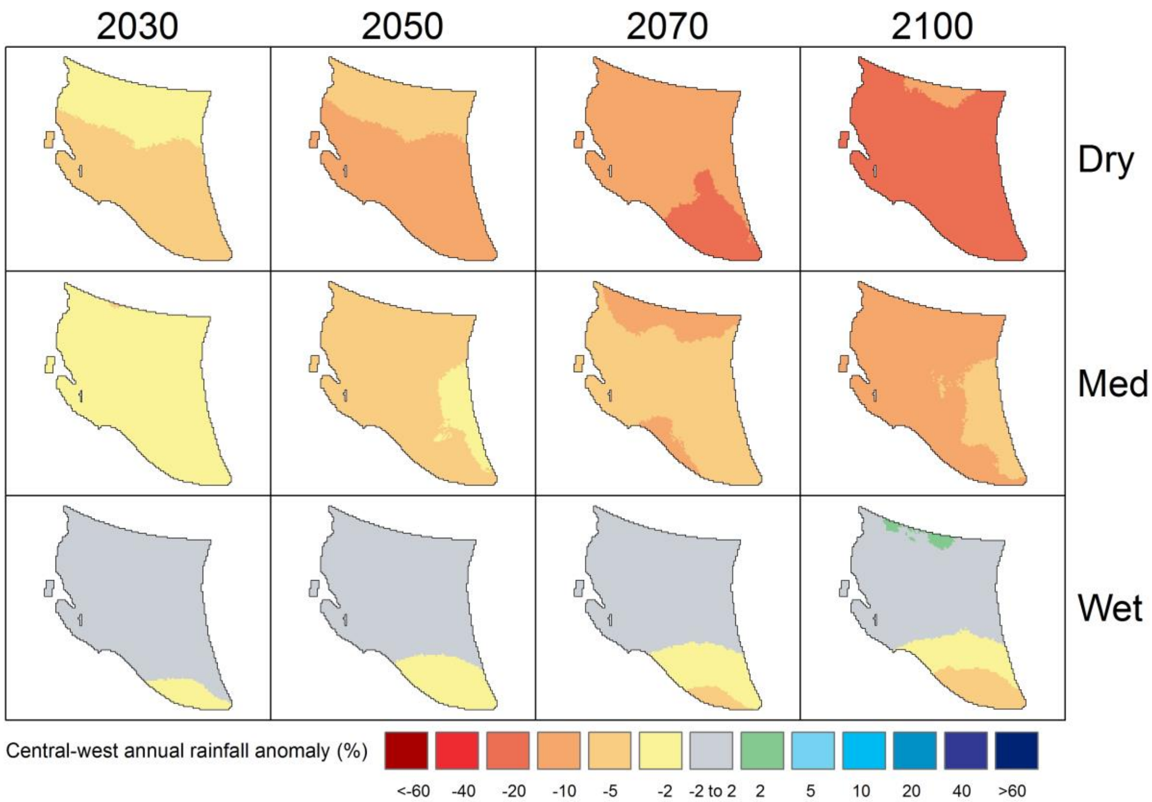


Figure 3-3: Change in average annual rainfall relative to the baseline period for Central-west region for representative wet, median and dry scenarios at future time horizons

Pilbara region

The results for this region are not as clear as for the South-west region. There is no consistency in the direction of the GCM results with both warmer wetter and warmer drier climates possible.

The climate scenarios developed here do not compare well with observed regional climate trends. The range of rainfall projected by the scenarios is narrower than the historical inter-annual and decadal rainfall variations. That is, the observed historical climate variability is stronger than the climate change signal.

Therefore, use the long-term historical climate rather than the Pilbara scenarios for water resource planning, as the scenarios are not representative of what may happen in the future. Although considerable uncertainty surrounds the scenarios for these regions, the temperature and PET projections may still be appropriate for use for some applications.

Percentile ranking of GCM results

The percentile ranking shown in Table 3-5 indicates that around half of the GCMs project a drying trend. The models which show a drying trend respond more strongly to global warming, with the driest model indicating a 35% decrease in average annual rainfall by 2100. In contrast, the wettest model indicates a 10% increase in rainfall. Around half of the models show very little change for the region as a whole and this is reflected by the median scenario with only 2% decrease in annual rainfall.

The selected scenarios for this region did not correspond directly to the 10th, 50th and 90th percentiles. Alternative scenarios were selected as they better represented the region as a whole.

Regional patterns of change

Figure 3-4 shows the spatial distribution of the change in annual rainfall across the Pilbara. The wet, median and dry scenarios all show that the western Pilbara may experience more drying than the eastern Pilbara, which is consistent with the recent trends in rainfall for the region. The eastern Pilbara shows changes –10% to +10% in annual rainfall by 2100, and the western Pilbara shows a range –20 to 2%.

Table 3-6 shows the changes in temperature, rainfall and PET projected for the four time horizons and selected scenarios. The wet scenario has a slight upward trend, the median scenario shows a small downward trend, but the dry scenario has a pronounced downward trend. The warming trend for the three scenarios is similar until the middle of the century, by 2100 the three scenarios diverge, with the dry scenario showing a 3.7 °C rise, and the wet scenario showing a 2.6 °C rise in mean daily temperature by the end of the century. The PET anomalies for the wet and median scenarios are similar for all time horizons, with the dry scenario showing larger rises in PET: 4% by 2050 and 10% by 2100.

Table 3-5: GCM results ranked by change in zonal rainfall at 2100 to 1961–1990 for the Pilbara region

Scenario		Mean annual rainfall		Mean annual temp.		
		Anomaly	Anomaly	Anomaly	Anomaly	
SRES	**GCM**	**(mm)**	**(%)**	**(°C)**	**(%)**	
A1FI	GFDLCM21	-109	-34.8%	6.34	24.5%	
A2	GFDLCM21	-99	-31.5%	5.48	21.2%	
A1B	GFDLCM21	-81	-25.6%	4.26	16.5%	
A1FI	UKHADGEM	-74	-23.6%	3.77	14.6%	
B2	GFDLCM21	-72	-22.8%	3.74	14.5%	**←10th**
A2	UKHADGEM	-64	-20.4%	3.25	12.6%	
A1FI	GFDLCM20	-56	-17.9%	5.87	22.7%	
A1B	UKHADGEM	-50	-15.8%	2.53	9.8%	
A2	GFDLCM20	-49	-15.5%	5.07	19.6%	
B2	UKHADGEM	-44	-13.9%	2.22	8.6%	
A1FI	FGOALS1G	-41	-13.2%	2.95	11.4%	
A1B	GFDLCM20	-38	-12.1%	3.94	15.2%	
A2	FGOALS1G	-36	-11.4%	2.55	9.9%	
B2	GFDLCM20	-33	-10.6%	3.46	13.4%	
A1B	FGOALS1G	-28	-8.9%	1.98	7.7%	
B2	FGOALS1G	-24	-7.8%	1.74	6.7%	
A1FI	GISS--ER	-24	-7.7%	6.80	26.3%	
A2	GISS--ER	-22	-6.9%	5.87	22.7%	
A1B	GISS--ER	-17	-5.4%	4.56	17.6%	
B2	GISS--ER	-15	-4.8%	4.01	15.5%	
A1FI	BCCRBCM2	-9	-3.0%	3.91	15.1%	
A2	BCCRBCM2	-9	-2.9%	3.38	13.0%	
A1B	BCCRBCM2	-7	-2.3%	2.62	10.1%	
B2	BCCRBCM2	-6	-2.0%	2.31	8.9%	
A2	ECHO--G	-5	-1.5%	3.59	13.9%	**←50th**
A1FI	ECHO--G	-5	-1.4%	4.15	16.1%	
A1B	ECHO--G	-4	-1.4%	2.79	10.8%	
B2	ECHO--G	-4	-1.2%	2.45	9.5%	
B2	MPIECH-5	4	1.3%	3.03	11.7%	
A1B	MPIECH-5	5	1.5%	3.45	13.3%	
A2	MPIECH-5	6	1.9%	4.44	17.1%	
A1FI	MPIECH-5	7	2.2%	5.13	19.8%	
B2	MRI-232A	9	2.9%	2.88	11.2%	
A1B	MRI-232A	10	3.3%	3.28	12.7%	
B2	MIROC-HI	13	4.1%	2.48	9.6%	
A2	MRI-232A	13	4.3%	4.22	16.3%	
B2	MIROCMED	14	4.3%	2.32	9.0%	
A1B	MIROC-HI	15	4.7%	2.82	10.9%	
A1B	MIROCMED	16	4.9%	2.64	10.2%	
A1FI	MRI-232A	16	5.0%	4.89	18.9%	
B2	CCSM--30	18	5.8%	2.40	9.3%	
A2	MIROC-HI	19	6.0%	3.63	14.0%	
A2	MIROCMED	20	6.4%	3.40	13.1%	
A1B	CCSM--30	21	6.6%	2.73	10.6%	**←90th**
A1FI	MIROC-HI	22	7.0%	4.21	16.3%	
A1FI	MIROCMED	23	7.4%	3.93	15.2%	
A2	CCSM--30	27	8.5%	3.51	13.6%	
A1FI	CCSM--30	31	9.9%	4.06	15.7%	

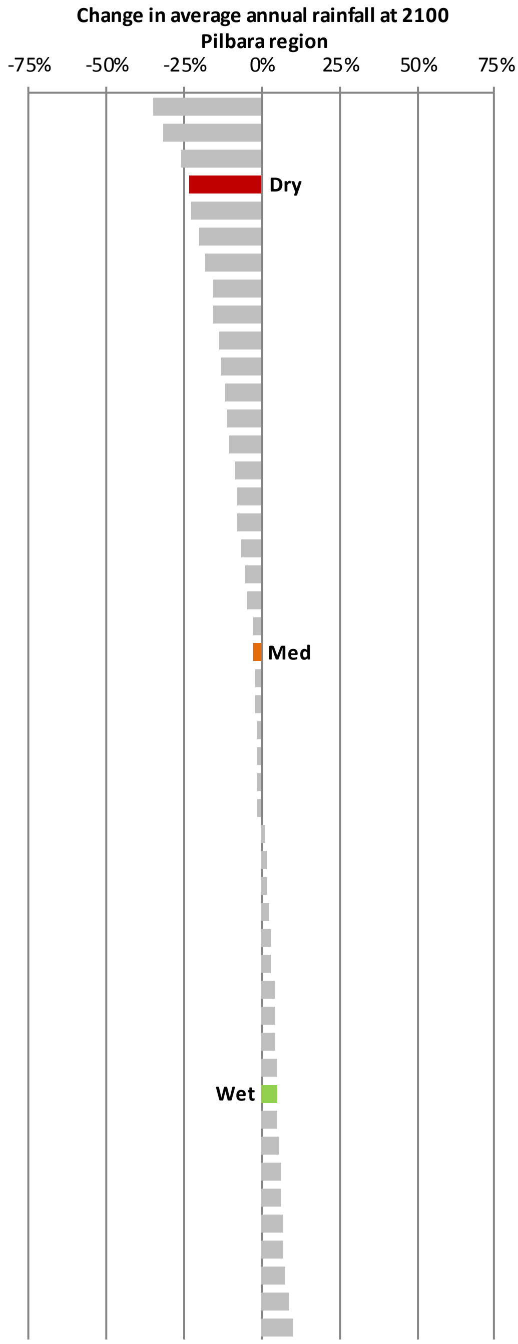
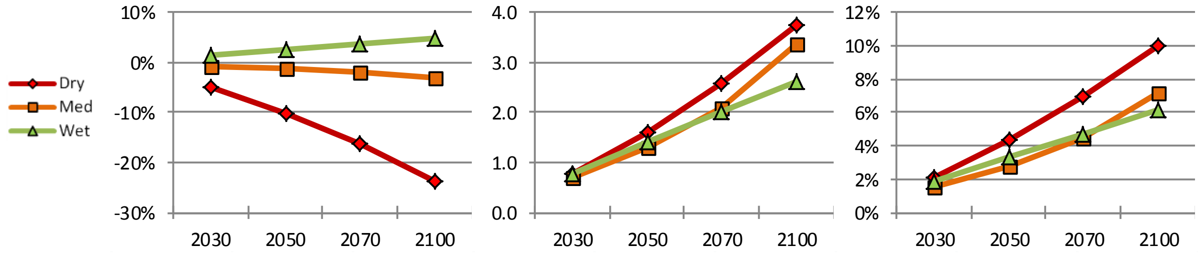


Table 3-6: Regional rainfall, temperature and PET anomalies for the Pilbara region at 2030, 2050, 2070 and 2100 relative to the 1961–1990 baseline

Year	Mean annual rainfall anomaly (%)			Mean daily temp. anomaly (°C)			Mean annual PET anomaly (%)		
	Dry	Med	Wet	Dry	Med	Wet	Dry	Med	Wet
2030	-5%	-1%	1%	0.8	0.7	0.8	2%	2%	2%
2050	-10%	-1%	3%	1.6	1.3	1.4	4%	3%	3%
2070	-16%	-2%	4%	2.6	2.1	2.0	7%	4%	5%
2100	-24%	-3%	5%	3.7	3.4	2.6	10%	7%	6%



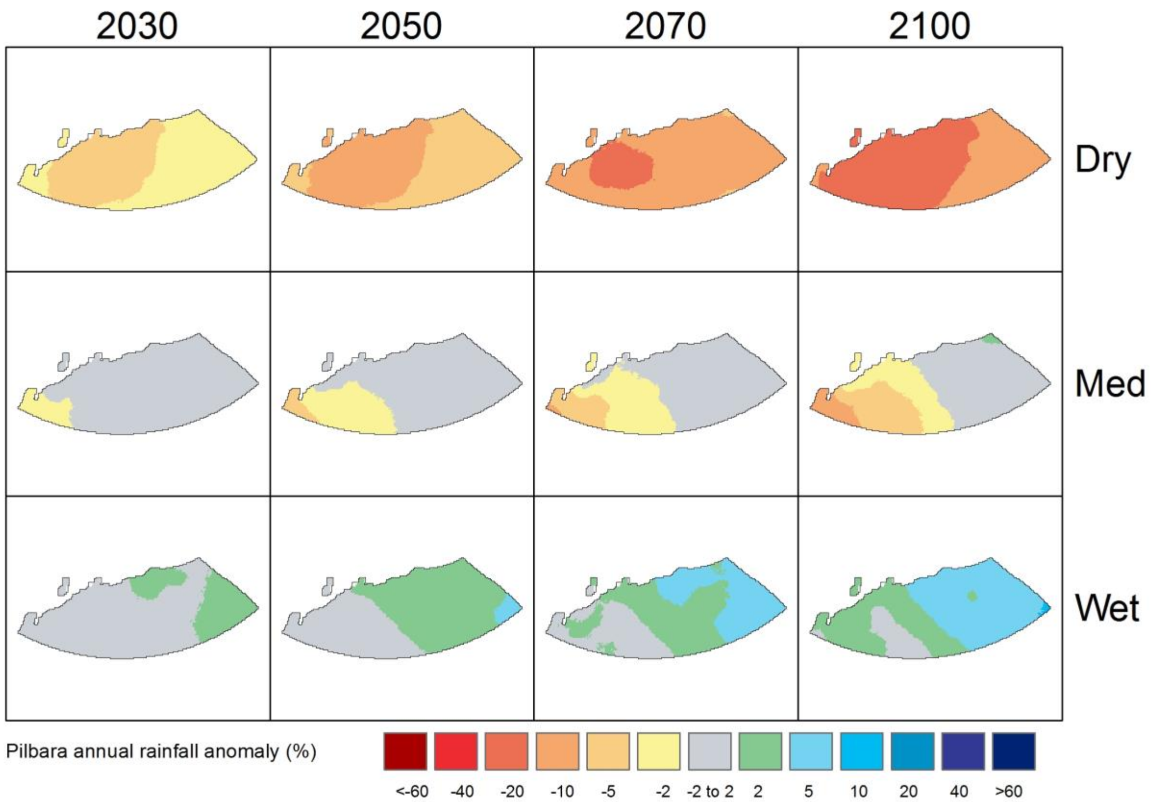


Figure 3-4: Change in average annual rainfall relative to the baseline period for Pilbara region for representative wet, median and dry scenarios at future time horizons

Kimberley region

As with the Pilbara, the results for this region are not as clear as for the South-west. There is no consistency in the direction of the GCM results with both warmer wetter and warmer drier climates possible.

The scenarios developed here do not compare well with observed regional climate trends. While there has been an upward trend in rainfall at some locations in the north, there is no evidence that this observed trend will continue. The projected range in rainfall for the scenarios is narrower than the historical inter-annual and decadal rainfall variations. That is, the observed historical climate variability is stronger than the climate change signal.

Therefore, use the long-term historical climate rather than the Kimberley scenarios in water resource planning, as the scenarios are not representative of what may happen in the future. Although considerable uncertainty surrounds the rainfall anomalies for these regions, the temperature and PET anomalies may still be appropriate for use; for example, in calculating crop water demand or evaporation from open water bodies.

Percentile ranking of GCM results

The ranking of GCMs in the Kimberley region shows that some models project wetter and some drier futures. The ‘driest’ GCM projects a 22% reduction in annual average rainfall by 2100 while the ‘wettest’ projects an 18% increase. More than 50% of the GCMs project a wetter future climate – reflected in the median GCM result which shows a 6% rainfall increase by 2100. The recent data indicates upward rainfall trends in the Kimberley. The *Northern Australian sustainable yields* project showed a similar distribution of changes in annual average rainfall, with slightly more than half of the GCMs analysed indicating future rainfall increases within the region (Li et al. 2009).

The selected representative scenarios are close to the 10^{th}, 50^{th} and 90^{th} percentiles of change in rainfall. These scenarios were selected as they represented a better range in temperature (hot/dry, med/med, wet/cool) than the scenarios associated with the exact percentiles.

Regional patterns of change

Figure 3-5 shows the change in annual average rainfall at various time horizons. For all three scenarios, the coastal areas show more drying, or a less pronounced wetting trend, compared to the interior. Over much of the region, all scenarios show only small increases in average annual rainfall until 2050, with a range of only ± 5%. In the second half of the century the differences are more pronounced. It is notable that the wettest scenario at 2030 is still drier than the recent wet period measured over the last decade in the Kimberley.

The dry scenario indicates a 5 °C temperature rise by the end of the century. The median and wet scenarios also project substantial (more than 3 °C) temperature rises. The raised temperatures and radiations result in higher PET for all scenarios: 3–5% by 2050, and 7–12% by 2100.

Table 3-7: GCM results ranked by change in zonal rainfall at 2100 to 1961–90 for the Kimberley region

Scenario		Mean annual rainfall		Mean annual temp.		
		Anomaly	Anomaly	Anomaly	Anomaly	
SRES	GCM	(mm)	(%)	(°C)	(%)	
A1FI	GFDLCM21	-131	-21.8%	5.97	22.2%	
A2	GFDLCM21	-116	-19.4%	5.16	19.2%	
A1B	GFDLCM21	-92	-15.3%	4.01	14.9%	
B2	GFDLCM21	-81	-13.5%	3.52	13.1%	
A1FI	GFDLCM20	-75	-12.5%	5.60	20.8%	←10th
A2	GFDLCM20	-65	-10.9%	4.84	18.0%	
A1B	GFDLCM20	-51	-8.5%	3.76	14.0%	
B2	GFDLCM20	-45	-7.5%	3.30	12.3%	
A1FI	UKHADGEM	-39	-6.6%	3.93	14.6%	
A1FI	FGOALS1G	-36	-6.0%	3.27	12.2%	
A2	UKHADGEM	-34	-5.7%	3.40	12.7%	
A2	FGOALS1G	-31	-5.2%	2.82	10.5%	
A1B	UKHADGEM	-26	-4.4%	2.64	9.8%	
A1B	FGOALS1G	-24	-4.0%	2.19	8.2%	
B2	UKHADGEM	-23	-3.9%	2.32	8.6%	
B2	FGOALS1G	-21	-3.5%	1.93	7.2%	
B2	GISS--ER	14	2.3%	3.63	13.5%	
A1B	GISS--ER	16	2.6%	4.14	15.4%	
A2	GISS--ER	21	3.5%	5.32	19.8%	
A1FI	GISS--ER	25	4.2%	6.16	22.9%	
B2	MIROC-HI	26	4.3%	2.40	8.9%	
A1B	MIROC-HI	30	4.9%	2.73	10.2%	
A2	MIROC-HI	38	6.4%	3.52	13.1%	
B2	BCCRBCM2	39	6.4%	2.14	8.0%	
B2	CCSM--30	40	6.6%	2.17	8.1%	←50th
B2	ECHO---G	41	6.8%	2.78	10.4%	
A1B	BCCRBCM2	44	7.3%	2.44	9.1%	
A1FI	MIROC-HI	44	7.4%	4.07	15.2%	
A1B	CCSM--30	45	7.5%	2.47	9.2%	
B2	MRI-232A	46	7.8%	2.78	10.3%	
A1B	ECHO---G	47	7.8%	3.17	11.8%	
B2	MIROCMED	52	8.7%	2.19	8.1%	
A1B	MRI-232A	53	8.8%	3.16	11.8%	
A2	BCCRBCM2	56	9.4%	3.14	11.7%	
A2	CCSM--30	58	9.7%	3.18	11.9%	
A1B	MIROCMED	59	9.9%	2.49	9.3%	
A2	ECHO---G	60	10.0%	4.08	15.2%	
B2	MPIECH-5	63	10.6%	2.90	10.8%	
A1FI	BCCRBCM2	65	10.9%	3.63	13.5%	
A1FI	CCSM--30	67	11.2%	3.69	13.7%	
A2	MRI-232A	69	11.5%	4.07	15.2%	
A1FI	ECHO---G	70	11.6%	4.72	17.6%	
A1B	MPIECH-5	72	12.0%	3.31	12.3%	
A2	MIROCMED	77	12.8%	3.21	11.9%	←90th
A1FI	MRI-232A	81	13.6%	4.71	17.5%	
A1FI	MIROCMED	89	14.8%	3.71	13.8%	
A2	MPIECH-5	93	15.5%	4.25	15.8%	
A1FI	MPIECH-5	107	17.9%	4.92	18.3%	

