Final report

Changes in summer rainfall and implications for agriculture

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Abstract

Annual and seasonal rainfall are important drivers of agricultural productivity and profitability in Australian agriculture and various climatological and synoptic drivers influence rainfall patterns in Australia's diverse climate. This study detects trends in past and future annual, seasonal and extreme rainfall across three important agricultural production regions in the Australian midlatitudes, using station and gridded data for the 1907 to 2018 period. Apart from region-wide changes, we find a positive trend in summer rainfall for two of the seventeen studied locations and a negative trend in winter rainfall for five of the seventeen locations. There is some indication of an increase in the number of very wet days and the number of days with heavy precipitation in the Northern Murray Darling Basin, and a decrease in the number of consecutive wet days in the coastal regions of Queensland and New South Wales and the Western Australia Wheat Belt. These patterns suggest a change of how rainfall is distributed over the year and a potential increase in rainfall intensity between 1907 and 2013.

Executive summary

Background

The aim of this study is to understand whether observed declines in rainfall in the midlatitudes are part of a longer-term or regional trend requiring transformational changes to the farming systems or merely attributed to natural variability. Rainfall is highly variable in Australia and rainfall variability is higher than could be expected for locations with similar mean rainfall (Nicholls, Drosdowsky and Lavery, 1997), (Nicholls et al., 1997) with coefficients of variation of 50-80%. The basis of this study were observations of unreliable summer rainfall over parts of northern New South Wales in the last ten years. This study will complement previously undertaken research, and test assumptions used for seasonal and annual rainfall in three study areas in the midlatitudes between 24 °S and 35 °S. This will support insights on the possibility for continuing the current production systems from a climate perspective and for regional forecasting of crop production in these regions. The focus is on general rainfall changes that are important for agricultural production in the study area, not a specific agricultural commodity. The results of this study are expected to provide insights into past, current and future rainfall and rainfall changes that have occurred and might occur in the future, in selected locations and across larger production areas. As producers take climate information into consideration when making management decisions, this can assist in climate related risk assessments for producers. The results of this study can assist in understanding if recently observed changes are part of a longer-term trend that can be expected to continue and would require transformational, system-wide adaptation.

Objectives

1. Provide detailed new knowledge about any changes in summer rainfall over the study area (in northern New South Wales, southern Queensland extended to the coast so as to include sugar areas, the northern Murray Darling Basin and at similar latitudes in Western Australia – the central / southern Wheat Belt) in recent years.
2. Assess the potential causes of any such changes and attribution to climate change, along with a discussion about the potential impact on agriculture in the area.

Objective one was met successfully as evidenced by material presented in section 4.1 and the Australian Rainfall Trend explorer: https://shiny.csiro.au/rainfall-trend-explorer/. Objective two was met successfully as evidenced by material presented in sections 5.1 and 5.2.

Methodology

The methodology applied consisted of four steps for analysing rainfall trends at seventeen selected locations and three agricultural production zones. The locations and regions were determined in consultation with members of the Managing Climate Variability Program (MCV) Project Management committee.

1. Temporal aggregation of monthly climate data to calculate seasonal, annual and decadal rainfall for the time period 1907-2018.

2. Detection of trends by applying parametric and non-parametric statistical tests to rainfall data, by analyzing anomalies in seasonal, annual and decadal rainfall compared to a reference time period and by comparing the last 20 years of rainfall with long-term rainfall records since 1907.

3. Analysis of large-scale drivers of rainfall variability and causes of rainfall changes if statistically significant trends were found, complemented by a review of previously published literature.
4. Analysis of future rainfall trends using climate model outputs for a range of emission scenarios and time periods.

Results/key findings

Robust trends with significant and long-term changes in seasonal rainfall in summer rainfall were noted for two out of the seventeen stations studied and for the Western Australia Wheat Belt. Spatial heterogeneity in rainfall is very high which makes it challenging to establish any regional trends from local observations. Although some locations experienced a long period of summers with below average rainfall, this does not constitute part of a long-term trend for the time period 1907-2018/19 and our current results suggest that they are part of natural variability in seasonal rainfall. Among the large-scale climate influences on seasonal rainfall in the Western Australia Wheat Belt, the El Nino-Southern Oscillation, the Southern Annular Mode and atmospheric blocking are the main influences on warm season rainfall. The decline in winter rainfall in Western Australia is expected to continue as there is high agreement in climate models for further declines in winter rainfall, while changes in rainfall in Eastern Australia are less certain.