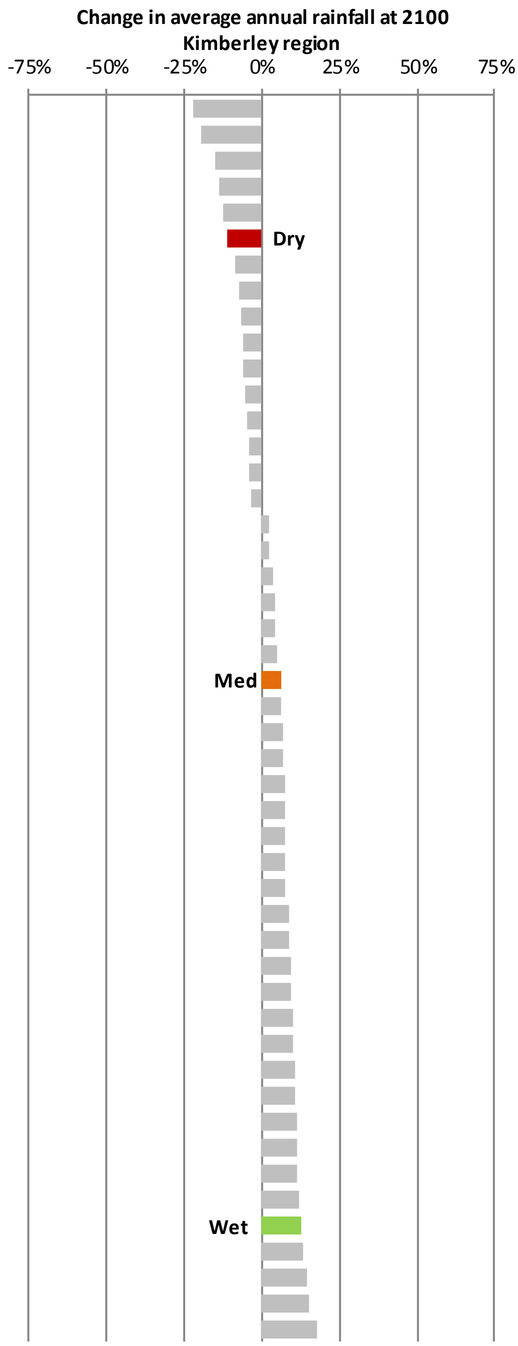
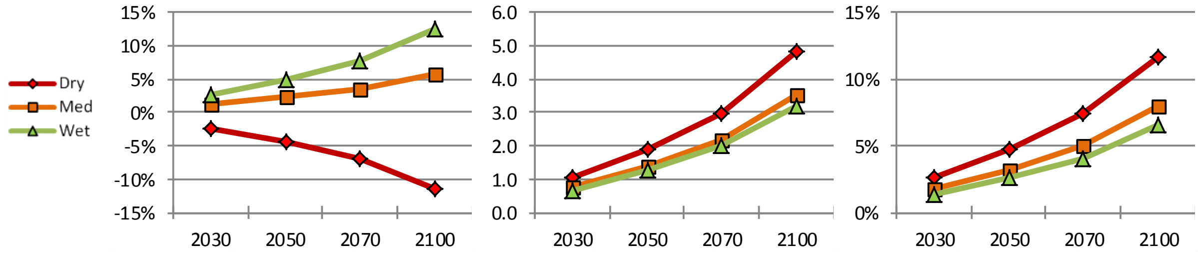


Table 3-8: Regional rainfall, temperature and PET anomalies for the Kimberley region at 2030, 2050, 2070 and 2100 relative to the 1961–90 baseline

	Mean annual rainfall anomaly (%)			Mean daily temp. anomaly (°C)			Mean annual PET anomaly (%)		
Year	**Dry**	**Med**	**Wet**	**Dry**	**Med**	**Wet**	**Dry**	**Med**	**Wet**
2030	-2%	1%	3%	1.0	0.7	0.7	3%	2%	1%
2050	-4%	2%	5%	1.9	1.4	1.3	5%	3%	3%
2070	-7%	4%	8%	3.0	2.2	2.0	7%	5%	4%
2100	-11%	6%	13%	4.8	3.5	3.2	12%	8%	7%



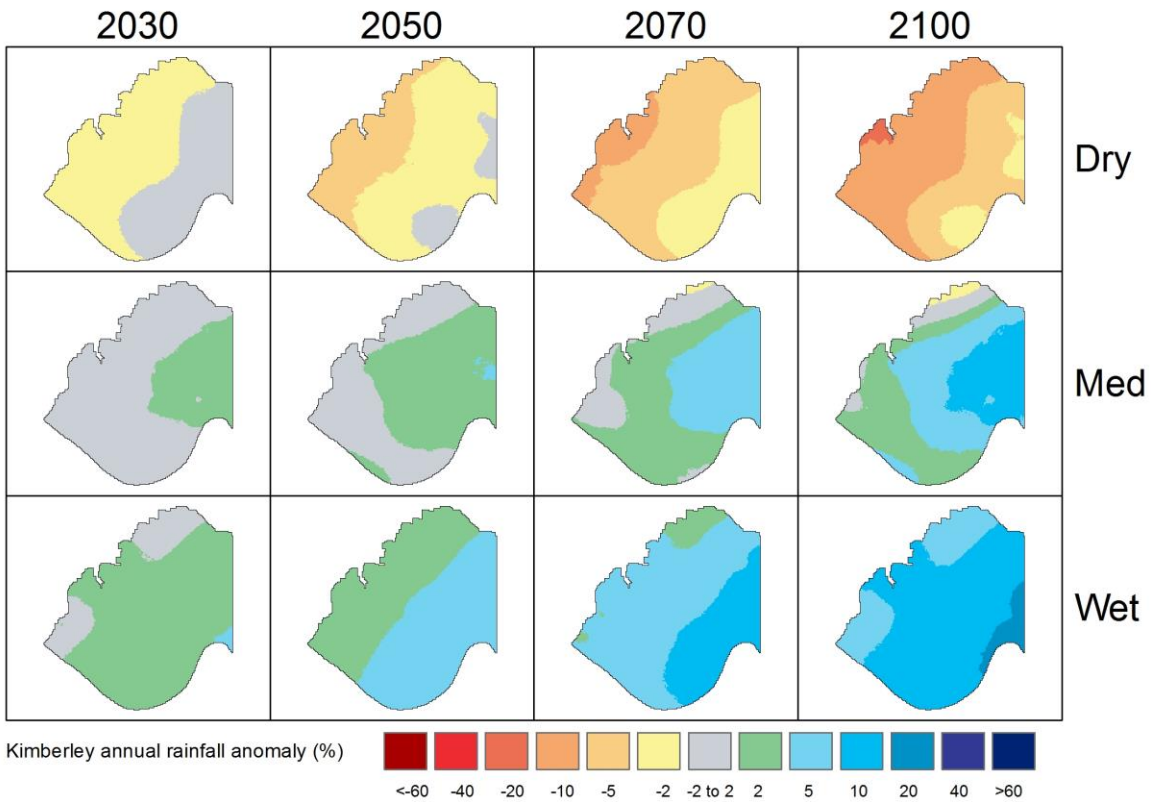


Figure 3-5: Change in average annual rainfall relative to the baseline period for Kimberley region for representative wet, median and dry scenarios at future time horizons

Central region

The results for this region are not as clear as for the South-west region. There is no consistency in the direction of the GCM results with both warmer wetter and warmer drier climates projected by different GCMs.

The current GCM projections don't compare well with historical regional climate data. Observed rainfall trends vary substantially from the range of projections produced by the scenarios. The rainfall range for the scenarios is narrower than the historical inter-annual and decadal rainfall variations. That is, the observed historical climate variability is stronger than the climate change signal.

Therefore, use the long-term historical climate rather than the Central region scenarios in water resource planning, as the scenarios are unlikely to include sufficient variability to capture the uncertainties in future rainfall. Although considerable uncertainty surrounds the rainfall anomalies for these regions, the temperature and PET anomalies may still be appropriate for example in calculating crop water demand or evaporation from open water bodies.

Percentile ranking of GCM results

The Central region is the largest and most sparsely populated subdivision considered in this study. Given the size of the region, and its varied climatic influences it is difficult to select individual scenarios which have consistent rainfall trends across the entire region. Many GCMs project little change in average annual rainfall for the whole region while still showing strong trends in some areas. Around half of the GCMs show only ± 5% change in rainfall by the end of the century but the strongest responding GCMs show changes of –50% and +25% by 2100.

The dry scenario selected for the central region corresponds to the 10^{th} percentile ranked GCM. The median scenario is one rank drier than the true 50^{th} percentile, and was selected as it was spatially consistent across the region. The wet scenario is one rank wetter than the 90^{th} percentile GCM, and was selected as it shows a consistent wetting trend throughout the region. Note that as relative humidity anomalies were not available for the wet scenario, zero change from baseline relative humidity was assumed for PET and evaporation calculations for the future time horizons.

Regional patterns of change

For the dry scenario, downward rainfall trends are projected across the region, more pronounced in the South-west and weaker inland of the Kimberley. Average annual rainfall is projected to decrease by an average of 17% across the region by 2100, with a relatively large temperature rise of 4.1°C and an associated 12% increase in PET.

For the median scenario, moderate 2.7 °C rises in average temperature are expected with effectively no change in average annual rainfall across the region while PET is projected to increase by 7% by the end of the century.

The wet scenario shows a moderate wetting trend across the region, strongest in the northern and central parts. Zonal average rainfall is projected to increase by 15% by the end of the century. Average temperature is projected to increase by 2.6 °C for this scenario, with PET increasing by 5%.

Table 3-9: GCM results ranked by change in zonal rainfall at 2100 to 1961–90 for the Central region

Scenario		Mean annual rainfall		Mean annual temp.		
		Anomaly	Anomaly	Anomaly	Anomaly	
SRES	GCM	(mm)	(%)	(°C)	(%)	
A1FI	GFDLCM21	-109	-49.7%	5.30	24.6%	
A2	GFDLCM21	-99	-45.2%	4.58	21.3%	
A1B	GFDLCM21	-81	-37.1%	3.56	16.5%	
B2	GFDLCM21	-72	-32.9%	3.12	14.5%	
A1FI	FGOALS1G	-38	-17.3%	4.08	19.0%	←10th
A2	FGOALS1G	-33	-14.9%	3.53	16.4%	
A1FI	GFDLCM20	-32	-14.7%	5.20	24.2%	
A2	GFDLCM20	-28	-12.7%	4.50	20.9%	
A1B	FGOALS1G	-25	-11.6%	2.74	12.7%	
B2	FGOALS1G	-22	-10.2%	2.41	11.2%	
A1B	GFDLCM20	-22	-9.9%	3.49	16.2%	
B2	GFDLCM20	-19	-8.7%	3.07	14.3%	
A1FI	UKHADGEM	-18	-8.2%	3.40	15.8%	
A2	UKHADGEM	-16	-7.1%	2.94	13.7%	
A1B	UKHADGEM	-12	-5.5%	2.29	10.6%	
B2	UKHADGEM	-11	-4.8%	2.01	9.3%	
A2	MRI-232A	-7	-3.1%	4.28	19.9%	
A1FI	MRI-232A	-7	-3.0%	4.96	23.1%	
A1B	MRI-232A	-5	-2.5%	3.33	15.5%	
B2	MRI-232A	-5	-2.2%	2.92	13.6%	
B2	BCCRBCM2	4	2.0%	2.59	12.1%	
B2	MIROC-HI	5	2.1%	2.37	11.0%	
A1B	BCCRBCM2	5	2.3%	2.95	13.7%	
A1B	MIROC-HI	5	2.3%	2.70	12.5%	
B2	GISS--ER	5	2.4%	3.57	16.6%	←50th
A1B	GISS--ER	6	2.7%	4.06	18.9%	
A2	MIROC-HI	7	3.0%	3.47	16.1%	
A2	BCCRBCM2	7	3.0%	3.80	17.7%	
A1FI	MIROC-HI	8	3.5%	4.02	18.7%	
A2	GISS--ER	8	3.5%	5.23	24.3%	
A1FI	BCCRBCM2	8	3.8%	4.39	20.4%	
B2	MIROCMED	9	4.0%	2.12	9.9%	
A1FI	GISS--ER	9	4.2%	6.05	28.2%	
A1B	MIROCMED	10	4.5%	2.42	11.3%	
B2	CCSM--30	12	5.6%	2.51	11.7%	
A2	MIROCMED	13	5.8%	3.11	14.5%	
A1B	CCSM--30	14	6.4%	2.86	13.3%	
A1FI	MIROCMED	15	6.7%	3.60	16.8%	
B2	MPIECH-5	15	7.0%	2.69	12.5%	
A1B	MPIECH-5	18	8.0%	3.06	14.2%	
A2	CCSM--30	18	8.2%	3.68	17.1%	
A1FI	CCSM--30	21	9.5%	4.26	19.8%	
A2	MPIECH-5	23	10.3%	3.94	18.3%	
A1FI	MPIECH-5	26	11.9%	4.56	21.2%	←90th
B2	ECHO---G	32	14.4%	2.62	12.2%	
A1B	ECHO---G	36	16.4%	2.99	13.9%	
A2	ECHO---G	47	21.2%	3.85	17.9%	
A1FI	ECHO---G	54	24.8%	4.45	20.7%	

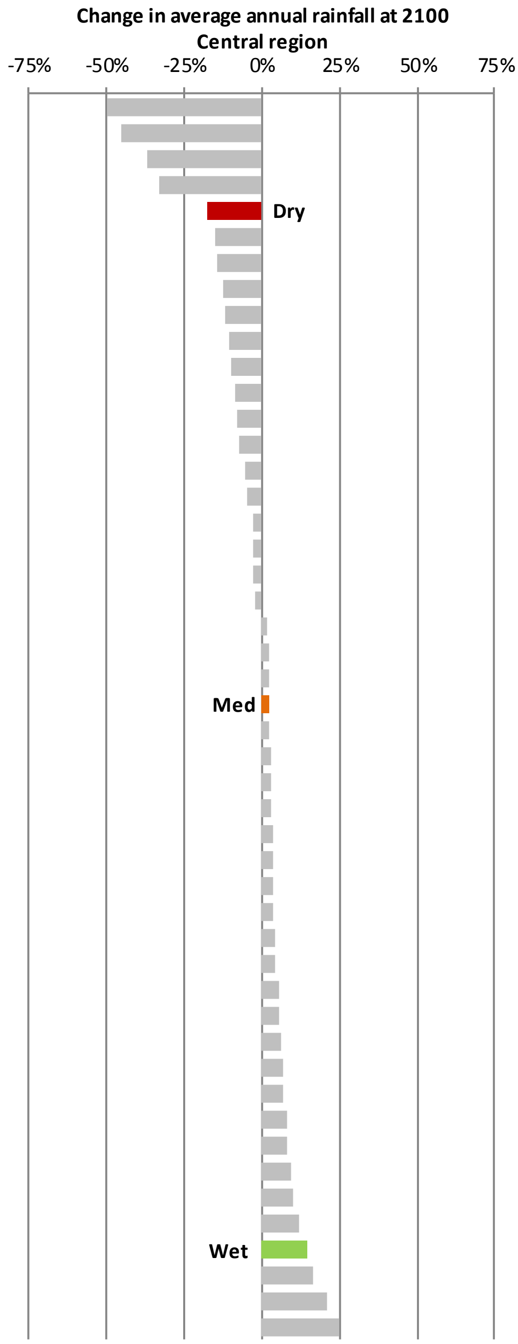
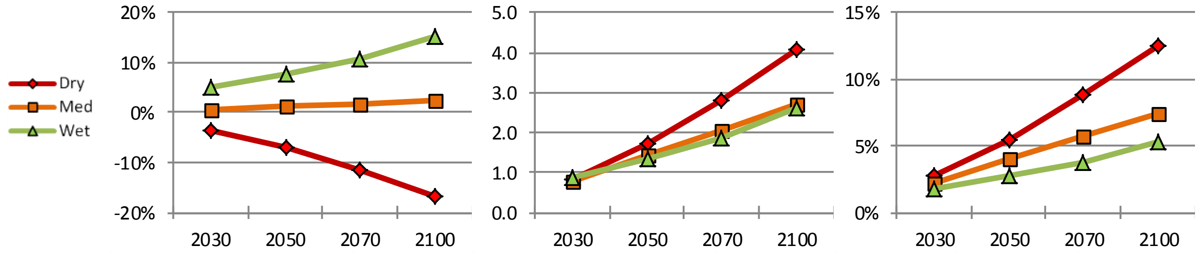


Table 3-10: Regional rainfall, temperature and PET anomalies for the Central region at 2030, 2050, 2070 and 2100 relative to the 1961–90 baseline

	Mean annual rainfall anomaly (%)			Mean daily temp. anomaly (°C)			Mean annual PET anomaly (%)		
Year	**Dry**	**Med**	**Wet**	**Dry**	**Med**	**Wet**	**Dry**	**Med**	**Wet**
2030	-3%	1%	5%	0.8	0.8	0.9	3%	2%	2%
2050	-7%	1%	8%	1.7	1.4	1.4	6%	4%	3%
2070	-12%	2%	11%	2.8	2.1	1.9	9%	6%	4%
2100	-17%	2%	15%	4.1	2.7	2.6	12%	7%	5%



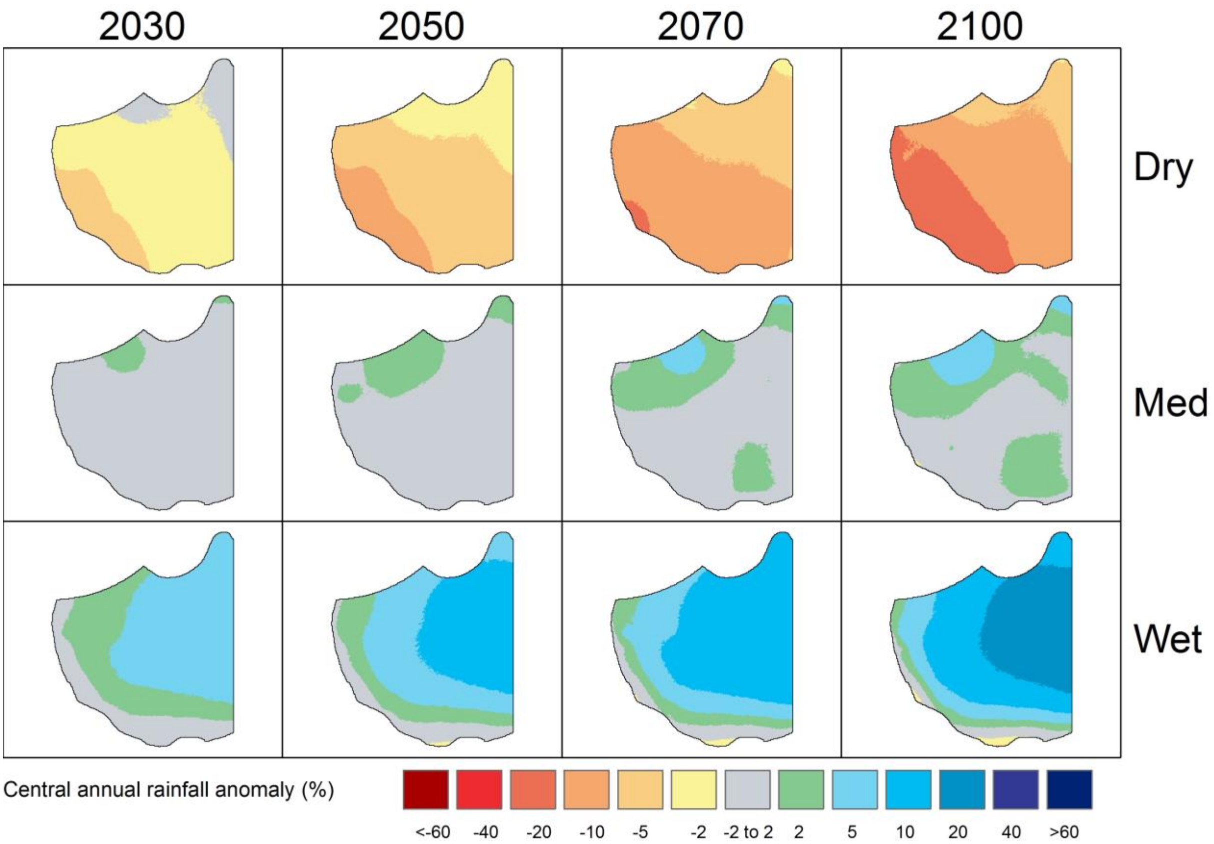


Figure 3-6: Change in average annual rainfall relative to the baseline period for Central region for representative wet, median and dry scenarios at future time horizons

4 Guidance for applying climate scenarios to water resource modelling, planning and management

The scenarios developed here will be used within the South-west region of the state to reduce uncertainty about climate change and to be consistent and systematic in the management of water resources.

When and where to use the climate scenarios

The primary purpose of the scenarios is to support yield calculations for groundwater and catchment modelling using a consistent method for the South-west. The results need to be analysed before they are implemented and depending on the application may not adequately represent the uncertainties associated with climate projections, particularly in areas with highly variable rainfall.

It is intended that, within the South-west region, the scenarios will be used for the following departmental business:

- Groundwater modelling to support allocation planning and to assess changes in groundwater recharge, flow and levels under a changing climate
- Surface water and catchment modelling to support allocation planning
- Assessment of the impacts of climate change on hydrological and nutrient modelling supporting water quality improvement planning
- Modelling the influence of climate change on integrated surface water and groundwater systems
- Future supply and demand projections modelling associated with water supply planning.

In addition, the scenarios *may* be appropriate for use for the following applications in the South-west region:

- Land use planning
- Assessment of subsurface drainage requirements in a changing climate
- Assessment of the effects of climate change on environmental water requirements
- Assessment of the suitability of managed aquifer recharge in a changing climate; for example, the availability of subsurface drainage water for aquifer recharge and changes to aquifer storage capacity.

There is subjectivity involved in deciding whether a climate scenario is appropriate for a given application, and it is important that the practitioner independently considers the scenarios in the context of the intended application. The practitioner needs to be satisfied with the scenarios before they are used in a project, and they should be checked, analysed and understood before they are used.

It is recommended that the following criteria are assessed before using these climate scenarios:

- The inter-annual rainfall variability in the scenario adequately represents the recent, and long-term variability recorded; for example, by comparing the coefficient of variation with the magnitude of the rainfall anomalies.
- The trend in rainfall observed since 1990 is broadly consistent with the range of trends projected for 2030 by the wet, median and dry scenarios. Where this is not the case, it may be an indication that the scenarios do not capture the full range of climatic variability and the trend magnitude for the location. In these cases it may be preferable to use the location's long-term historical record.
- The intended application of the scenarios requires estimates of seasonal changes but not changes in daily rainfall distribution (e.g. occurrence of rain days) or rainfall intensity. For example, the scenarios are not appropriate for flood modelling but may be appropriate for setting antecedent conditions.
- The intended application focuses on rainfall, and not on temperature or some other variable – as the scenarios were selected on the basis of changes of total annual rainfall. For example, the scenarios are not appropriate for assessing changes in the number of days of extreme fire risk.

The applicability of the scenarios for each of the regions analysed is shown in Table 4-1. The table is intended as a guide, and the practitioner should consider the implications of scenario analysis for each project on an individual basis. In most cases outside of the South-west, variability in future climate will be better estimated by analysing the long-term historical record at the location.

The scenarios represent the projected rainfall variations around a future time horizon (e.g. 2030) that might be expected based on GCM results. A single year in the future climate series does not represent a particular future year or prediction. Rather, the entire series represents the average change which might be expected for a given amount of global warming at a future point in time. Therefore, statistics derived from the scenarios should use the entire period. For example, a simulation of the future dry climate at 2030 using a groundwater model could be used to calculate average change in recharge at 2030 or the number of years of below-average recharge for the whole 30-year period. The results could not be used to calculate recharge or groundwater level for a specific year. The intention of the scenarios is to provide general information on the possible influence of climate change within a reasonable range to enable responsible, informed risk assessment and decision making.

Rainfall variability and climate projections

The IPCC (2007b) note that *"Responses to external forcing in regional precipitation trends are expected to exhibit low signal-to-noise ratios".* In this instance the 'signal' refers to the measured or observed trend in rainfall, and the noise refers to the natural variability of rainfall. In regions which have high signal to noise ratio for rainfall, the magnitude of the trend will be large relative to the coefficient of variation (CV – mean annual rainfall divided by standard deviation of rainfall). Where rainfall is highly variable and the projected trend in average rainfall is small, GCM projections may add little value to estimating changes in rainfall, as the annual or decadal variability is likely to have more influence for a given time horizon than the underlying trend.

Appendix E shows the coefficient of variation for the long term historical rainfall record (1900–2010) in comparison to rainfall projections in 2100 for the wet, median and dry scenarios. For locations in south-west WA, the ratio the projected rainfall trend to CV is substantially higher than for the remainder of the state.

Table 4-1: General applicability of climate scenarios by project and region

Region	**Inter-annual variability appropriate in future climate scenarios**	**Recent rainfall trend is within the range projected by future climate scenarios**
South-west	**Yes.**	**In most cases.** Some locations have a recent wetting or drying trend that is not captured by the scenarios.
Central-west	**In some cases.** Variability in rainfall should be compared for historical and projected climate. Inland areas are generally more variable. Long term historical rainfall should be included as a scenario for comparison.	**In most cases.** Drying or stable rainfall is projected in the west. However, areas in the east show a recent wetting trend above that projected in the future wet scenario.
Central	**In some cases.** Parts of this region have very high variability in rainfall, and the 30yr period may be insufficient to capture this variability.	**In some cases.** Strong trends in rainfall are present in some parts of the Central region.
Kimberley	**In some cases.** Parts of this region have very high variability in rainfall, and the 30yr period may be insufficient to capture this variability.	**In some cases.** The Kimberley region has experienced a strong wetting trend recently beyond the range projected by the representative scenarios.
Pilbara	**In some cases.** The Pilbara has high-interannual variability. In some locations the last decade has experienced extreme wet years which were not present in the WMO period. As such, projected scenarios may under-estimate potential for very-wet years. Scenarios may be used, but the long-term record should also be analysed.	**In some cases.** Strong wetting and drying trends are present in different areas of the Pilbara. Projected scenarios should be considered case-by-case.

How to make future climate scenarios at point locations

Monthly anomalies are available in GIS for the wet, median and dry scenarios for 0.05° grid cells across the five regions for the eight variables considered. A simple monthly scaling method can be used to modify baseline climate data from 1961 to 1990 for any location within WA.

Applying the monthly anomalies is a process of identifying the time horizon and variable of interest, specifying a location, and extracting the monthly anomaly from the appropriate gridded data. The monthly anomalies are then used to scale the baseline dataset at the same location, using the correct scaling factor for each month. The baseline time period which is scaled must always be the period 1961–90, as the anomalies in this study are reported relative to this period.

For example, at a given location in the South-west region a daily time-series of the future climate in 2030 can be calculated by using 1961–90 observed data from a meteorological station and multiplying the time-series by the monthly scaling factors. This would result in a hypothetical climate series of 30 years, centred on the year 2030. This future climate can then be used in further analysis and compared to other time periods or scenarios.

Although the baseline period used for scaling is 1961–90, the scenarios can be compared with any period of interest; for example, the future climate may be compared with the long-term historical record or the most recent 10-year period.

Anomalies are reported in units of percentage change (from the equivalent baseline month) with the exception of temperature. Temperature anomalies are reported in units of absolute change in temperature. Figure 4-1 shows the monthly scaling process applied to data from the Perth Airport meteorological station.

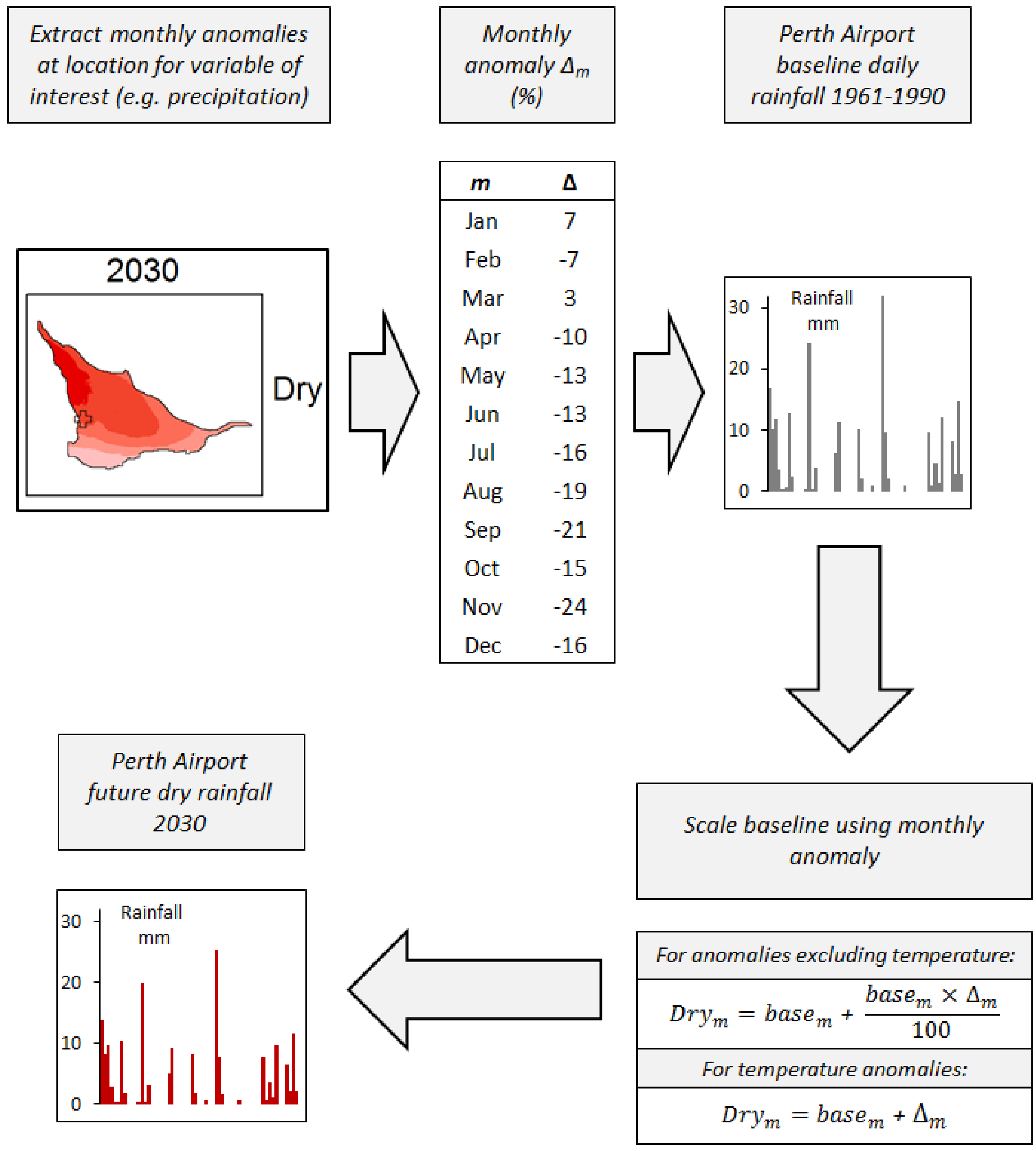


Figure 4-1: Flow diagram showing method of monthly scaling

Examples of scaled datasets at point locations

This section provides examples of scaled future time-series derived as described in Figure 4-1. Two examples are presented: the first is a scaled dataset using data from the Perth Airport in the South-west region; and the second using data from Halls Creek in the Kimberley region. In the Perth Airport example, the climate projections are consistent with rainfall variability and trend, and are appropriate for use in catchment and aquifer yield estimation. In the Halls Creek example, the high inter-annual variability and rainfall trends are not captured by the scenarios, making them inappropriate for yield estimation, so estimates of potential changes in rainfall should be based on the historical data.

Perth Airport

Baseline rainfall at Perth Airport was scaled using the climate anomalies developed in this study to generate wet, median and dry scenarios for 2030. Figure 4-2 shows box and whisker plots of the annual rainfalls for these scenarios compared to three historical periods (WMO 1961–90, the recent 30 years 1981–2010 and the recent 10 years 2001–10). The plot shows that the dry scenario has a distribution of annual rainfall similar to the recent 10-year period and is substantially drier than the WMO baseline period and the recent 30-year period.

Figure 4-2 also shows the long-term scenarios generated at Perth Airport in comparison to historical rainfall, and a 30-year moving average of annual rainfall. At this location, the rainfall trend is tracking along the dry scenario, and the wettest and driest years from the recent 10-year period are within the range of the projected scenarios. The wettest and driest projected years were calculated by scaling the baseline dataset for each future time horizon and calculating the wettest and driest year from the full 30 year series.

It is possible that Perth’s average annual rainfall in 2030 will be outside the ranges projected by the scenarios. However, the analysis presented here demonstrates that both the variability in annual rainfall and recent trends in rainfall are consistent with the range shown by the scenarios. Therefore, at this location the three scenarios are considered appropriate for use in estimating possible future catchment and aquifer yields under changing rainfall conditions.

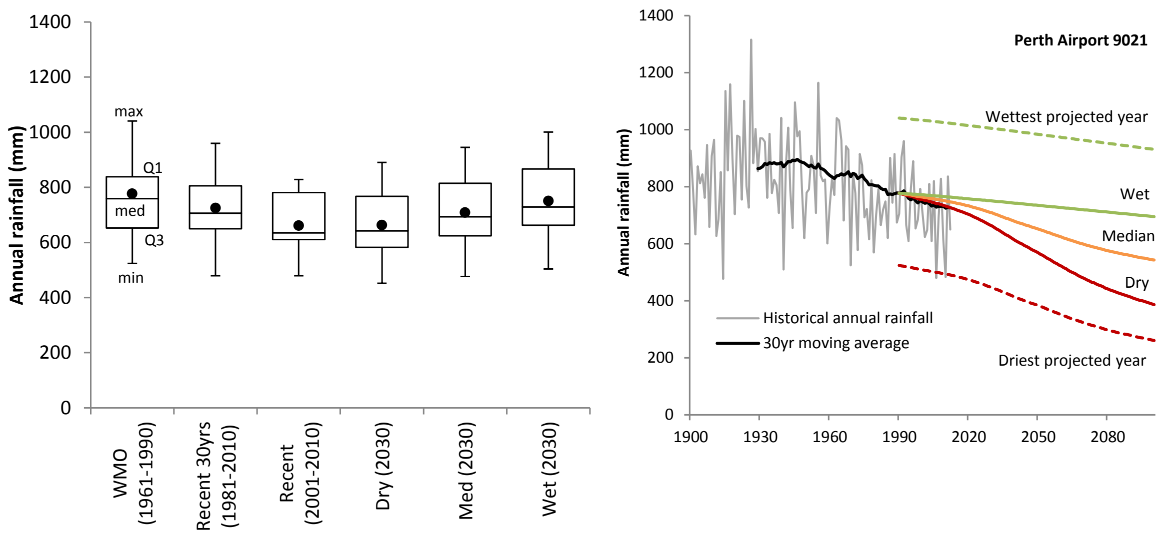


Figure 4-2: Box and whisker plots of annual rainfall for historical periods and climate scenarios for 2030 (mean showed by dot); and scenarios at Perth Airport, projected mean annual rainfall to 2100 for the wet, median and dry scenarios

Halls Creek Airport

Figure 4-3 shows climate scenarios developed for the Halls Creek Airport in the Kimberley region in the form of a box and whisker plot and long term projection. Compared with Perth, this location has highly variable annual rainfall that can vary between 200 and 1200 mm. The area has also experienced a strong wetting trend since 1960. The box and whisker plot shows that the wet, median and dry scenarios fail to represent the inter-annual variability in rainfall observed over the last 30 years, in particular, the extremely wet years. In addition, the wet scenario only projects a moderate wetting trend. However, the 30-year moving average of annual rainfall shows a much stronger upward trend in rainfall. So, it is unlikely that the selected scenarios will adequately capture the range of possible annual rainfalls at 2030 using only the scaled 30-year baseline data.

To calculate potential catchment and aquifer yields at this location, the long-term rainfall record is likely to better represent the full range of potential rainfall scenarios. This does not preclude the use of the wet, median and dry scenarios, but requires additional scenarios to be considered in analysis; for example, selecting dry or wet periods from the long-term record may be more appropriate for some modelling exercises.

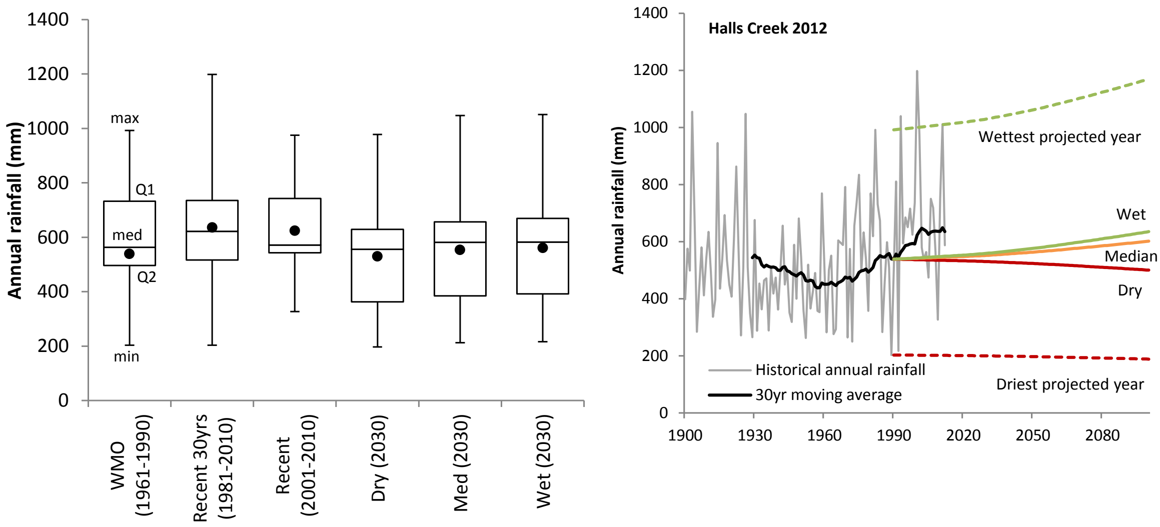


Figure 4-3: Box and whisker plots of annual rainfall for historical periods and climate scenarios at 2030 (mean showed by dot); and climate projections at Halls Creek Airport, projected mean annual rainfall to 2100 for the wet, median and dry scenarios

Rainfall projections for other locations

Appendix F shows graphs comparing historical rainfall for the meteorological stations mapped in Figure 1-5, with the future wet, median and dry scenarios. The graphs give some indication of how the projections compare with the variability of historical rainfall. The ‘wettest’ and ‘driest’ projected years indicate the highest and lowest rainfall years that would result from scaling the baseline rainfall, using the wet and dry climate anomalies respectively.

Which scenario to use for water resource applications based on uncertainty and risk management?

Constructing and using a range of climate scenarios aids decision making in an environment of uncertainty. Quantifying uncertainty is a way of describing the extent to which things cannot be accurately measured. For climate science, this term has a specific and limited meaning – it is concerned with how to reduce errors in projections as far as possible, and to quantify the remaining known errors. There is a relatively high level of *certainty* that a simulated climate for a particular location will be within the range of the selected 'wet' and 'dry' scenarios. There is more uncertainty associated with climate projections for later in the 21st century relative to those for earlier in the century, and the recent observed variability in climate may not be representative of potential long-term changes in climate.

The range of possible futures can be used in conjunction with risk-based techniques to justify the basis of a certain selection. Climate-change risk assessment and management is an emerging, inter-disciplinary science, and new approaches and methods for incorporating information about future climates into assessments are constantly being developed (CSIRO 2007). In the context of water resource management, climate uncertainty and the associated risk are defined by the range of scenarios (wet, median and dry) used to underpin a plan or policy.

Various methods can be used by policy makers to select which climate projection(s) to use in planning or policy. A range of approaches for water resource management projects are outlined in Table 4-2. The most appropriate method is largely dictated by a project's objectives and context, and a 'one size fits all' approach is generally not suitable. Given that consistency in the application of climate science is important for this project, it is recommended that the approaches listed in Table 4-2 assist in the development of a standard approach or framework for each discipline within the department (for example, allocation, drainage, or water supply planning).

The framework will vary based on the management focus and the attendant risks posed by the climate projections. For example, a framework for drainage is likely to focus on the risks of flooding while a framework for water allocation planning will focus on the risks of water shortage.

The applicability of the climate scenarios for each of the regions in Western Australia was discussed in Section 3.2. In the South-west region it is appropriate to apply the scenarios to support water plans and strategies but beyond the South-west, the historical climate should be used instead of (or as well as) the scenarios. Before a climate scenario is used, the data needs to be analysed against the criteria in Section 3.2.

For areas where the scenarios are not appropriate for use in a project or plan, use historical climate sequences, as these are likely to provide a better estimate of the future climate. Like the scenarios, the most appropriate method for the specific use of historical climate data in projects and plans is dictated by a project's objectives and context, and once again, a 'one size fits all' approach is not suitable. A standard approach or framework for each discipline within the department should also include the proposed use of historical data where the climate scenarios are not appropriate. A range of approaches for water resource management projects where historical climate is used for a project or plan is outlined in Table 4-3.

Figure 4-4 provides an example of how the water allocation planning branch of the department developed a framework to incorporate future climate into water allocation planning (Water Allocation Planning, DoW, in prep).

Table 4-2: Common approaches to incorporate the range of climate scenarios and aid decision making in water resource management planning and policy

	Approach	Advantages	Disadvantages
1	A risk analysis is performed before modelling commences (through methods such as stakeholder forums, multi-criteria analysis, cost-effectiveness) to estimate the relative risk of selecting a 'dry', 'median' or 'wet' future climate to underpin the project or plan. The choice of climate to be used in the plan is dependent on the outcomes of the risk analysis.	• Takes into account the range of uncertainties in future climate. • Transparent and defensible selection process which is based on risk, so encompasses best management principles. • A suite of model scenarios does not need to be simulated for 'wet', 'median' and 'dry' climates, so less time-consuming than (2).	• Risk analysis can be subjective and swayed by interest groups on the panel. • Time consuming and can be expensive. • It can be difficult to communicate, as it appears that a future climate is 'selected' even when all future climates can be equally probable. • Can be difficult to quantify the risk to the resource if the modelling is not performed *a priori.*
2	All three climate scenarios ('dry', 'median' and 'wet') are simulated in a surface water or groundwater model for a range of management options. Risk-based techniques are used to assess the outcomes of each option under the 'dry', 'median' and 'wet' scenarios. The choice of management option to be used in the plan is dependent on the outcomes of the risk analysis.	• A solution is calculated for each climate scenario, so provides a better understanding of sensitivities of the system under the range of potential climates. • Takes into account the full range of uncertainty in future climates. • Process is transparent and defensible if done correctly, and based on risk-process so encompasses best management principles.	• Many scenarios are required – so large amounts of data and analysis are required. • Time consuming and expensive, and in some cases more onerous than necessary for the requirements of the project. • Risk based processes are subjective, and can be swayed by the beliefs or motivations of panel members.
3	The 'precautionary principle' is applied, and the most conservative climate scenario is selected.	• A well-established method of policy making when uncertainty prevails, on the basis that it is better to be safe than sorry. • Quick and simple to apply (does not require a detailed risk analysis). • Does not require a full suite of model scenarios to be simulated for 'wet', 'median' and 'dry' climate. • Unlikely to result in less water available than is predicted in the plan.	• There is likely a perception of favouring environment over users if poorly communicated – as it can be viewed as too risk averse. • Does not account for all of the risks associated with predicting a drier than average future; for example, the public backlash that may result if a 'dry' scenario is selected for allocation planning and rainfall increases in the next decade (e.g. Murray Darling after millennium drought).
4	The 'median' scenario is selected as it is a trade-off between risk of predicting a too 'wet' or a too 'dry' future climate.	• Quick and simple to apply (does not require a detailed risk analysis). • Does not require a full suite of model scenarios to be simulated for 'wet', 'median' and 'dry' climate. • Can be communicated as being neither overly risky or too risk adverse. • Can be suitable for studies where climate sensitivity is not large or not the most important factor for a project.	• Does not take into account the full range of uncertainties in future climate. • As it is not a risk-based approach, it does not treat sensitive or high-risk systems differently from systems with low climate risk. • Can be difficult to defend if not assessed against a 'wetter' or 'drier' scenario.