Benefits to industry

Climate change impact assessments for specific commodities and regions can build on the findings of this study by using the information provided on model consensus for directions of change in rainfall. Agricultural impact studies could use the climate models and the rainfall indicators identified here to determine if the positive or negative trends in the past continue into the future. For the Western Australia Wheat Belt where the direction of change in seasonal rainfall is more certain, this knowledge can assist in developing coping strategies or inform transformation processes.

Future research and recommendations

Future research should focus on extending the analysis provided to include locations in the New England and North West region in New South Wales and Far West and Orana region in New South Wales to confirm whether the high anomaly in summer rainfall in the recent decade found for Narrabri and Curlewis can be observed elsewhere. For now, this is a very localized trend as none of the locations in the larger Northern Murray Darling basin has experienced the same changes and is therefore very difficult to explain other than suggesting that it is part of large year-to-year rainfall variability in the area. It would also be beneficial to extend the list of rainfall variables used here to consider not only changes in the growing season rainfall and extreme rainfall across the year, but also changes in rainfall related to specific management decisions, such as planting or to specific adverse events such as droughts increasing in frequency or intensity.

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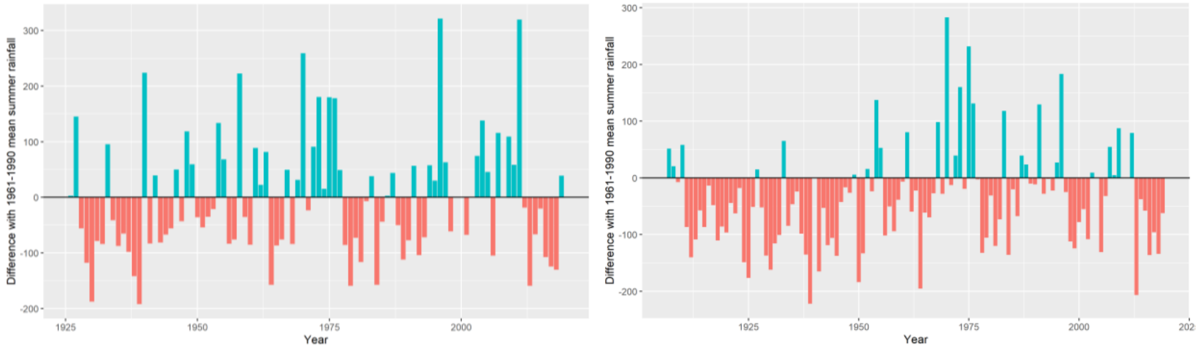
1. Background

1.1 Problem description

Australia’s climate is highly variable in association with a range of climate drivers and has warmed since national temperature records began in 1910 by about 1.44 ± 0.24°C (CSIRO and Australian Bureau of Meteorology, 2020) increasing the risk for heavy rainfall events becoming more intense and rainfall and rainfall variability to change (Pendergrass *et al.*, 2017).

Geographically, several studies on rainfall and agriculture focused on the northern and southern production zones and they suggest that recent decades have been drier than previous decades, especially in winter in the southwest (Hennessy, Suppiah and Page, 1999; Haylock and Nicholls, 2000; Smith, 2004; Murphy and Timbal, 2008) and in autumn and winter in the southeast of Australia (Timbal, 2009; CSIRO, 2010; Hope *et al.*, 2017). In contrast, rainfall especially in the wet season has been slightly higher than before in north-western Australia (Freund *et al.*, 2017; Contractor, Donat and Alexander, 2018). There is limited knowledge for other key agricultural production regions located in the midlatitudes, between the tropical and temperate climate zones, and long-term rainfall changes in other seasons. In these parts of Australia’s agricultural areas, for example in northern New South Wales (NSW), farmers have experienced seasonal rainfall in the previous years as unreliable which increases the risk for agriculture. For example, in Narrabri, New South Wales, the seven summers 2012/13 to 2018/19 have been dry with rainfall below the long-term average which was followed by a wetter summer 2019/20. This number of consecutive dry summers is unprecedented since 1926 as even during the World War II drought (1935-1945) with six consecutive years of below average summer rainfall the seventh year had above average summer rainfall. Another example is Curlewis, 120 km southeast of Narrabri in New South Wales, where the last seven summers have been dry with below average rainfall which is however not unprecedented.