Table 4-3: Common approaches to incorporate historical climate in water resource management planning and policy

Approach	When to use	Advantages	Disadvantages
Using real historical climate data			
The previous 'x' years of historical data is used in a plan (where 'x' may be 10, 20, 30, 40, 50... years)	● Where the previous 'x' years is representative of the entire climate sequence (average rainfall and variation in rainfall). ● Where large periods of data are not available and real data is required. ● Where models have relatively long run-times.	● Fast run times compared to models with many decades of data. ● Real data preserves any auto correlation within the time series and variability of the data. ● There is consistency amongst all models in the region as to the time-period that is used.	● The past 'x' years may not be representative of the early part of the century (in terms of average climate and climate variability). ● Can be difficult to accurately quantify climate uncertainty for a project (a Monte-Carlo approach may not be possible using observed data).
The entire record of data is used	● Where there is a very large variability in rainfall (e.g. the rainfall is driven by periodic inter-annual cyclonic events). ● Where decadal droughts or wet periods have occurred in the past century. ● Where long periods of real data are available.	● Where long periods of real data are available. Takes into account decadal variations in climate which may not be captured in the recent historical climate. ● Where long periods of real data are available. Real data preserves any auto correlation in the time-series and variability of the data. ● Where long periods of real data are available. Utilising the entire dataset can provide greater precision around the variability in climate.	● There may not be consistency amongst all models in the region as different time frames may be used. ● Can be difficult to accurately quantify climate uncertainty for a project (a Monte-Carlo approach may not be possible using observed data). ● Slower run times for models which may inhibit model projects.
Selection of 'wet' and 'dry' periods to produce wet and dry future scenarios	● When future climate projections using GCMs are not appropriate, and it is not feasible to use the entire modelling period. ● Where there are significant 'wet' or 'dry' periods throughout the rainfall record (e.g. dry period 1930s and wet period in the post-2000 in Kimberley).	● Serial autocorrelation between rainfall years is preserved (as the time series is based on real data). ● Easy to communicate, as we can relate it to a period in history.	● There may not be consistency amongst all models in the region as different time frames may be used or different wet/dry periods may be used.
Using simulated climate data based on historical climate sequence			
Interpolated data (e.g. SILO) where 'x' years of historical data is used.	● Where the accuracy of the historic data is not important. ● Where large periods of data are not available and real data is required. ● Where the previous 'x' years is representative of the entire climate sequence .	● Continuous time-series means no data-gaps. ● Preserves any auto correlation within the time series and variability of the data. ● There is consistency amongst all models in the region as to the time-period that is used.	● There is consistency amongst all models in the region as to the time-period that is used. Not as accurate as real data, in some areas where there is very little real data (regionally) the accuracy may be questionable (e.g. in the early century for the Pilbara).
Statistically simulated time series data (Markov Models, generalised linear models, direct sampling methods)	● Where hundreds or thousands of years of data are required for the model (eg to quantify climate uncertainty or variability).	● Good for quantifying climate uncertainty (Monte-Carlo approaches). ● Can generate data sequences much longer than available historic data. ● Can capture variability and co-variation of the real data using statistical methods.	● May not preserve auto-correlation within the real time series, and may not represent variability adequately. ● Can be difficult to set up, and difficult to replicate if random number seeds are used. Also difficult to present and communicate effectively. ● Only as accurate as real data that was used to generate it.
Probabilistic data to determine 1 in 100, 200, 500… annual rainall events	● Flood applications, where flooding is related to an entire year's rainfall.	● Can use different ARI periods to assess different levels of flooding risk. ● Can extrapolate annual rainfall quantities to account for rainfall quantities outside of the observed time series.	● Mostly relevant for flooding/drainage applications, as method does not create a time-series of data which is useful for most water resource projects.

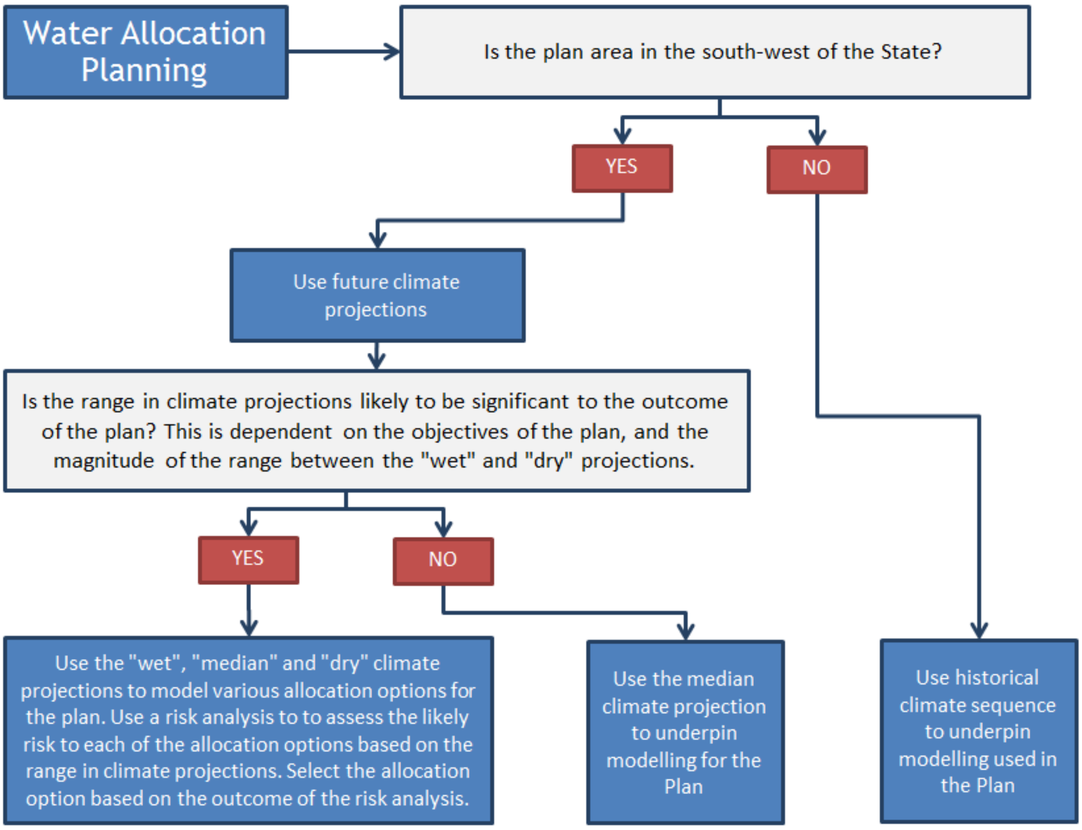


Figure 4-4: Department framework used to select an approach to incorporate climate in water allocation planning

5 Concluding remarks

This project used a systematic process to select climate scenarios for five regions of WA. The process involved selecting four of the six emissions scenarios developed in the IPCC *Special Report on Emissions Scenarios* (IPCC 2000): A1FI, A2, A1B and B2 scenarios. Results from 12 of the 23 general circulation models were used to extract climate projection information for WA, using measures of model skill to select the subset of models. A standard baseline period of 1961–90 was selected for use in simple scaling to derive scenarios. By ranking results from the GCMs and emissions scenarios, it was possible to select a range of projected rainfall changes for each region. From these results representative dry, median and wet scenarios were selected to provide a standard set of scenarios in each region.

In the South-west region, all of the GCMs analysed showed rising temperature and falling rainfall trends in the 21st century. The dry scenario indicated that, relative to the baseline period, the region on average would experience a 14% reduction in average annual rainfall by 2030 and a 0.7 °C rise in temperature. The median scenario showed a 5% reduction in rainfall and the wet scenario showed only a 2% reduction. All scenarios showed a steady rise in temperature and PET over the 21st century. In the Perth region, the dry scenario showed a distribution in annual rainfall similar to the last decade. For the South-west, the range of rainfall anomalies encompassed by the scenarios is consistent with previous studies and also with the observed trends over much of the region. Based on the analysis completed in this study, the wet, median and dry scenarios are likely to be reasonable estimates of the potential climate by 2030, and are appropriate for use in hydrological modelling and impact assessment for the region.

For the remaining regions of the state, analysis showed less consistency between GCM projections, and observed rainfall trends vary substantially from the changes estimated by the climate scenarios. In the arid and summer rainfall dominated parts of the state, rainfall variability is high, and the substantial decadal variation in rainfall is unlikely to be replicated by scaling a 30-year baseline period. Given these issues, it is recommended that the longest available historical record is used for hydrological modelling and impact assessment, as the scenarios are unlikely to include sufficient variability to capture the uncertainties in future rainfall. All GCMs project higher temperatures and incoming solar radiation. Since changes in surface temperature, evaporation and PET are directly related to the radiation balance, the scenarios for these variables may be of use in calculating evaporation losses or crop demand.

This study aimed to objectively define climate scenarios for five regions in WA, using results from models in the CMIP3 archive. General circulation models are the best available tool for making projections about changes to climate. However, there are many sources of uncertainty, and it is not possible to know that the range of projections made by even a large suite of GCMs will capture the full range of possible climates. So, the scenarios developed as part of this project should be used with caution. They represent a range of possible climates, but they will obviously not be the exact climate experienced in the future. Practitioners using the scenarios developed here need to be aware of the baseline period, the variability of rainfall, the recent observed trends in rainfall, and assess the appropriateness of the scenarios for the application.

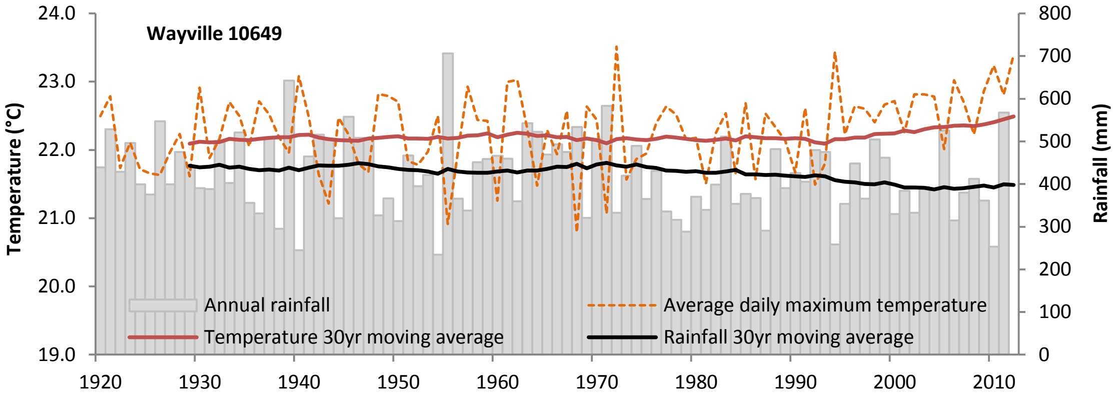
The IPCC's fifth assessment report (IPCC 2013) and the associated model results are now available in the CMIP5 archives. CSIRO and the Bureau of Meteorology are currently working on projects analysing the model results in an Australian context (CSIRO 2012), and the report associated with this work is now available (CSIRO & BoM 2015). It discusses the latest global emission scenarios and their influence on Australian climate. As the datasets associate with this are made available the department will review, and may revise the standard scenarios developed for Western Australia.

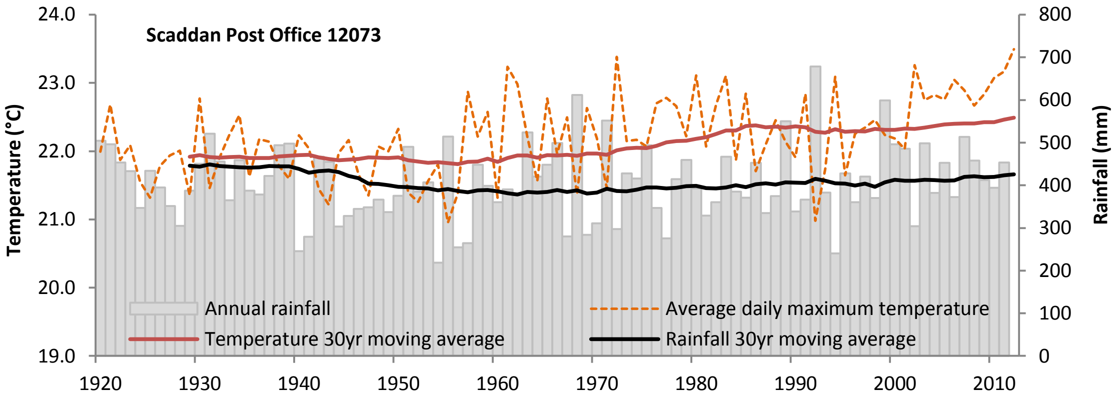
Appendices

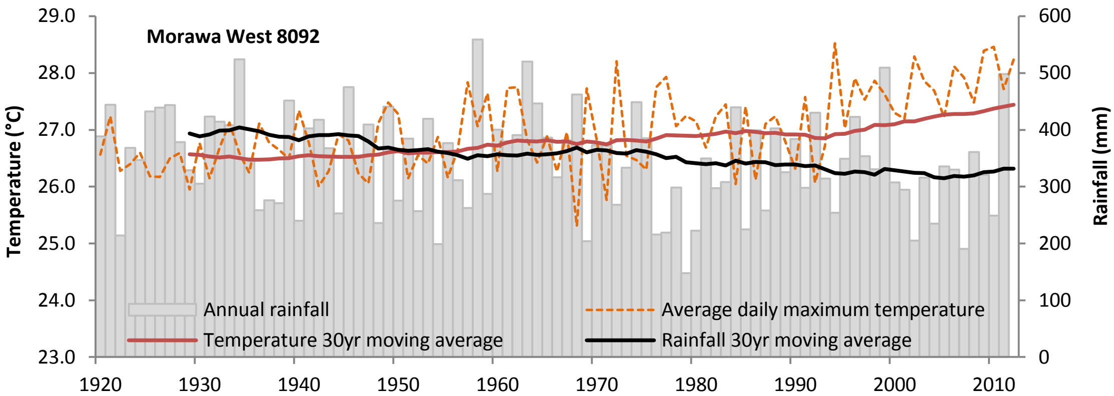
Appendix A: Long term rainfall and temperature record for selected meteorological stations

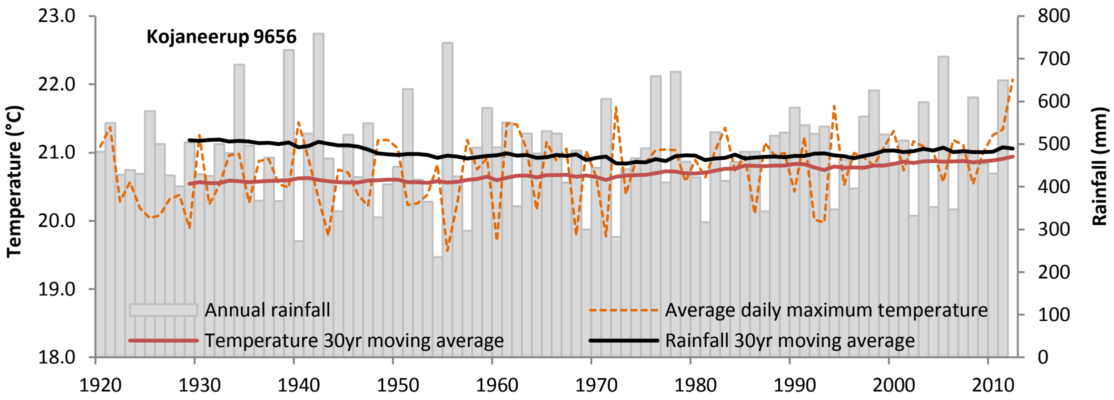
Rainfall and temperature data, including trend lines, were calculated using a 30-year backward moving average for representative meteorological stations in each region. Data was sourced from the SILO patch point database (QDERM 2013). See Table 1-1 for statistical analysis of trends and changes in mean annual rainfall for each station.

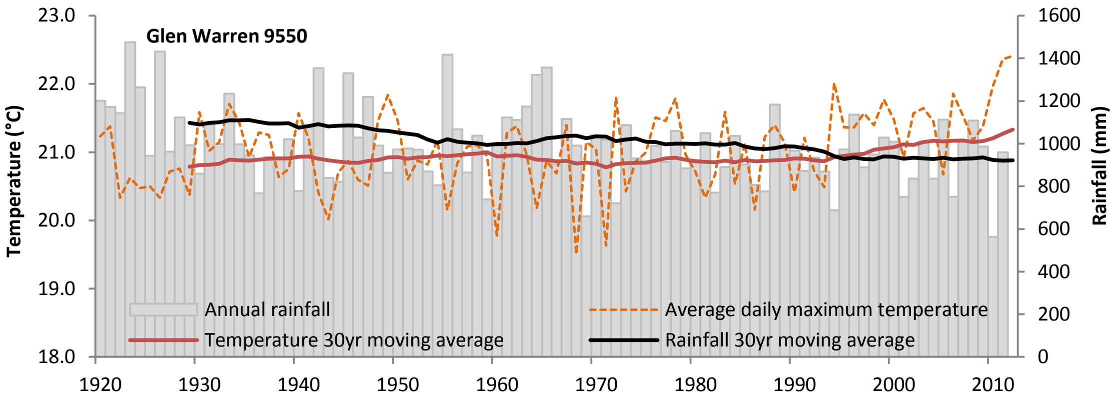
South-west

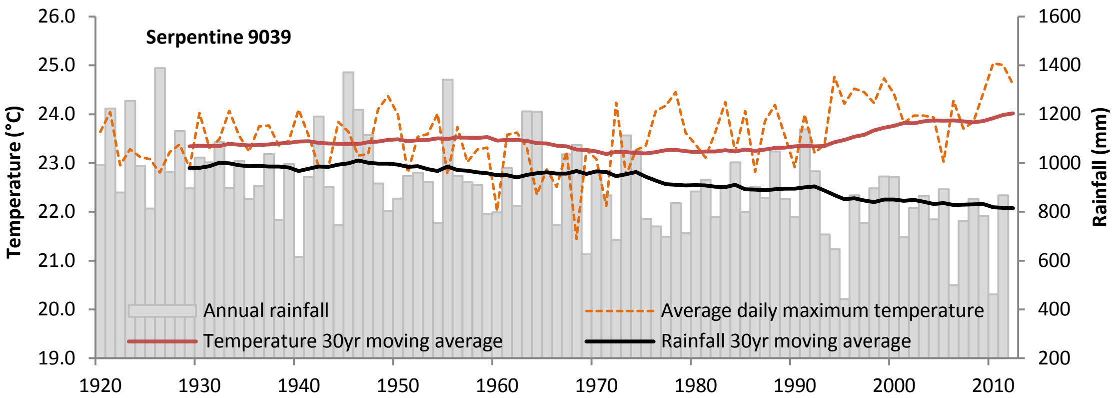




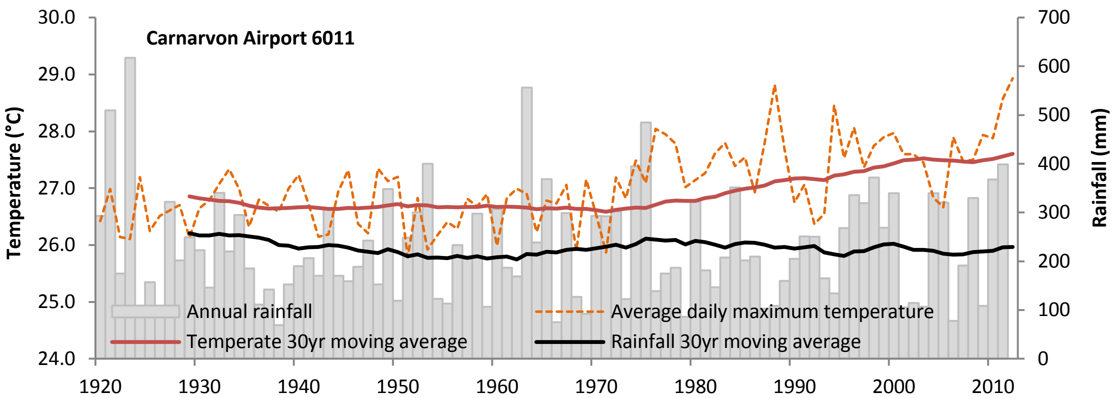


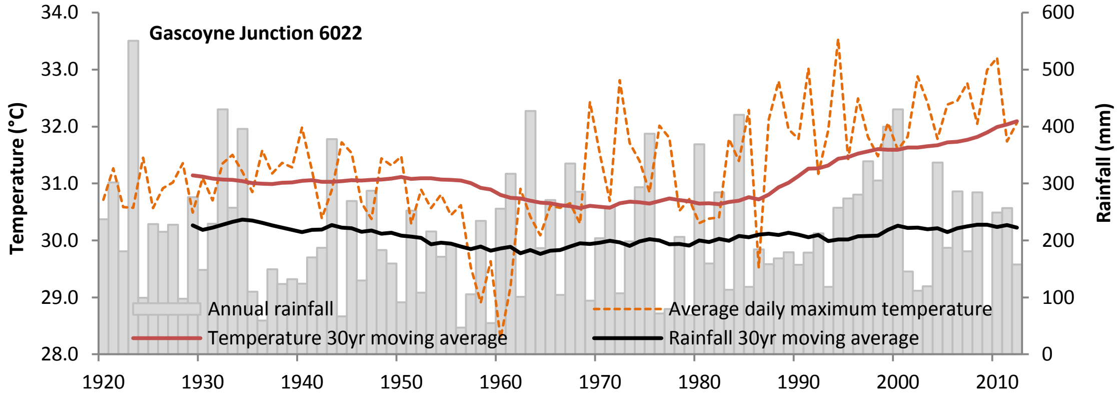


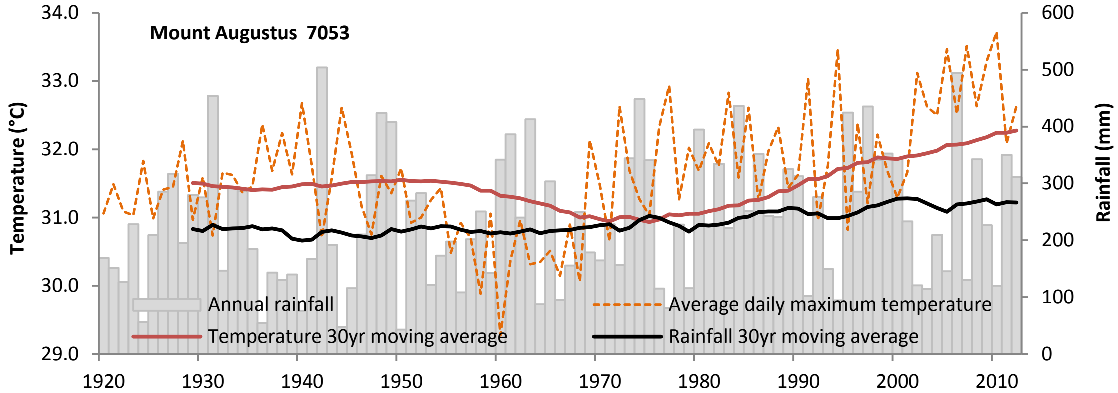


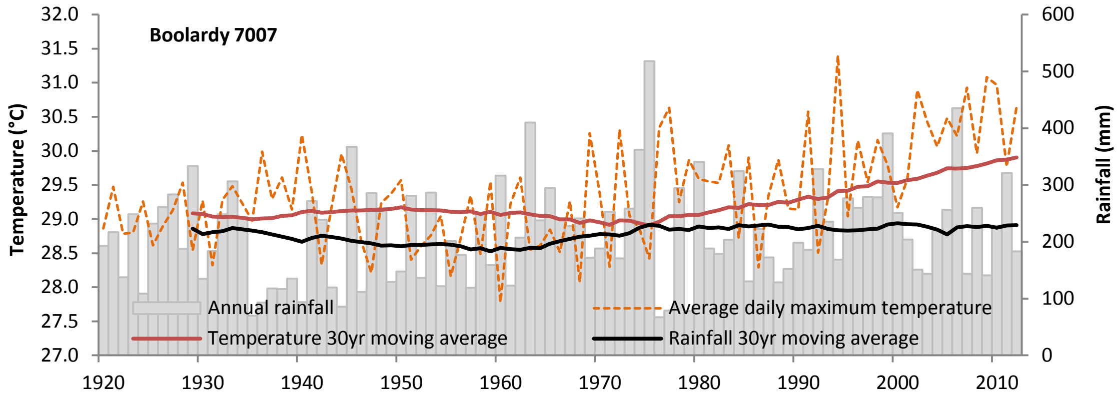


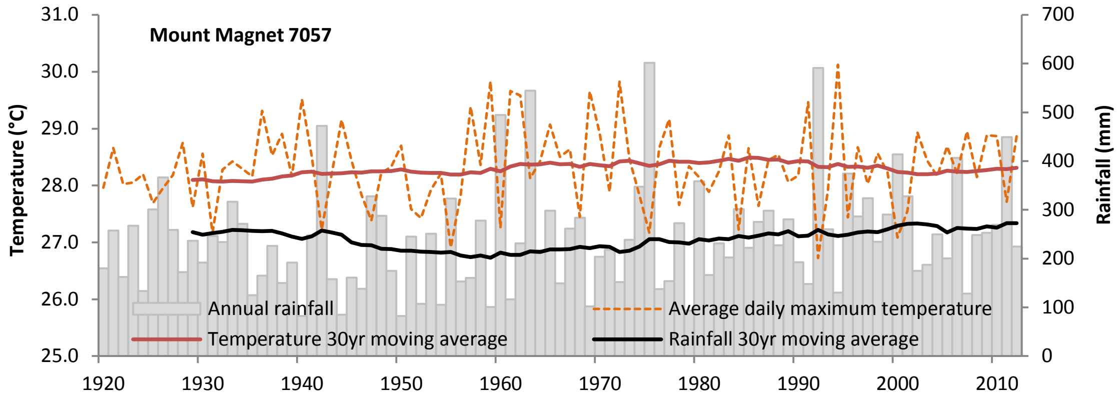
Central-west

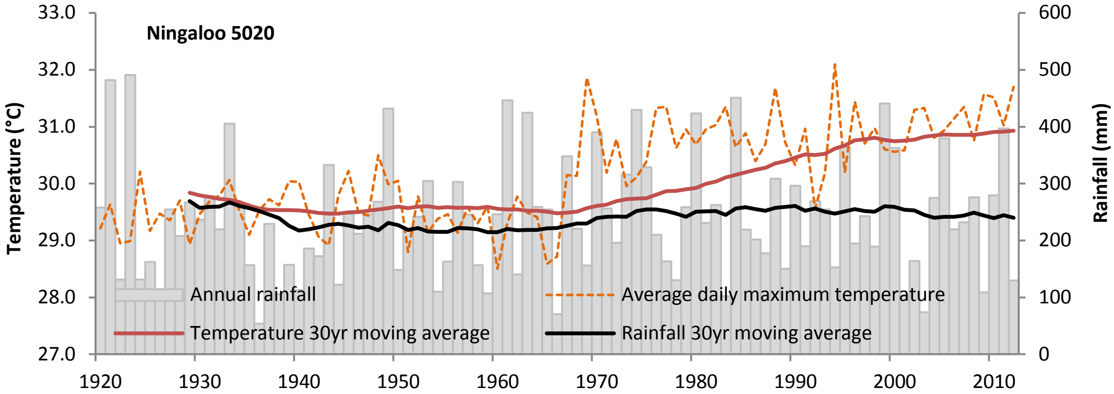



Gascoyne Junction 6022
Temperature (°C)
Rainfall (mm)
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average

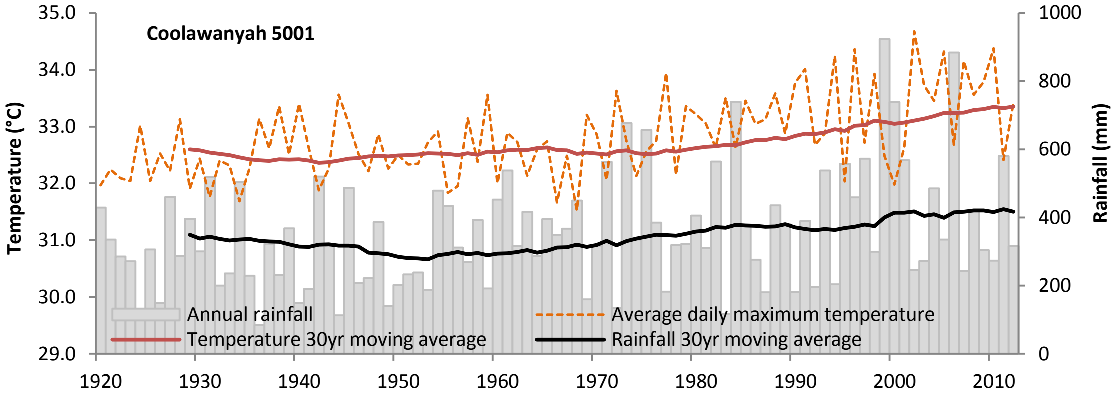

Mount Augustus 7053
Temperature (°C)
Rainfall (mm)
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average

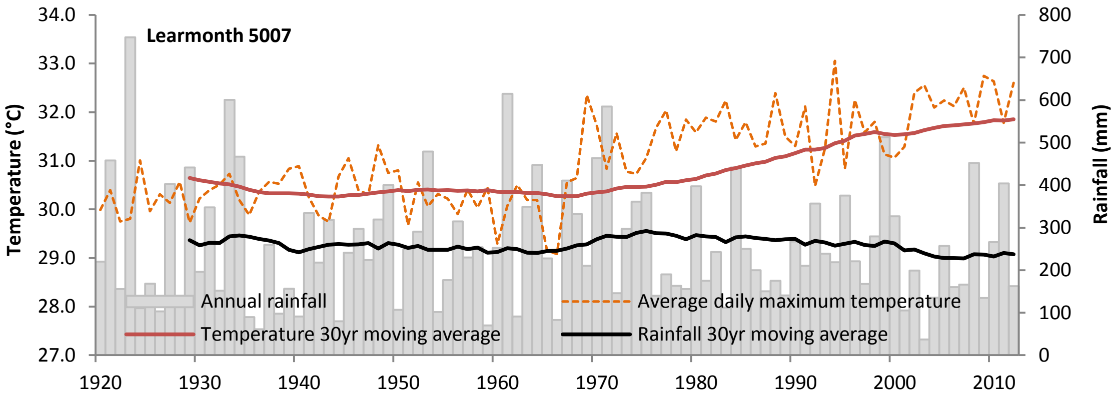

Boolardy 7007
Temperature (°C)
Rainfall (mm)
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average

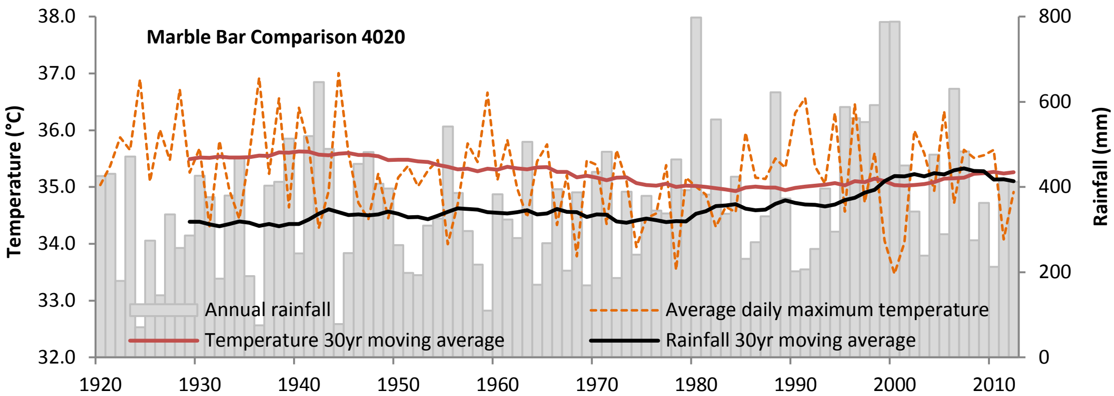

Mount Magnet 7057
Temperature (°C)
Rainfall (mm)
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average

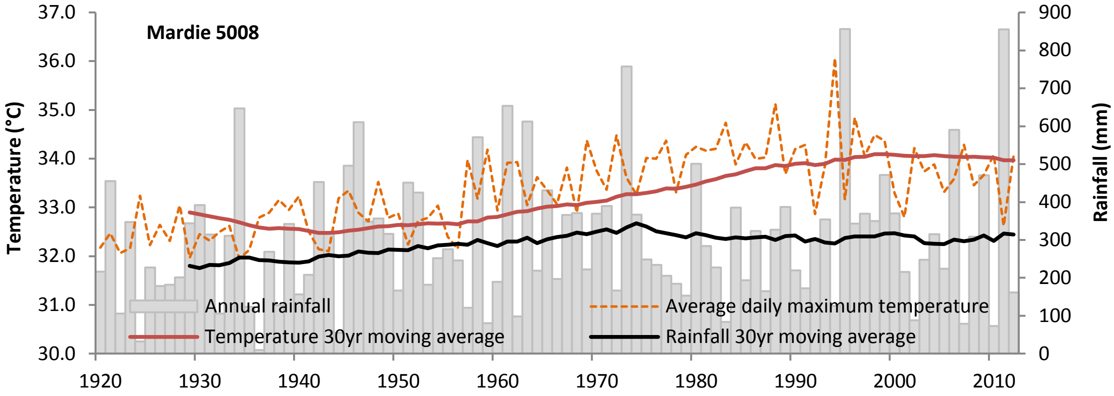

Ningaloo 5020
Temperature (°C)
Rainfall (mm)
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average

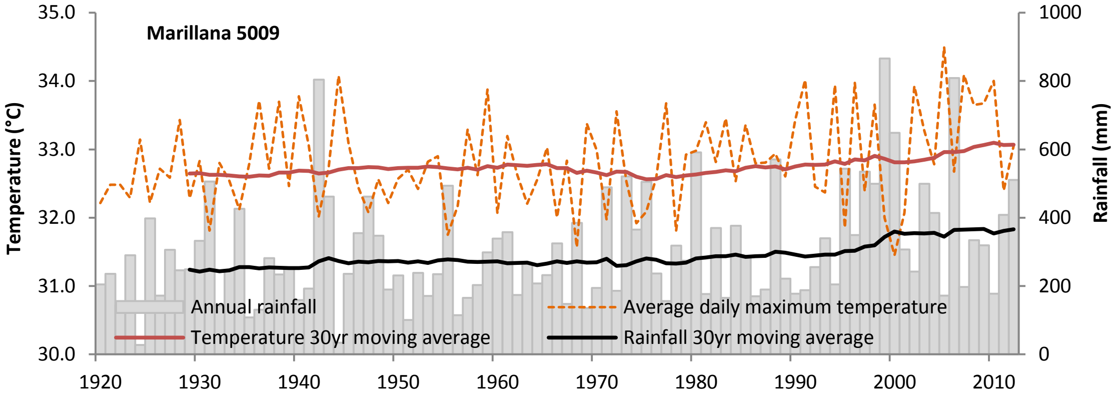
Pilbara

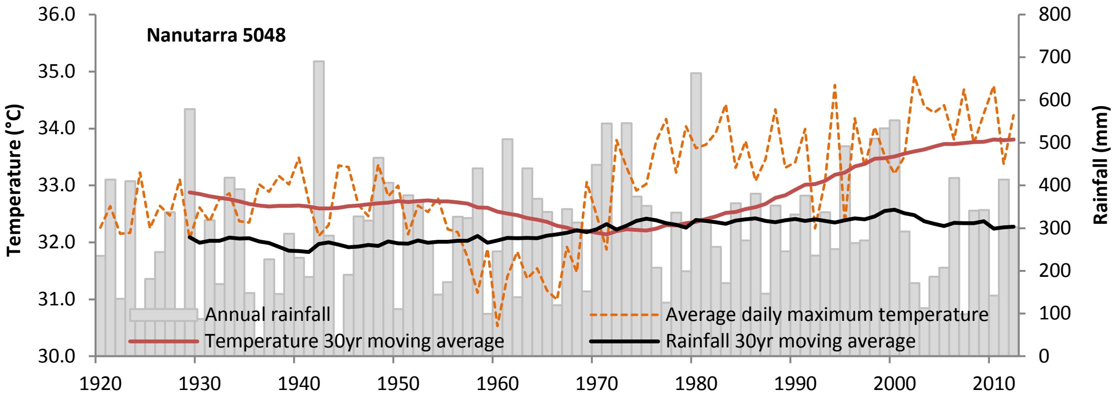

Coolawanyah 5001
Temperature (°C)
Rainfall (mm)
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average

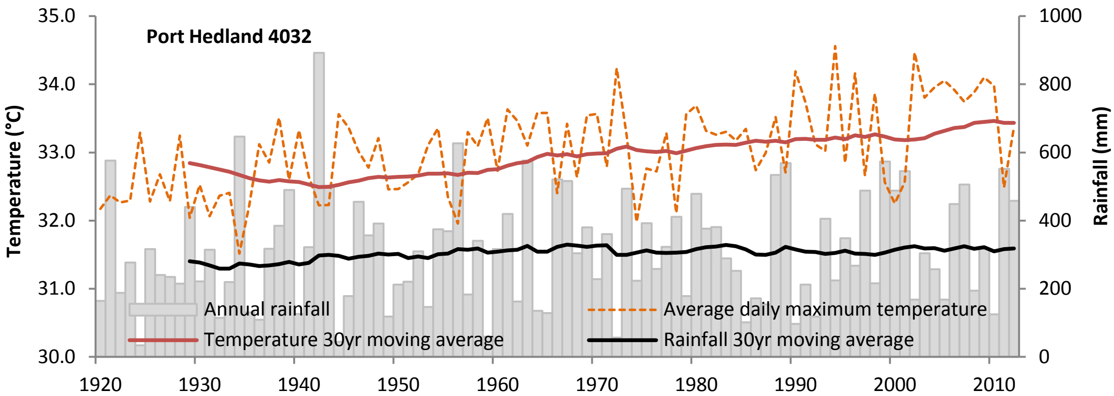

Learmonth 5007
Temperature (°C)
Rainfall (mm)
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average


Marble Bar Comparison 4020
Temperature (°C)
Rainfall (mm)
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average

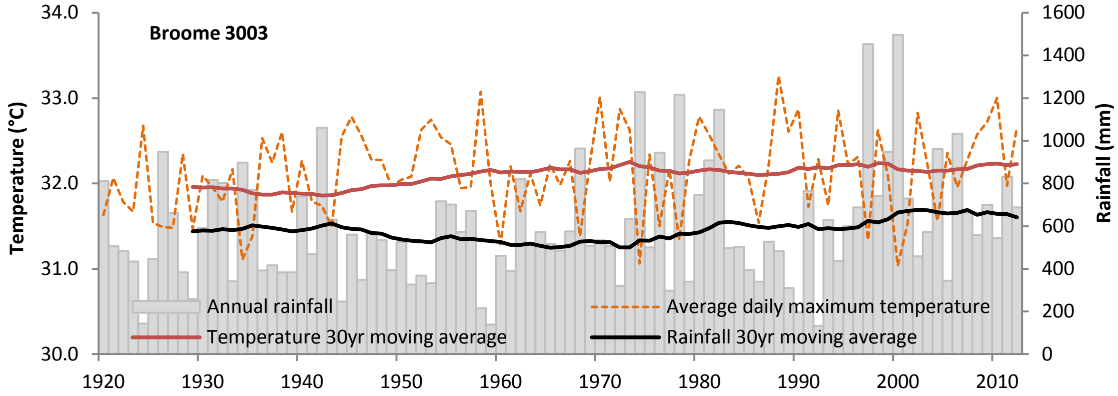

Mardie 5008
Temperature (°C)
Rainfall (mm)
37.0
36.0
35.0
34.0
33.0
32.0
31.0
30.0
900
800
700
600
500
400
300
200
100
0
1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average


Marillana 5009
Temperature (°C)
Rainfall (mm)
35.0
34.0
33.0
32.0
31.0
30.0
1000
800
600
400
200
0
1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average

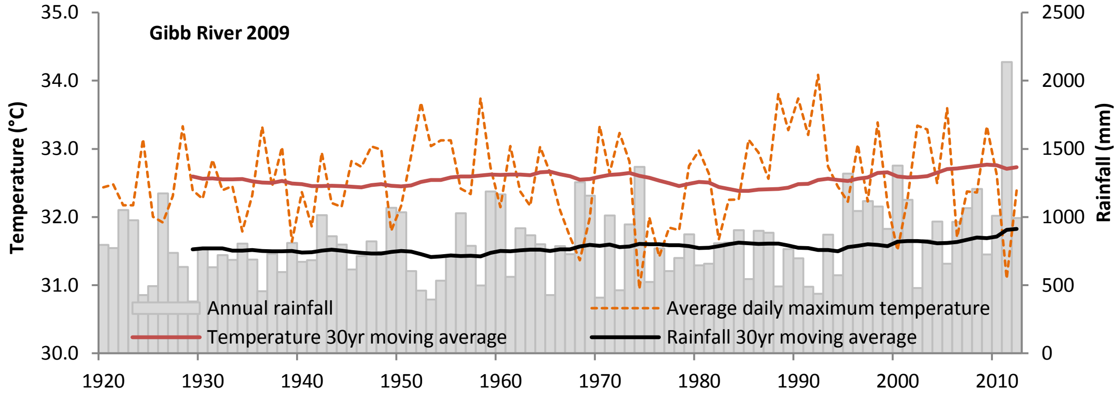

Nanutarra 5048
Temperature (°C)
Rainfall (mm)
36.0
35.0
34.0
33.0
32.0
31.0
30.0
800
700
600
500
400
300
200
100
0
1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average


Port Hedland 4032
Temperature (°C)
Rainfall (mm)
35.0
34.0
33.0
32.0
31.0
30.0
1000
800
600
400
200
0
1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
Annual rainfall
Average daily maximum temperature
Temperature 30yr moving average
Rainfall 30yr moving average