Figure 1. Summer rainfall anomaly in Narrabri, New South Wales 1926-2019 (left) and Curlewis, New South Wales 1907-2019 (right). Data source: Bureau of Meteorology Climate Data Online, data shown is a composite of stations 55045 (Curlewis - Pine Cliff) and 55014 (Curlewis Post Office) and 55026 (Narrabri - Mollee) and 54038 (Narrabri Airport)



Examples of implications of continuous dry years in these areas include increased water and heat stress for crops and livestock, increased demand for irrigation water, high costs for replanting and decreased production efficiencies and profitability for producers in regional communities. All crop and livestock production in Queensland and New South Wales in 2016-17 have been estimated to be worth $19 billion (ref). The economic damage to these industries can be substantial. During the millennium drought 2001 to 2009, agricultural production and its contribution to Australia's economy fell significantly and affected especially rural communities (van Dijk *et al.*, 2013). In the last 30 years, droughts, wildfires and heat waves in Australia have caused an overall economic damage of an estimated AU$13.1 billion (18% of all disaster damage) and affected 11.7 million people (72% of all people affected by disasters) (CRED / UCLouvain, 2021).

1.2 Aim of this study

The aim of this study is to understand whether observed declines in rainfall in the midlatitudes are part of a longer-term or regional trend requiring transformational changes to the farming systems or merely attributed to natural variability. Rainfall is highly variable in Australia and rainfall variability is higher than could be expected for locations with similar mean rainfall (Nicholls, Drosdowsky and Lavery, 1997) with coefficients of variation of 50-80%. The coefficient of variation in summer rainfall for example in Narrabri in New South Wales was 50% between 1926 and 2019 which indicates that, on average, every second summer has a 50% rainfall deviation from the long-term mean. It is unclear to what extent observed rainfall declines are part of a long-term trend and to what extent underlying climatological drivers such as the El Niño–Southern Oscillation (ENSO) are already influenced by global climate change (Vecchi and Wittenberg, 2010; Power *et al.*, 2013; Cai *et al.*, 2014, 2018). Our study will complement previously undertaken research, and test assumptions used for seasonal and annual rainfall in three study areas in the midlatitudes between 24 °S and 35 °S. This will support insights on the possibility for continuing the current production systems from a climate perspective and for regional forecasting of crop production in these regions. We do not focus on a specific agricultural commodity but rather on general rainfall changes that are important for agricultural production in the study area.

1.3 Points of differentiation to previous research and how to use results

Previous R&D projects have focused on either (i) forecasting rainfall to support producer's decision making in terms of what and when to plant or (ii) impacts on production and efficiencies resulting from climate change projections generated from downscaled global climate model scenarios. Geographically, these projects focused on the northern or southern production zones (e.g. the South Eastern Australian Climate Initiative) so there is limited knowledge for example on the northern Murray-Darling basin, bridging the tropical and temperate climate zones. What also remains unclear is whether the lower than average summer rainfall in parts of these areas in the last years is part of a longer term trend that will likely continue or rather attributed to a single event (or string of events) caused by natural variability in the climate system. It is debated in the literature to what extent these systems are already influenced by global climate change and it is difficult to attribute some single climate events (e.g. drought) to consistent changes in the global climate system. This work will complement and test assumptions used in the previously undertaken research. In gaining this better understanding this will give strong insights on the practicability for continuing the current production systems from a climate perspective and for regional forecasting of crop production in these regions. Another point of distinction is that we do not focus on specific agricultural commodities but rather on general rainfall changes that are important for agricultural production in the study regions.

2. Objectives

1. Provide detailed new knowledge about any changes in summer rainfall over the study area (in northern New South Wales, southern Queensland extended to the coast so as to include sugar areas, the northern Murray Darling Basin and at similar latitudes in Western Australia – the central / southern Wheat Belt) in recent years.

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Objective one was met successfully as evidenced by material presented in section 4.1 and the Australian Rainfall Trend explorer: https://shiny.csiro.au/rainfall-trend-explorer/. Objective two was met successfully as evidenced by material presented in sections 5.1, 5.2 and 5.3.