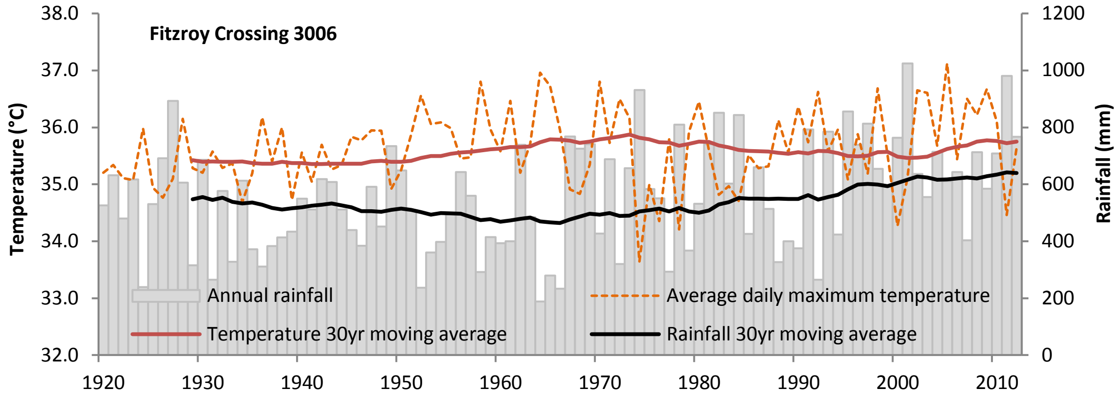
Kimberley



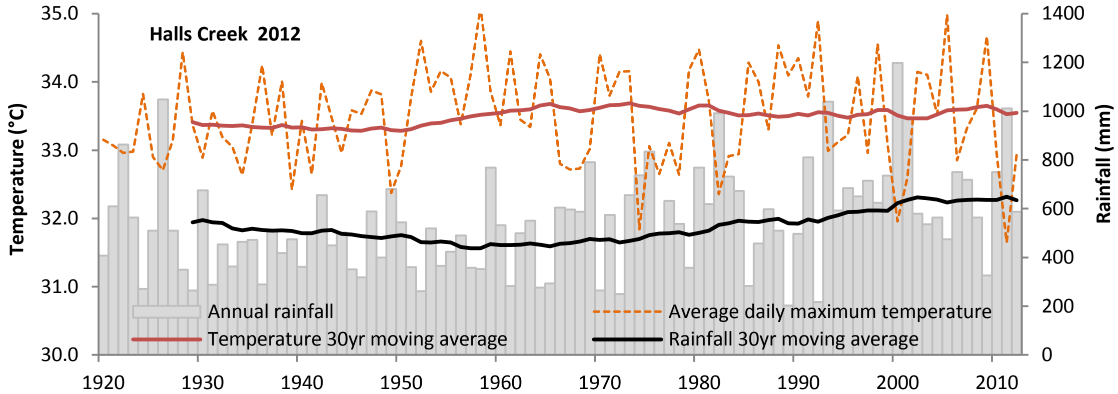
Broome 3003
Temperature (°C)
Rainfall (mm)
Annual rainfall
Temperature 30yr moving average
Average daily maximum temperature
Rainfall 30yr moving average



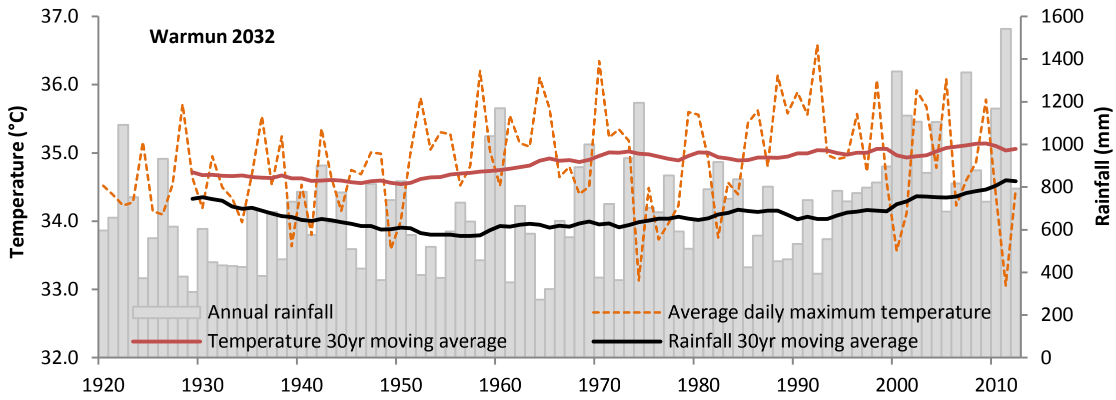
Gibb River 2009
Temperature (°C)
Rainfall (mm)
Annual rainfall
Temperature 30yr moving average
Average daily maximum temperature
Rainfall 30yr moving average

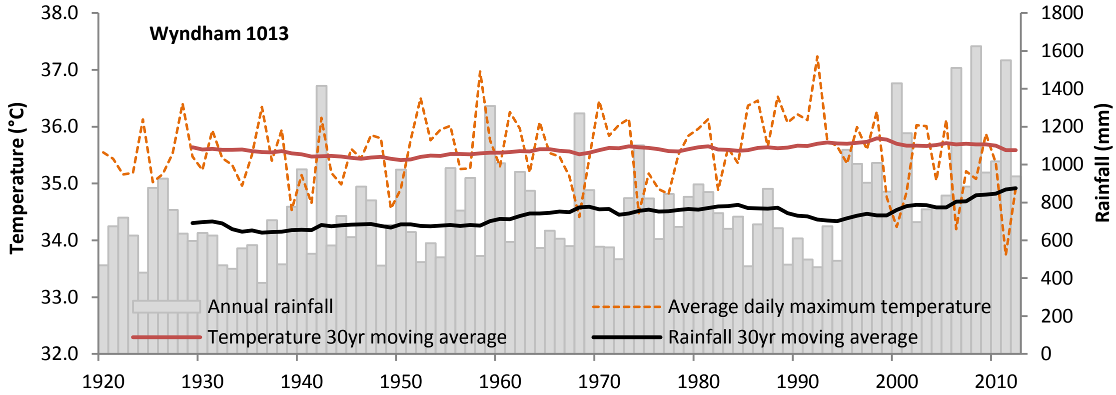


Fitzroy Crossing 3006
Temperature (°C)
Rainfall (mm)
Annual rainfall
Temperature 30yr moving average
Average daily maximum temperature
Rainfall 30yr moving average

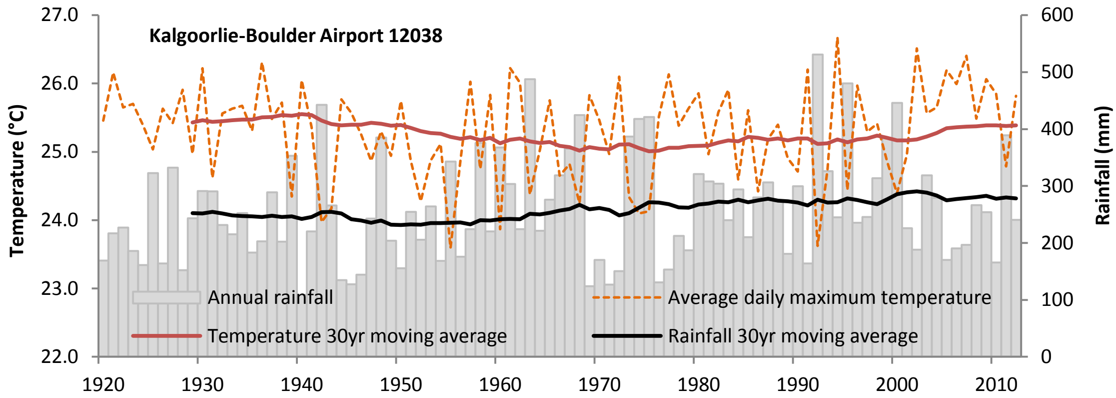


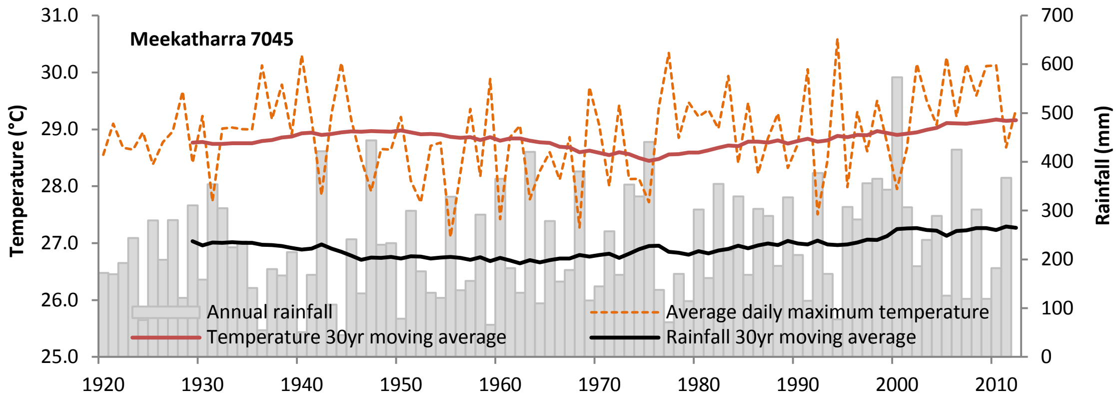
Halls Creek 2012
Temperature (°C)
Rainfall (mm)
Annual rainfall
Temperature 30yr moving average
Average daily maximum temperature
Rainfall 30yr moving average

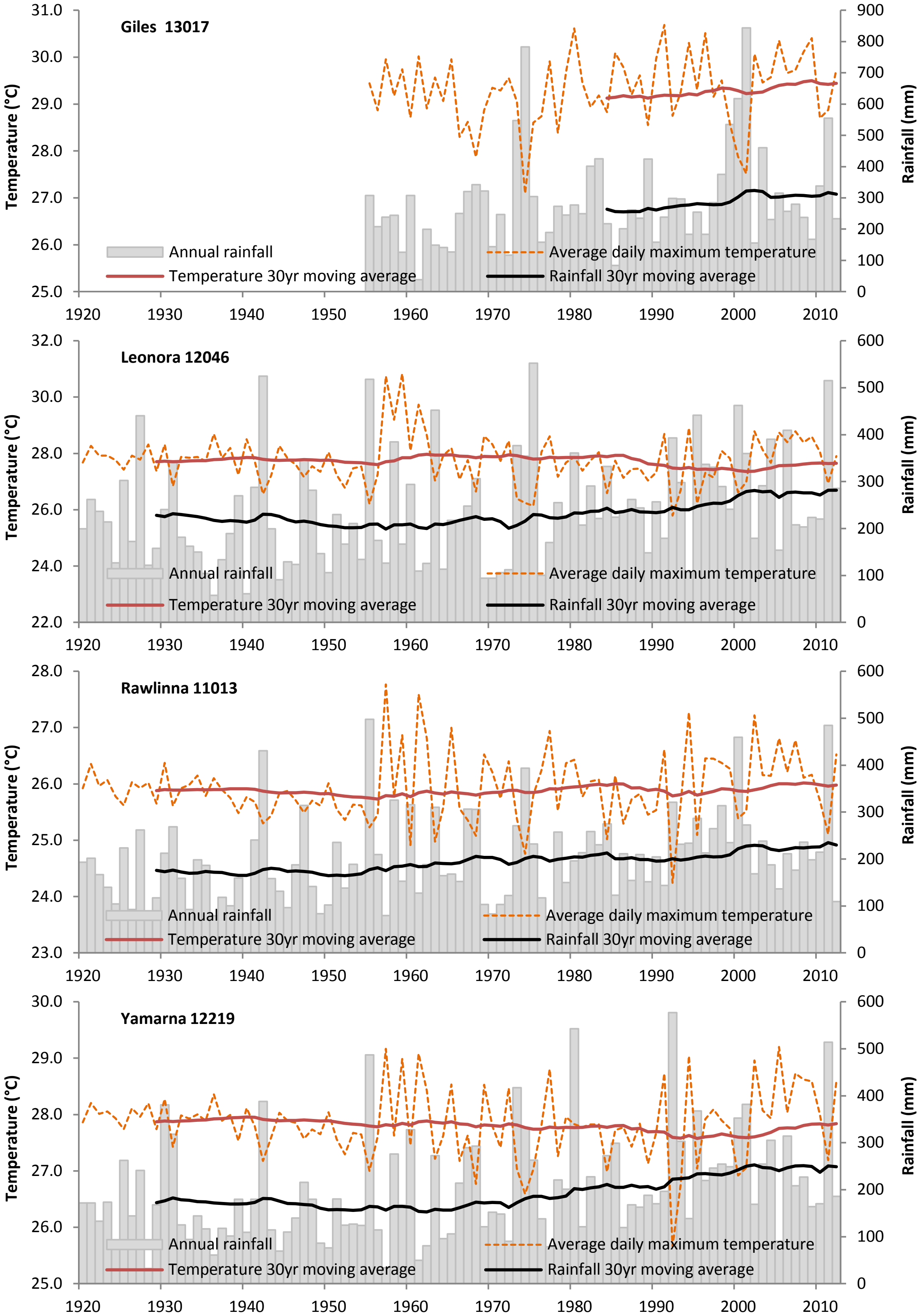

Warmun 2032
Temperature (°C)
Rainfall (mm)
37.0
36.0
35.0
34.0
33.0
32.0
1600
1400
1200
1000
800
600
400
200
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Annual rainfall
Temperature 30yr moving average
Average daily maximum temperature
Rainfall 30yr moving average


Wyndham 1013
Temperature (°C)
Rainfall (mm)
38.0
37.0
36.0
35.0
34.0
33.0
32.0
1800
1600
1400
1200
1000
800
600
400
200
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Annual rainfall
Temperature 30yr moving average
Average daily maximum temperature
Rainfall 30yr moving average

Central


Kalgoorlie-Boulder Airport 12038
Temperature (°C)
Rainfall (mm)
27.0
26.0
25.0
24.0
23.0
22.0
600
500
400
300
200
100
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Annual rainfall
Temperature 30yr moving average
Average daily maximum temperature
Rainfall 30yr moving average


Meekatharra 7045
Temperature (°C)
Rainfall (mm)
31.0
30.0
29.0
28.0
27.0
26.0
25.0
700
600
500
400
300
200
100
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Annual rainfall
Temperature 30yr moving average
Average daily maximum temperature
Rainfall 30yr moving average


Giles 13017
Leonora 12046
Rawlinna 11013
Yamarna 12219
Temperature (°C)
Rainfall (mm)
Annual rainfall
Temperature 30yr moving average
Average daily maximum temperature
Rainfall 30yr moving average
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

Appendix B: Calculation of FAO56 reference evapotranspiration and Penman evaporation

Step 1 – Radiation calculations

a. Calculate gridded latitude for WA and convert to radians φ.

b. Calculate representative monthly Julian day.

Month	Julian day
1	16
2	46
3	76
4	107
5	137
6	168
7	198
8	229
9	260
10	290
11	321
12	351

c. Calculate the average monthly solar declination for the month of calculation:

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right)$$

Month	δ (radians)	δ (degrees)
1	-0.36	-20.8
2	-0.23	-13.1
3	-0.03	-1.9
4	0.17	9.9
5	0.33	19.1
6	0.40	23.1
7	0.36	20.9
8	0.22	12.9
9	0.03	1.5
10	-0.18	-10.3
11	-0.34	-19.3
12	-0.40	-23.1

d. Calculate gridded sunset hour angle for each month:

$\omega_s = cos^{-1}(-tan\varphi tan\delta)$

e. Calculate gridded day length for each month:

$N = \frac{24}{\pi}\omega_s$

f. Calculate the eccentricity correction for each month, this corrects for the elliptical orbit of the Earth:

$d_r = 1 + 0.033\cos(\frac{2\pi}{365}\mathrm{J})$

g. Calculate the gridded extra-terrestrial radiation for each month (MJ $m^{-2}d^{-1}$):

$$R_a = \frac{G_{sc}}{\pi} d_r(\omega_s sin\varphi sin\delta + cos\varphi cos\delta sin\omega_s)$$

where G_{sc} is the solar constant of 118 MJ $m^{-2}d^{-1}$

h. Calculate clear sky radiation using default FAO equation:

$$R_{s0} = (0.75 + 2 \times 10^{-5}z)R_a$$

where z is elevation in metres above sea level

i. Calculate net outgoing longwave radiation:

$R_{nl} = \left(0.34 - 0.139\sqrt{e_a}\right)\left(a_1\frac{R_s}{R_{s0}} + b_1\right)\sigma\left[\frac{(T_{max} + 273.15)^4 + (T_{min} + 273.15)^4}{2}\right]$

where; R_s is the net incoming shortwave radiation at ground level, sourced from BOM baseline gridded climate data, or projected radiation from SimCLIM (scaled using GCM anomalies); e_a is actual daily saturation vapour pressure (see step 2 below), σ is the Stephen-Boltzmann constant, and a_1 and b_1 are constants set to 1.35 and -0.35 respectively (FAO recommended defaults).

j. Calculate net incoming solar radiation:

$$R_{ns} = (1 - \alpha)R_s$$

where α is surface albedo, set to 0.23 for the FAO56 reference crop, and 0.08 for water.

k. Calculate net radiation:

$$R_n = R_{ns} - R_{nl}$$

Step 2 – FAO56 reference evapotranspiration and Penman evaporation calculations

a. Calculate daily average saturation vapour pressure:

$$e_s = 0.6108exp\left(\frac{a_2T}{T + b_2}\right)$$

where T is temperature in °C and a_2 and b_2 are constants set to 17.27 and 237.3 (FAO recommended defaults). e_s was calculated for the maximum and minimum daily temperature and averaged.

b. Calculate the slope of the saturation vapour–temperature curve:

$$\Delta = \frac{abe_s}{(T + b)^2}$$

c. Calculate the daily actual saturation vapour pressure:

$$e_a = e_sW$$

where W is relative humidity. e_a was calculated for the maximum and minimum daily temperature and averaged.

d. Calculate FAO56 reference PET:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{(T_m + 273)}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

where G is the soil heat flux set to zero, U is the wind velocity, set to 2 m/s, and Ύ is the psychrometric constant, set to 0.066 kPa/°C.

e. Calculate Penman evaporation:

$$E_L = \frac{1}{\lambda}\left[\left(\frac{\Delta}{\Delta + \gamma}\right)R_n + \left(\frac{\gamma}{\Delta + \gamma}\right)f(U)(e_s - e_a)\right]$$

where λ is the latent heat of vaporisation of water, and f(U) is the wind function given by:

$$f(U) = 1.3 + 0.016U_2$$

where U_2 is wind run, set to 4 km/d.

Step 3 - Calculate FAO56 PET and Penman evaporation anomalies

a. For each month calculate the percentage change in PET and evaporation, for a future time horizon, relative to the baseline period.

$$\Delta PET_m = base_m + \frac{Dry_m - base_m}{base_m}$$

where m denotes the month of the year.

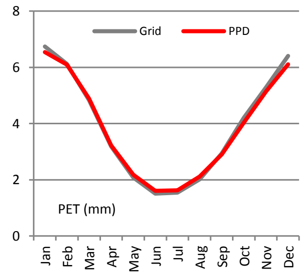
b. Use the same equation to calculate the annual anomaly for PET and evaporation.

Appendix C: Assessment for selection of wet, median and dry future climate scenarios

Extract SILO PPD at a meteorlogical station

Extract monthly baseline from gridded climate data at a point location

Compare gridded and point baseline data for consistency. Assess PET and evaporation calculations against PPD values.

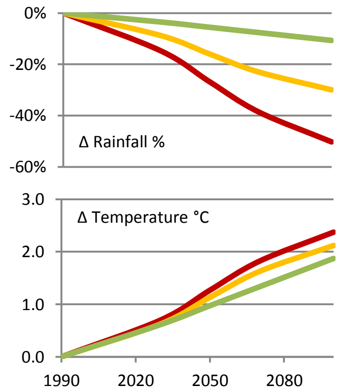


Extract gridded anomaly data for all variables

Assess monthly anomalies for extreme, inconsistent or erroneous values.

Month	Rainfall
January	7%
February	-7%
March	3%
April	-10%
...	...
November	-24%
December	-16%

Assess trend in anomaly for multiple time horizons, and consistency between scenarios.

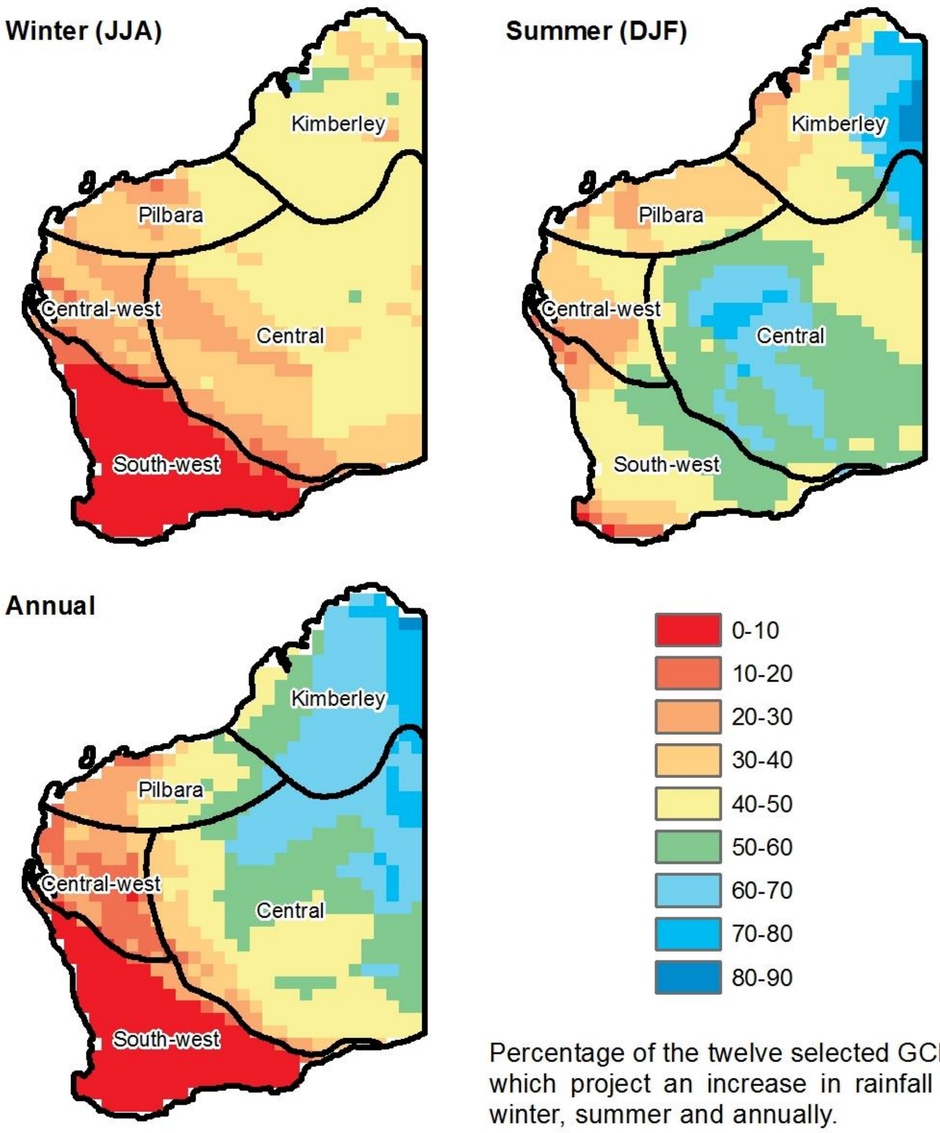


Scale baseline timeseries data and assess projected timeseries for extreme values.

Determine if representative wet, median and dry scenarios are acceptable, and repeat process with alternate GCM if required.

Appendix D: GCM agreement for direction of rainfall trends

These grids represent the levels of agreement among the 12 GCMs in the direction of rainfall trends projected for the 21st century. The grids show the percentage of models which agree on an upward trend in rainfall for winter, summer and annually. Therefore, a value of 0% would indicate that all models project a drying trend, 100% would indicate that all models project a wetting trend and values 40–60% indicate less agreement between GCMs. In the South-west, there is strong agreement among GCMs that the winter and annual total rainfall will continue to decline through the 21st century. Grid cells are at 0.5° resolution.



Percentage of the twelve selected GCMS which project an increase in rainfall for winter, summer and annually.

Appendix E: Coefficient of variation and rainfall anomaly for selected meteorological stations

Region	Station	CV (1900-2010)	2100 anomaly dry[1]	2100 anomaly med[1]	2100 anomaly wet[1]	[Δ]/CV dry[2]	[Δ]/CV med[2]	[Δ]/CV wet[2]
South-west	Serpentine	0.21	-0.38	-0.29	-0.09	1.86	1.39	0.46
	Perth Airport	0.20	-0.50	-0.30	-0.11	2.54	1.51	0.54
	Morawa West	0.27	-0.54	-0.15	-0.09	2.01	0.57	0.35
	Wayville	0.21	-0.45	-0.24	-0.09	2.15	1.14	0.44
	Glen Warren	0.18	-0.38	-0.29	-0.09	2.13	1.59	0.52
	Scaddan Post	0.22	-0.46	-0.12	-0.05	2.10	0.57	0.21
	Kojaneerup	0.22	-0.38	-0.22	-0.08	1.76	1.02	0.39
Pilbara	Mardie	0.57	-0.33	-0.03	0.04	0.58	0.06	0.06
	Learmonth Airport	0.58	-0.19	-0.17	0.02	0.33	0.29	0.04
	Nanutarra	0.48	-0.28	-0.11	0.03	0.59	0.23	0.06
	Coolawanyah	0.46	-0.32	-0.04	0.04	0.69	0.09	0.08
	Marillana	0.53	-0.21	0.00	0.06	0.39	0.00	0.11
	Port Hedland	0.51	-0.27	0.00	0.07	0.53	0.00	0.14
	Marble Bar	0.42	-0.24	0.00	0.07	0.57	0.00	0.16
Kimberley	Broome	0.44	-0.19	0.02	0.09	0.44	0.05	0.20
	Fitzroy Crossing	0.33	-0.13	0.11	0.15	0.39	0.33	0.45
	Halls Creek	0.37	-0.08	0.13	0.19	0.21	0.35	0.52
	Warmun	0.34	-0.06	0.13	0.18	0.17	0.39	0.53
	Gibb River	0.29	-0.11	0.08	0.12	0.39	0.26	0.41
	Wyndham	0.33	-0.09	0.11	0.15	0.26	0.33	0.46
Central	Meekatharra	0.47	-0.08	0.04	0.21	0.17	0.08	0.46
	Giles	0.54	-0.08	0.04	0.21	0.15	0.07	0.40
	Kalgoorlie	0.35	-0.27	-0.01	0.03	0.79	0.04	0.10
	Leonora	0.45	-0.25	0.01	0.13	0.56	0.01	0.28
	Yamarna	0.52	-0.19	0.00	0.21	0.36	0.01	0.41
	Rawlinna	0.43	-0.20	0.02	0.05	0.47	0.05	0.12
Central-west	Boolardy	0.43	-0.30	-0.11	-0.04	0.69	0.27	0.08
	Carnarvon	0.42	-0.26	-0.10	0.01	0.63	0.24	0.03
	Gascoyne	0.48	-0.26	-0.11	0.00	0.55	0.24	0.01
	Mt Augustus	0.50	-0.21	-0.14	0.00	0.43	0.28	0.01
	Mt Magnet	0.46	-0.32	-0.10	-0.06	0.71	0.21	0.14
	Ningaloo	0.47	-0.24	-0.09	0.02	0.51	0.20	0.05

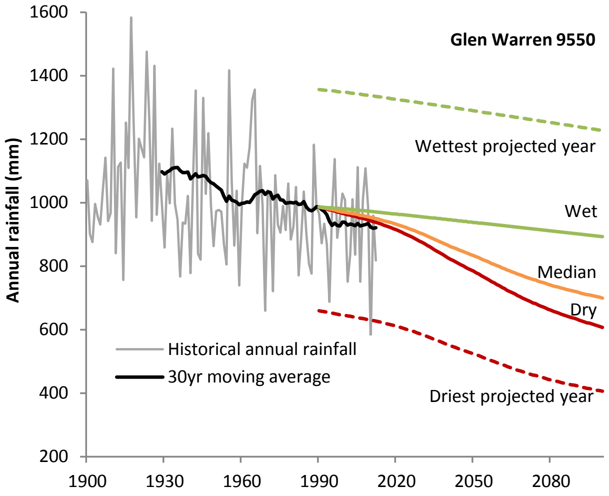
[1] Precipitation anomaly at 2100 *[2] Absolute value of anomaly divided by coefficient of variability*

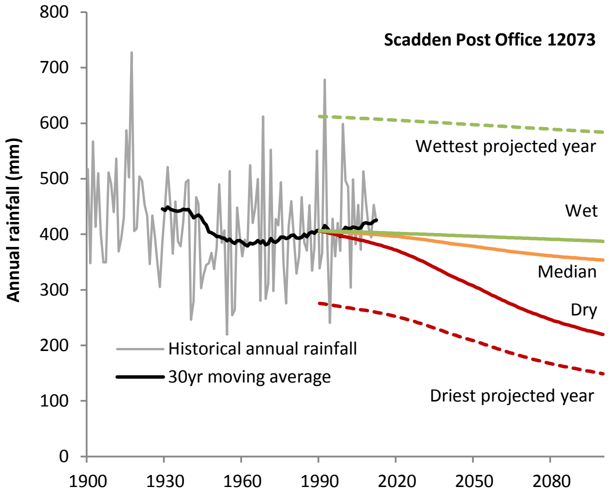
Appendix F: Long-term climate projections and historical annual rainfall at selected rainfall stations

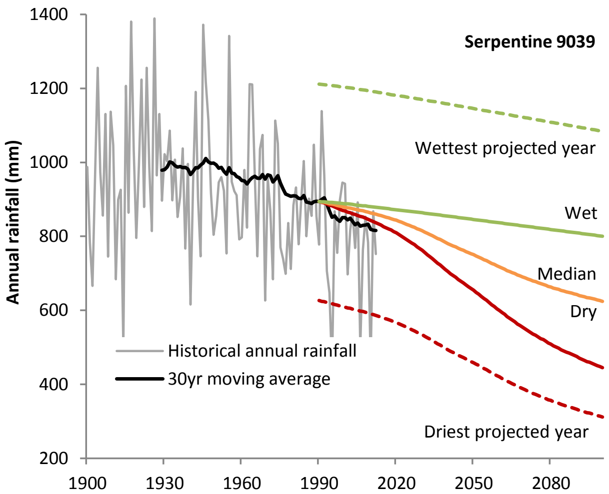
The graphs presented here show the long-term climate projections from 1990 to 2100 calculated for the wet, median and dry scenarios at the location of representative meteorological stations for each region. The historical annual rainfall and 30-year backward moving average are plotted for comparison. The graphs give some indication of inter-annual rainfall variability, and compare recent rainfall trends with those projected by the representative scenarios.

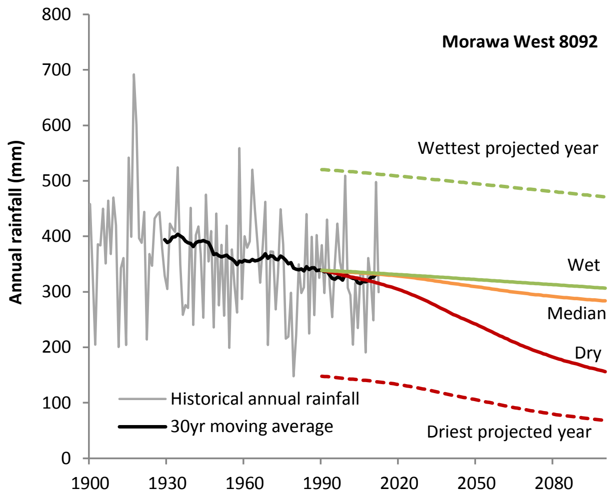
The ‘climate trend’ shows the projected trend in average annual rainfall at the location for each scenario. The ‘wettest’ and ‘driest’ projected years indicate the highest and lowest rainfall years that would result from scaling the baseline rainfall, using the wet and dry climate anomalies respectively.

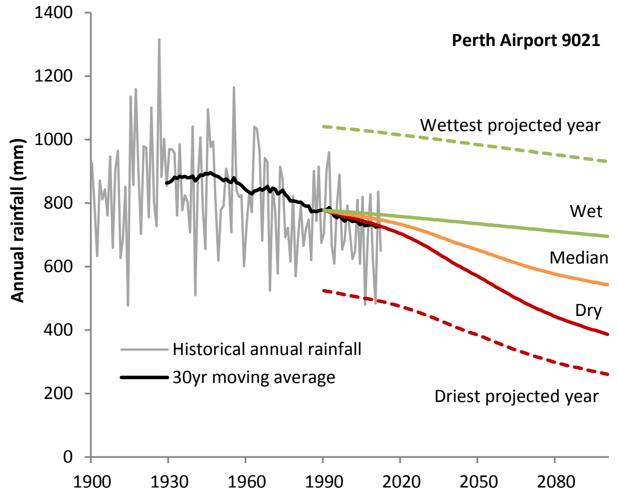
South-west

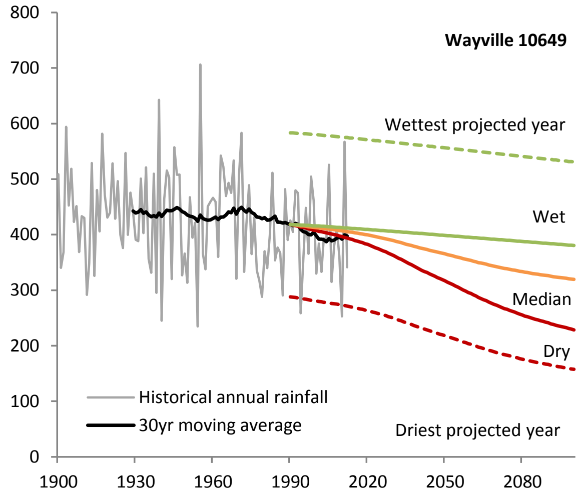


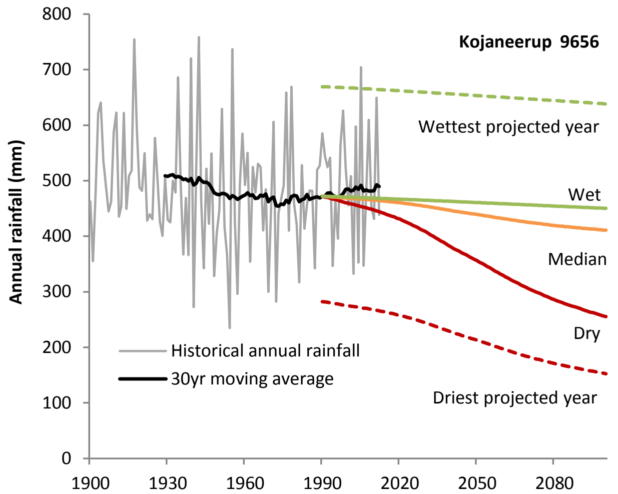












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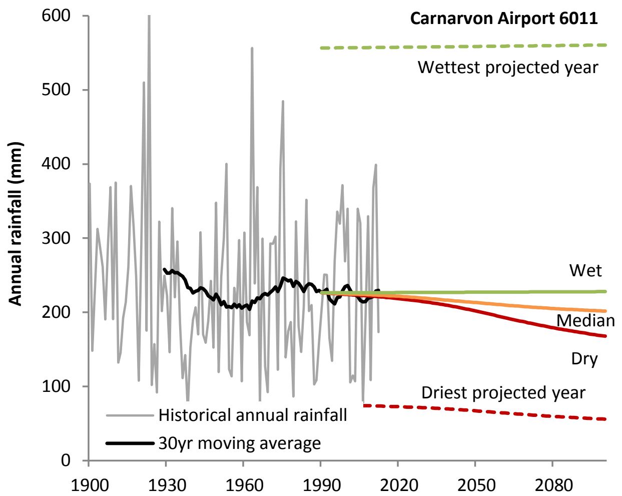