3. Methodology

The methodology applied consisted of four steps for analysing rainfall trends at seventeen selected locations and three agricultural production zones (Figs. 4-5). The locations and regions were determined in consultation with members of the Managing Climate Variability Program (MCV) Project Management committee.

- Temporal aggregation of monthly data to calculate seasonal, annual and decadal rainfall for the time period 1907-2018, and

- detection of trends by applying parametric and non-parametric statistical tests to rainfall data, by analyzing anomalies in seasonal, annual and decadal rainfall compared to a reference time period and by comparing the last 20 years of rainfall with long-term rainfall records,

- analysis of drivers of rainfall variability and causes of rainfall changes if statistically significant trends were found, complemented by a review of previously published literature, and

- analysis of future rainfall trends using climate model outputs for a range of emission scenarios and time periods.

Figure 2 Overview of methodology applied to station rainfall data.

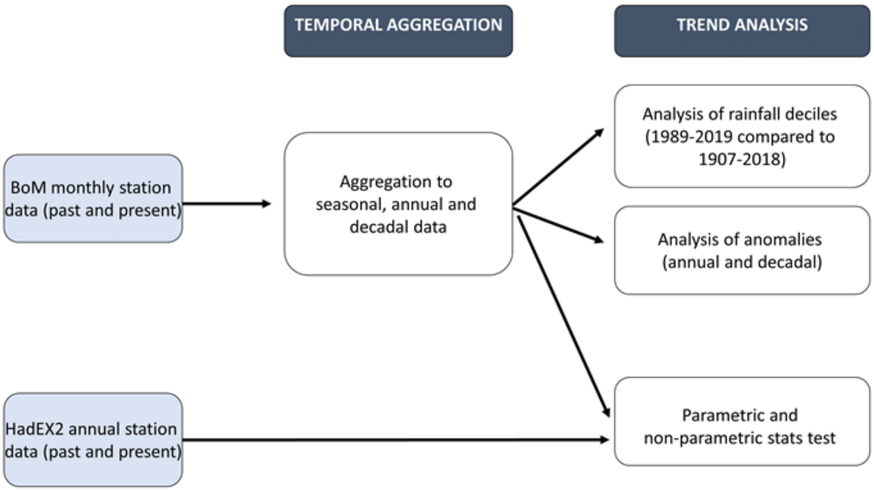
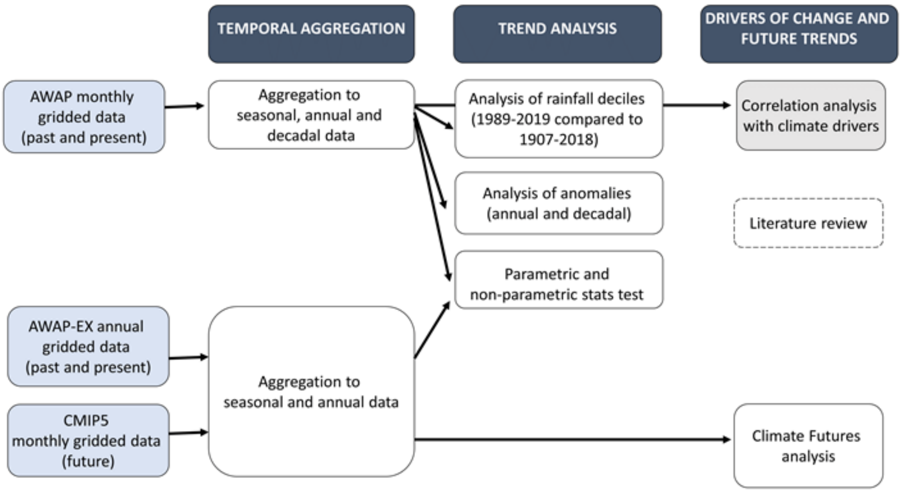


Figure 1 Overview of methodology applied to regional rainfall data.



3.1 Study area

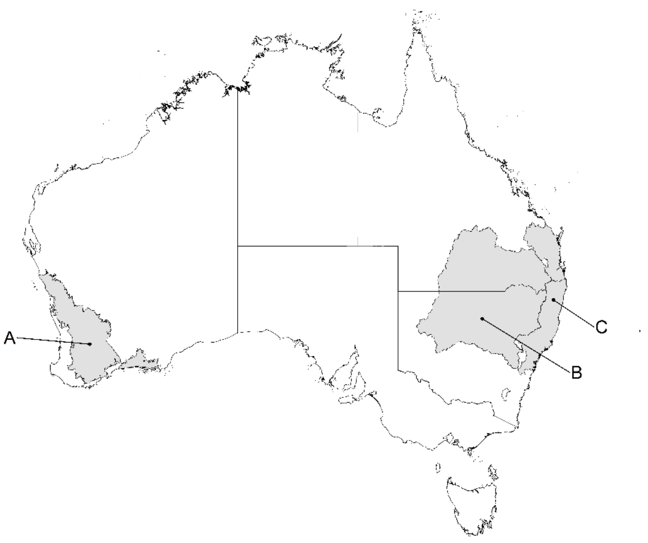
We choose study areas located in the midlatitudes between 24 °S and 35 °S and between the tropical and temperate climate zone with associated complexities in the climate system. We also aim for the study areas to represent different agroecology, agricultural systems and commodities. The three study areas are located across Western Australia (WA), southern Queensland (QLD) and northern New South Wales (NSW) (Fig. 4):

- (A) The Western Australia Wheat Belt ranging from 28°S to 35 °S and 114°E to 124°E.

- (B) The Northern Murray Darling Basin ranging from 25°S to 34°S and 142°E to 153°E

- (C) Coastal Midlatitude New South Wales and Queensland region ranging from 24°S to 34°S and 150°E to 154°E

Figure 4. Study area for analysing seasonal rainfall changes, including the Western Australia Wheat Belt (A), the Northern Murray Darling Basin in southern Queensland and northern New South Wales (B) and the Coastal areas in southern Queensland and northern New South Wales (C).



The Western Australia Wheat Belt region (WA-Wheat Belt hereafter) spreads across the agricultural regions in Western Australia producing wheat, barley, wool and canola with an approximate gross value of production of AUD$ 4.7 billion (~8% of national total). Crop production alone contributes AUD$3.2 billion. The WA-wheatbelt is dominated by winter rainfall, receiving 26-68% of its annual rainfall during the austral winter season June-August and three quarters of all years in the last 120 years having received 40% or more of its annual rainfall in the winter season. The main sowing period for wheat is April-June.

In the east of Australia, the main agricultural commodities in the Northern Murray Darling Basin region (N-MDB hereafter) are cattle, sheep, wool, cotton, sorghum and eggs with an approximate gross value of production of AUD$7.2 billion (~12% of national total). Crop production contributes AUD$ 2.1 billion. The Coastal Midlatitude New South Wales and Queensland region (East coast hereafter) includes parts of seventeen different statistical regions with a combined gross value of production of AUD$ 5.7 billion (~10% of national total). The main agricultural commodities are cotton, wheat, barley, sugar and cattle. The East Coast is dominated by summer rainfall, receiving 11-84% respectively of its annual rainfall during the austral summer season December-February and one third of all years in the last 120 years having received 40% or more of its annual rainfall in the summer season. The main sowing period for winter crops is April-June and for summer crops September-November.

Each study area spans across different climate zones that are defined using a modified Köppen climate classification used by the Australian Government Bureau of Meteorology (Stern, de Hoedt and Ernst, 2000). The modified scheme is based on the climatic limits of the native vegetation and identifies three climate zones in the study areas: grassland climate that corresponds to the steppe subdivision of the dry climate group (B climates) in the original Köppen classification, a subtropical climate group with mean annual temperature of at least 18 °C and a temperate climate group with mean annual temperature less than 18 °C. The subtropical and temperate climate groups correspond to the temperate climate group (C climates) in the original Köppen classification.

3.2 Historic rainfall data

We use monthly rainfall data from the Australian Bureau of Meteorology (Bureau of Meteorology, 2013) and selected stations included in the Bureau's Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) (Trewin, 2018). ACORN-SAT was developed to study climate variability and change as the data spans over more than 100 years, from 1907 to 2018. It was developed to monitor changes in temperature only, but we assume here that the stations included also report reliable rainfall data. We select seventeen stations across the three study areas, three stations with different climate in the Western Australian-wheat belt and the East Coast and eight in the N-MDB (**Table 1**). Merredin is also a station included in the enhanced daily rainfall dataset developed for Western Australia to analyse rainfall changes over the last 100 years (Bureau of Meteorology, 2021).