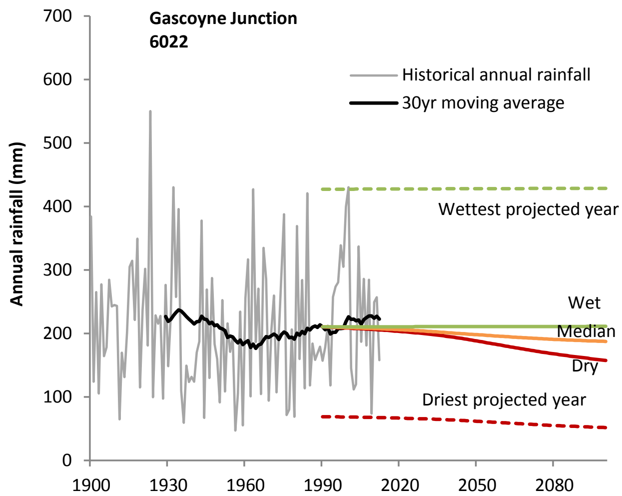

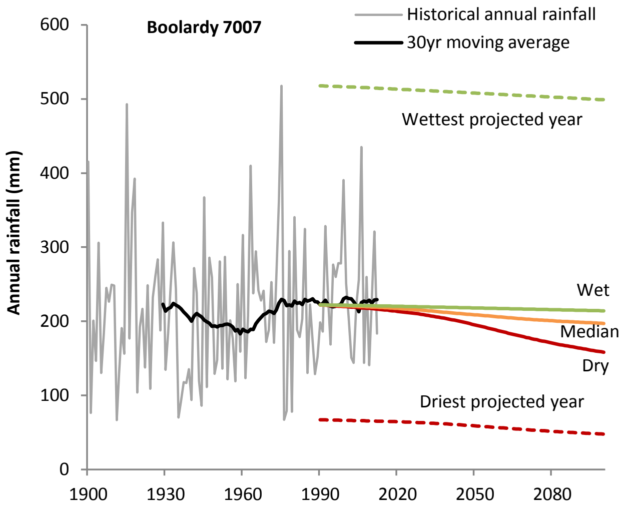
Boolardy 7007
Historical annual rainfall
30yr moving average
Wettest projected year
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Median
Dry
Driest projected year
Annual rainfall (mm)
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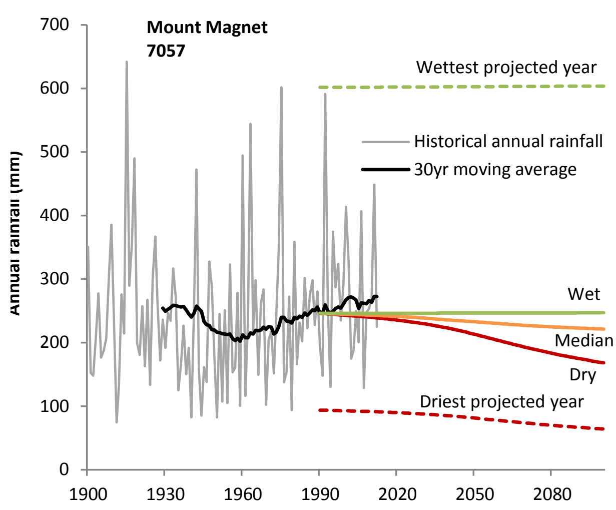
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Median
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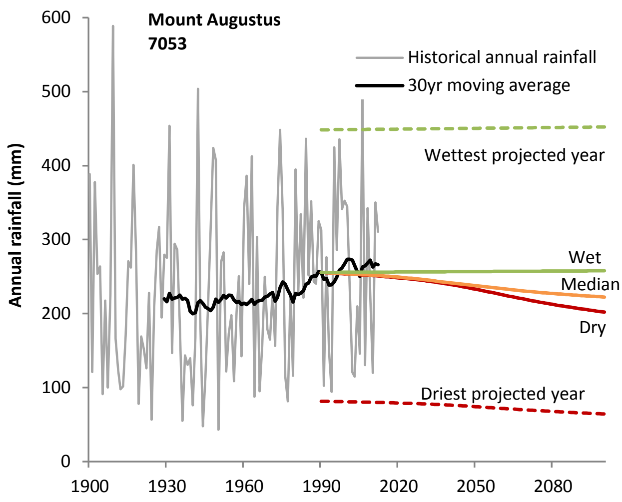
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30yr moving average
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Median
Dry
Driest projected year
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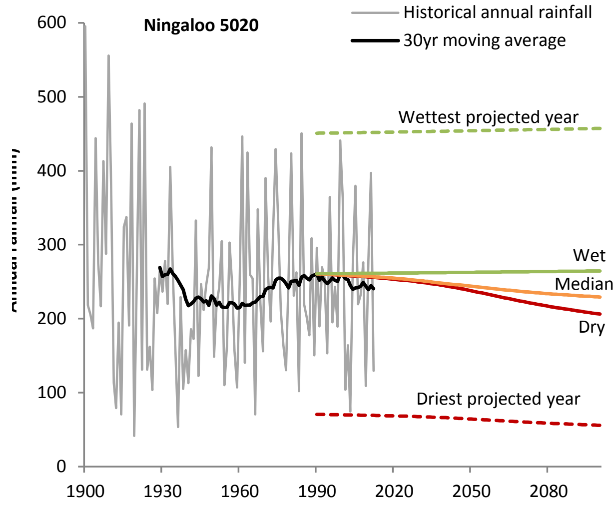
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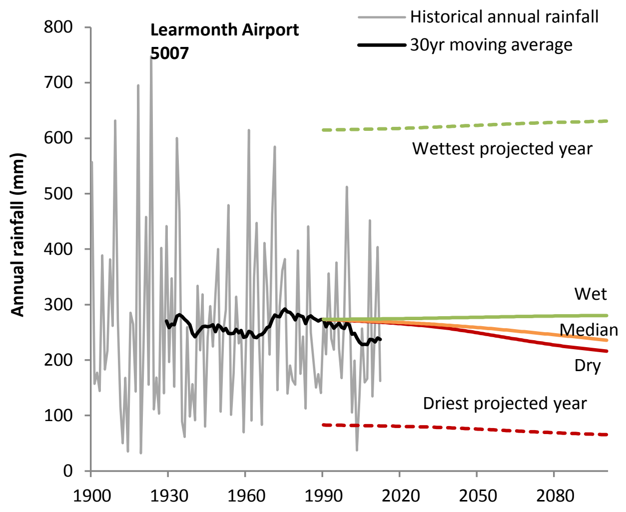
Pilbara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Median
Dry
Driest projected year
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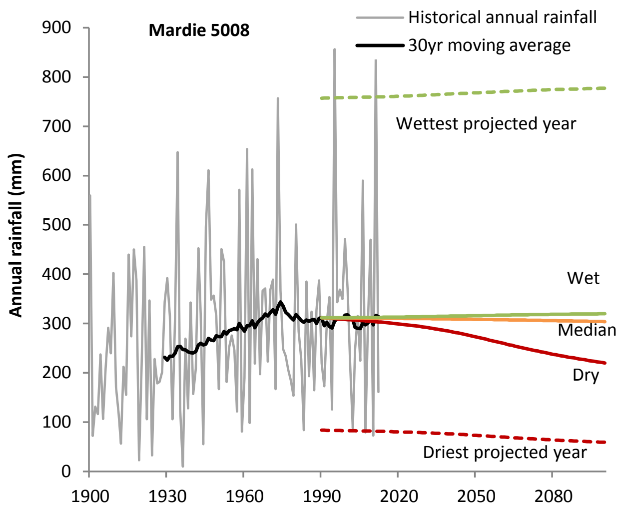
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Median
Dry
Driest projected year
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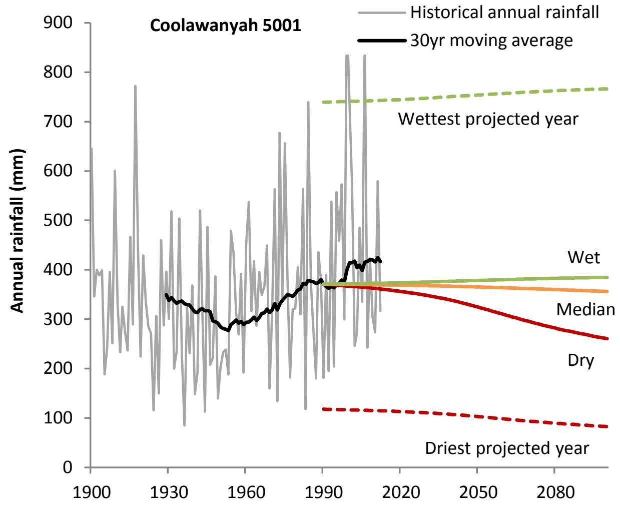
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Median
Dry
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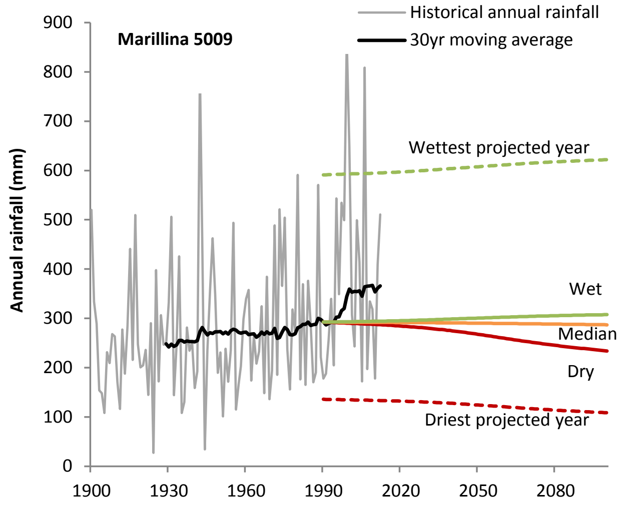
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Median
Dry
Driest projected year
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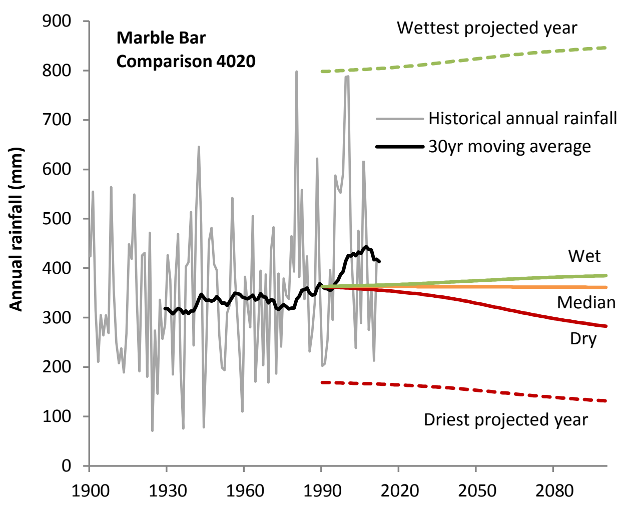
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Comparison 4020
Wettest projected year
Historical annual rainfall
30yr moving average
Wet
Median
Dry
Driest projected year
Annual rainfall (mm)
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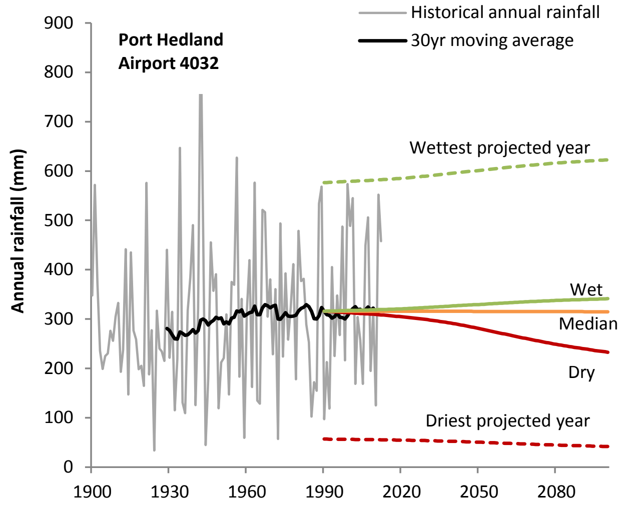
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Airport 4032
Historical annual rainfall
30yr moving average
Wettest projected year
Wet
Median
Dry
Driest projected year
Annual rainfall (mm)
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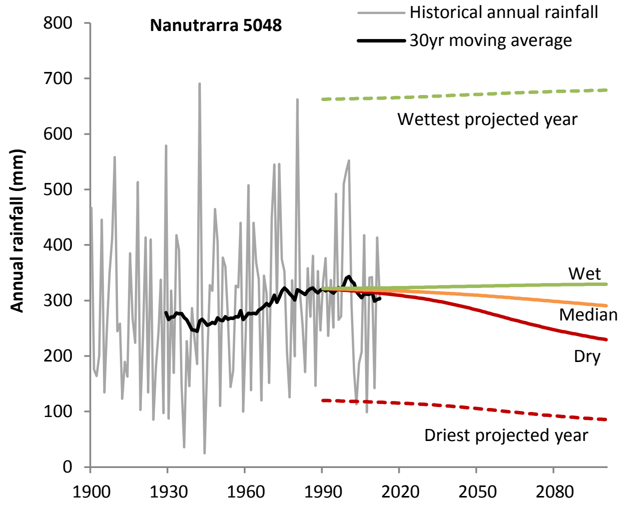
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30yr moving average
Wettest projected year
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Median
Dry
Driest projected year
Annual rainfall (mm)
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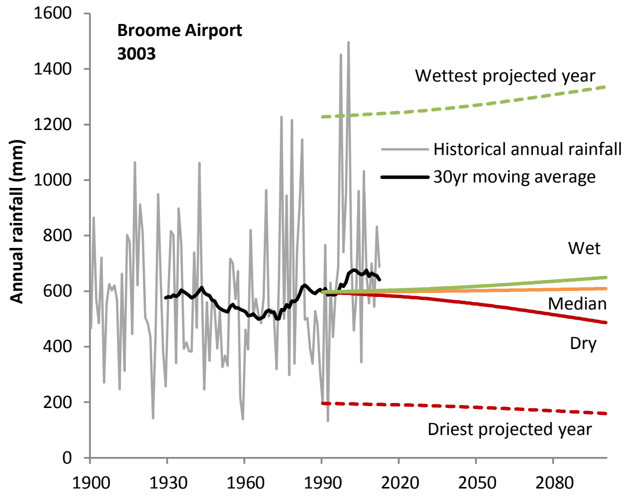
Kimberley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3003
Wettest projected year
Historical annual rainfall
30yr moving average
Wet
Median
Dry
Driest projected year
Annual rainfall (mm)
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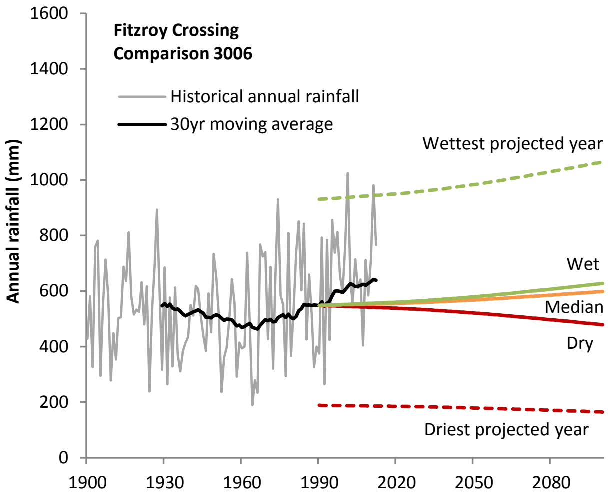
Fitzroy Crossing
Comparison 3006
Historical annual rainfall
30yr moving average
Wettest projected year
Wet
Median
Dry
Driest projected year
Annual rainfall (mm)
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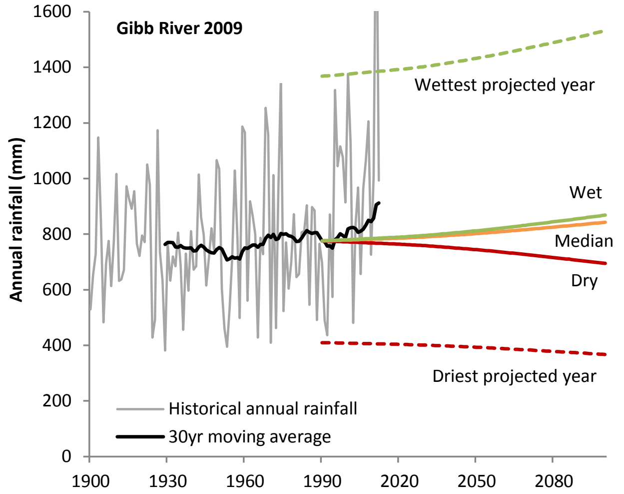
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Wettest projected year
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Median
Dry
Driest projected year
Historical annual rainfall
30yr moving average
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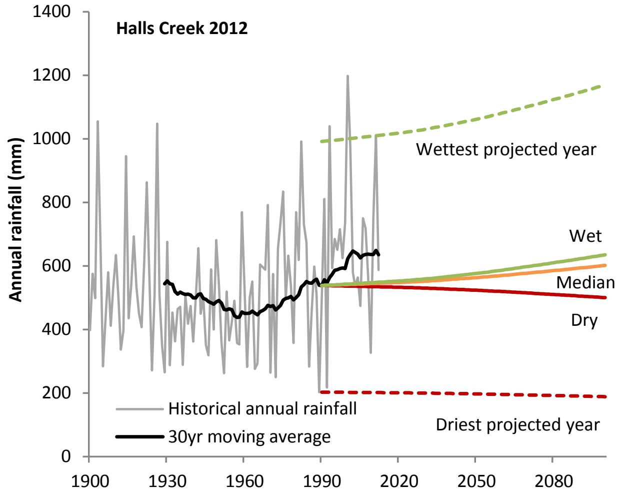
Halls Creek 2012
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Historical annual rainfall
30yr moving average
Driest projected year
Annual rainfall (mm)
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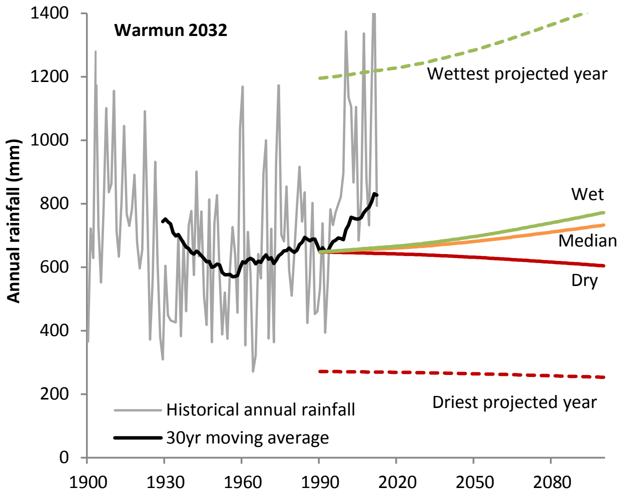
Warmun 2032
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Median
Dry
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Annual rainfall (mm)
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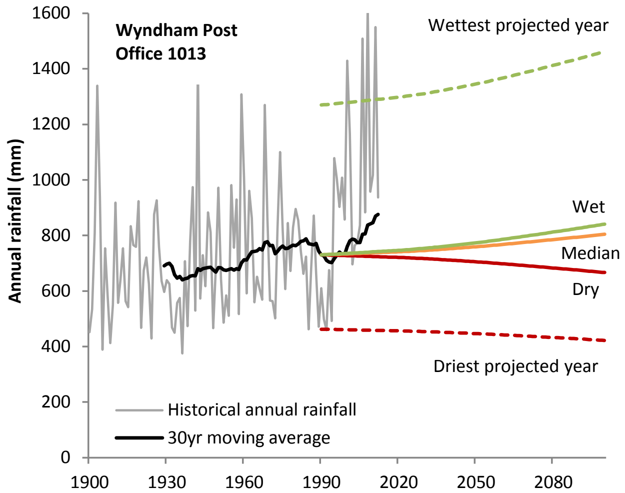
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Office 1013
Wettest projected year
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Median
Dry
Driest projected year
Historical annual rainfall
30yr moving average
Annual rainfall (mm)
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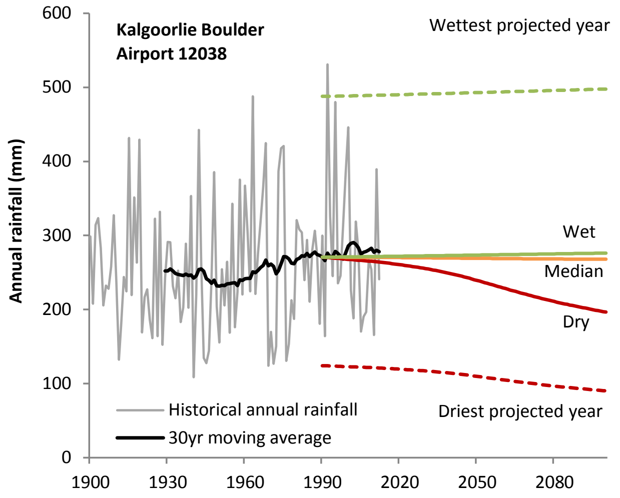
Kalgoorlie Boulder
Airport 12038
Wettest projected year
Wet
Median
Dry
Driest projected year
Historical annual rainfall
30yr moving average
Annual rainfall (mm)
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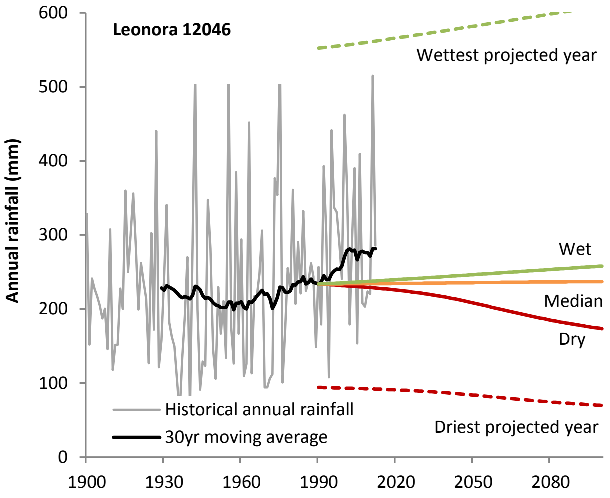
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Median
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Driest projected year
Historical annual rainfall
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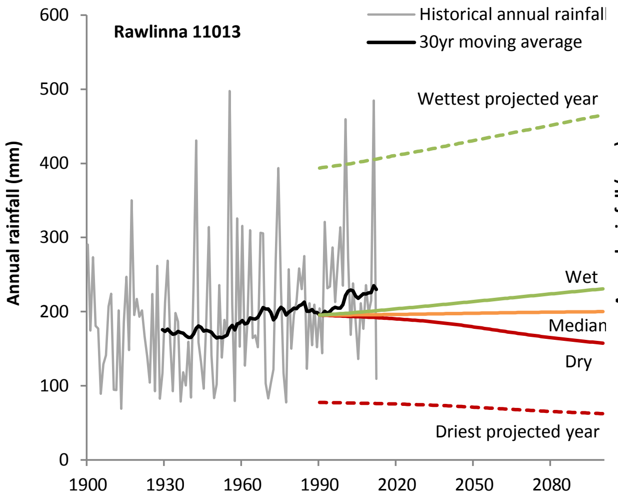
Rawlinna 11013
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30yr moving average
Wettest projected year
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Median
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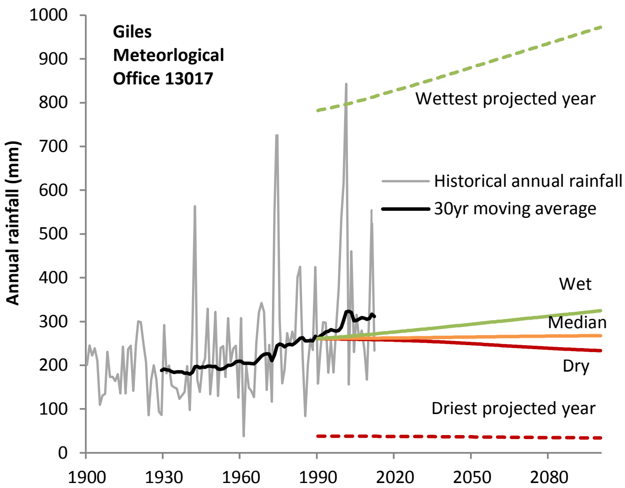
Giles
Meteorlogical
Office 13017
Wettest projected year
Historical annual rainfall
30yr moving average
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Dry
Driest projected year
Annual rainfall (mm)
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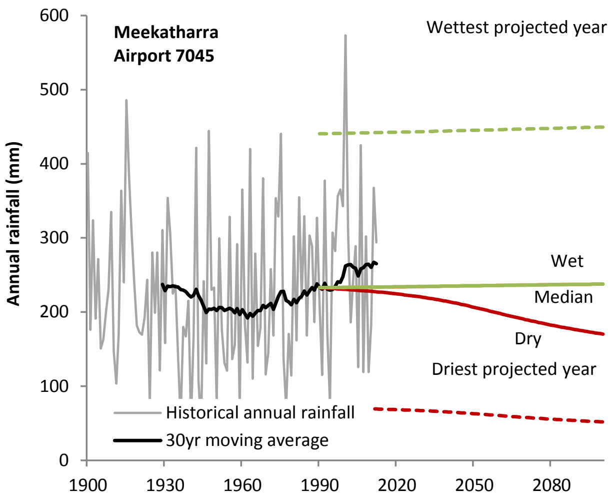
Meekatharra
Airport 7045
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Dry
Driest projected year
Historical annual rainfall
30yr moving average
Annual rainfall (mm)
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Shortened forms

APC	Anomaly Pattern Correlation
BoM	Bureau of Meteorology
CO_2	Carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DoW	Department of Water (Western Australia)
ESRL	Earth Systems Research Laboratory
FAO	Food and Agricultural Organization of the United Nations
FAO56	Food and Agricultural Organization Irrigation and Drainage Paper #56
GCM	General Circulation Model
IOCI	Indian Ocean Climate Initiative
IPCC	Intergovernmental Panel on Climate Change
NOAA	National Oceanic and Atmospheric Administration
PET	Potential Evapotranspiration
QDERM	Queensland Department of Environment and Resource Management
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RMS	Root Mean Square
SRES	Special Report on Emissions Scenarios
SWWASY	South-west Western Australia Sustainable Yields
WMO	World Meteorological Organisation
ESRI	Environmental Systems Research Institute
CMIP3/5	Coupled Model Intercomparison Project
AR4/5	Assessment Report 4/5

General Circulation Models

GCM shortened form	Research Institute	Model ID (CMIP3)
BCCRBCM2	Bjerknes Centre for Climate Research	BCCR-BCM2.0
CCCMA T47	Canadian Centre for Climate Modelling & Analysis	CGCM3.1(T47)
CCCMA T63	Canadian Centre for Climate Modelling & Analysis	CGCM3.1(T63)
CCSM--30	National Center for Atmospheric Research	CCSM3
CNRM-CM3	Météo-France / Centre National de Recherches Météorologiques	CNRM-CM3
CSIRO-30	CSIRO Atmospheric Research	CSIRO-Mk3.0
CSIRO-35	CSIRO Atmospheric Research	CSIRO-Mk3.5
ECHO--G	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group.	ECHO-G
FGOALS1G	LASG / Institute of Atmospheric Physics	FGOALS-g1.0
GFDLCM20	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	GFDL-CM2.0
GFDLCM21	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	GFDL-CM2.1
GISS-AOM	NASA / Goddard Institute for Space Studies	GISS-AOM
GISS--EH	NASA / Goddard Institute for Space Studies	GISS-EH
GISS--ER	NASA / Goddard Institute for Space Studies	GISS-ER
INMCM-30	Institute for Numerical Mathematics	INM-CM3.0
IPSL_CM4	Institut Pierre Simon Laplace	IPSL-CM4
MIROC-HI	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	MIROC3.2(hires)
MIROCMED	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	MIROC3.2(medres)
MPIECH-5	Max Planck Institute for Meteorology	ECHAM5/MPI-OM
MRI-232A	Meteorological Research Institute	MRI-CGCM2.3.2
NCARPCM1	National Center for Atmospheric Research	PCM
UKHADCM3	Hadley Centre for Climate Prediction and Research / Met Office	UKMO-HadCM3
UKHADGEM	Hadley Centre for Climate Prediction and Research / Met Office	UKMO-HadGEM1

Glossary

baseline	The period of time against which change is calculated.
climate anomaly	The difference in a given climatic variable between a baseline period and a future time horizon.
climate change	A change in climate over time. Climate is defined as average weather, and the World Meteorological Organisation typically use an averaging period of 30 years to define climate.
climate projections	The modelled responses of the climate system to changes in greenhouse gas concentrations or emissions to the atmosphere. Not analogous to climate predictions.
climate scenarios	A scenario which describes potential changes in climatic variables based on the results of ocean atmosphere modelling and assumptions about future greenhouse gas concentrations.
climate sensitivity	The equilibrium temperature change in response to a change in radiative forcing.
downscaling	Deriving local-scale climate information from larger-scale models.
emissions scenarios	Scenarios describing the potential future releases of greenhouse gases and other pollutants into the atmosphere.
GCM pattern	The pattern of change of a GCM variable in relation to a change in mean global temperature.
general circulation model (GCM)	A numerical model which represents physical processes of the atmosphere, ocean, cryosphere and land surface, using equations of physics.
Intergovernmental Panel on Climate Change (IPCC)	A scientific intergovernmental body established to provide assessment of anthropogenic climate change.
model skill	A measure of a GCM’s ability to replicate some observed climatic phenomena.
pattern scaling	A statistical method used to quantify GCM response to changes in global temperature.

representative concentration pathways	Greenhouse gas concentration trajectories for the 21^{st} century.
stationarity	Statistical parameters that do not change with time.
time horizon	A future point in time.

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