For every year, we calculate the total annual rainfall as well as summer and winter rainfall as the sum of monthly rainfall in December, January, February (of the following year) and June, July, August, respectively. For example, the 2018 summer rainfall is the sum of the monthly rainfall from December 2018 to February 2019. Annual and decadal anomaly are calculated as the deviation from the annual average rainfall of the period 1961-1990 and from the decadal average rainfall of the period 1907-2018, respectively.

To describe trends in rainfall extremes, we use station data from the HadEX2 dataset for 1901-2010 (Donat *et al.*, 2013), updated to 2013, for five rainfall extreme indices:

- number of heavy precipitation days calculated as the annual count of days when precipitation is larger or equal to 10mm (R10mm),
- very wet days calculated as annual total precipitation from days with precipitation larger than the 95th percentile (R95p),
- maximum five-day precipitation amount (Rx5day),
- maximum number of consecutive days with precipitation of 1mm or more (CWD), and
- the maximum number of consecutive days with precipitation less than 1mm (CDD).

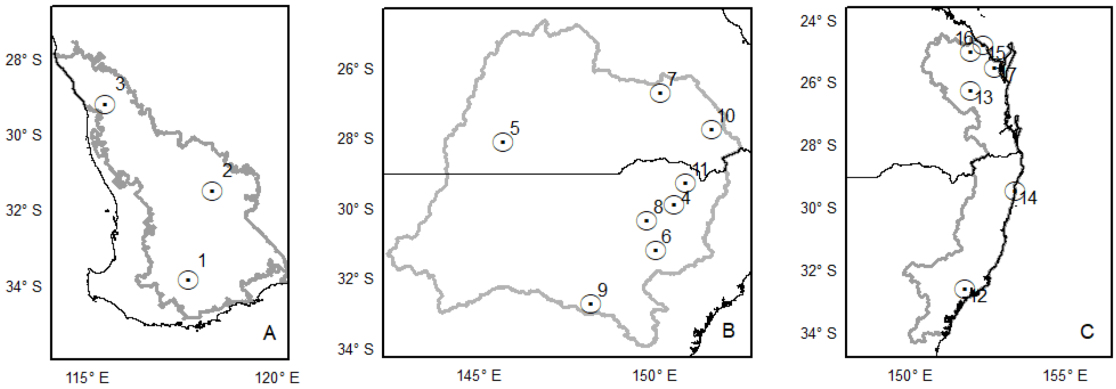
The 95th percentile is calculated for the time period 1961-1990 and can adequately represent extreme rainfall in wet regions and wet seasons with more than 45 rain days but in dry regions and seasons it may be as low as the median rain intensity (Hennessy, Suppiah and Page, 1999).

We analyse long term trends for 1907 to 2018 and for some stations and regions complement this with an analysis of 30-years trends for 1999 to 2018.

Table 1 Weather stations selected by study area, climate classification and land use. Source (Bureau of Meteorology, 2013; ABARES, 2016; Australian Bureau of Agricultural and Resource Economics and Science, 2016; Australian Government Bureau of Metorology, 2016)

ID	**Station** (name (state) - Bureau of Meteorology station ID)	**Coordinates**	**Climate classification** (major group/sub-group of modified Köppen classification - Seasonal rainfall characteristics)	**Average annual rainfall** (1961-1990)
Western Australia Wheat Belt				
1	Broomehill (WA) - 10525	Lat: 33.84° S, Lon: 117.64° E	Temperate / Distinctly dry and warm summer - Wet winter and low summer rainfall	440 mm/year
2	Merredin (WA) - 10092	Lat: 31.48° S, Lon: 118.28° E	Grassland / Warm, summer drought - Wet winter and low summer rainfall	327 mm/year
3	Mingenew (WA) - 08088	Lat: 29.19° S, Lon: 115.44° E	Subtropical / Distinctly dry summer - Marked wet winter and dry summer	393 mm/year
Northern Murray Darling Basin				
4	Bingara (NSW) - 54004	Lat: 29.87° S Lon: 150.57° E	Temperate / No dry season, hot summer - Wet summer and low winter rainfall	743 mm/year
5	Cunnamulla (QLD) - 44026	Lat: 28.07° S, Lon: 145.68° E	Grassland / Hot, persistently dry - Uniform rainfall	370 mm/year
6	Curlewis (Pine Cliff) (NSW) - 55045	Lat: 31.18° S Lon: 150.03° E	Temperate / No dry season, hot summer – Wet summer and low winter rainfall	653 mm/year
7	Miles (QLD) - 42023	Lat: 26.66° S, Lon: 150.18° E	Subtropical / No dry season to moderately dry winter - Wet summer and low winter rainfall	638 mm/year
8	Narrabri (NSW) - 53026	Lat: 30.26° S Lon: 149.68° E	Subtropical / No dry season - Wet summer and low winter rainfall	602 mm/year
9	Peak Hill (NSW) - 50031	Lat: 32.72° S, Lon: 148.19° E	Temperate / No dry season, hot summer - Uniform rainfall	565 mm/year
10	Pittsworth (QLD) - 41082	Lat: 27.72° S Lon: 151.64° E	Temperate / No dry season, hot summer - Wet summer and low winter rainfall	731 mm/year
11	Wallangra (QLD) - 54036	Lat: 29.24° S Lon: 150.89° E	Temperate / No dry season, hot summer – Wet summer and low winter rainfall	771 mm/year
Coastal QLD and NSW				
12	Clarence Town (NSW) - 61010	Lat: 32.59° S, Lon: 151.77° E	Temperate / No dry season, hot summer - Wet summer and low winter rainfall	1,077 mm/year
13	Murgon (QLD) - 40152	Lat: 26.24° S, Lon: 151.94° E	Subtropical / No dry season - Wet summer and low winter rainfall	766 mm/year
14	Yamba (NSW) - 58012	Lat: 29.43° S, Lon: 153.36° E	Subtropical /No dry season - Wet summer and low winter rainfall	1,468 mm/year
15	Fairymead Sugar Mill (QLD) - 39037	Lat: 24.79° S, Lon: 152.36° E	Subtropical / No dry season - Wet summer and low winter rainfall	1,094 mm/year
16	Gin Post Office (QLD) - 39040	Lat: 24.99° S, Lon: 151.96° E	Subtropical / No dry season - Wet summer and low winter rainfall	1,033 mm/year
17	Maryborough (QLD) - 40126	Lat: 25.51° S, Lon: 152.72° E	Subtropical / No dry season - Wet summer and low winter rainfall	1,135 mm/year

Figure 5. Weather stations used in the three study areas: Western Australia Wheat Belt (A), Northern Murray Darling Basin (B) and Coastal Queensland and New South Wales (C). The numbers 1-17 correspond to the ID column in Table 1. Letters A-C correspond to the study areas shown in **Error! Reference source not found.**4.



In addition to station data we use the Australian Gridded Climate Data (AGCD v1) / AWAP developed by the Australian Bureau of Meteorology to represent rainfall trends in the larger regions. The gridded rainfall data has a spatial resolution of 0.05 degrees or 3 arc minutes, starts in 1900 and is refreshed daily as new observational data becomes available. Rain gauge data from 6,000-7,000 stations across Australia was used. Gridded rainfall is produced using an anomaly-based approach where rainfall is divided in its long-term average and an associated anomaly and for the spatial interpolation the Barnes successive-correction method that applies a weighted averaging process to the station data (Jones, Wang and Fawcett, 2009). We calculate monthly and then annual and season rainfall data from daily rainfall and spatially averaged over each study region.

Data for the same extreme indices as used in the station data analysis was calculated from AGCD v1 / AWAP after aggregating from the original 0.05 degrees resolution to 0.5 degrees resolution and will hereafter be referred to as AWAP-EX.

3.3 Projections of future rainfall

We use projections from global and regional climate models as well as statistically downscaled results. The global climate model (GCM) data are from the modelling experiments (CMIP5) that informed the IPCC's Fifth Assessment Report as well as those used for the earlier Fourth Assessment Report (CMIP3). In addition to accessing the GCM data at the native grid size of each model (between approximately 60 and 300 km), some of these data have been downscaled using dynamical and or statistical techniques. Downscaled results include those from CSIRO's Conformal-Cubic Atmospheric Model (CCAM; McGregor and Dix, 2008) and the Bureau of Meteorology statistical downscaling model (BOM-SDM; Timbal and McAvaney, 2001).

3.4 Change detection and trend analysis

The statistical analysis was conducted with the statistical software R 3.6.2 (2019-12-12). To assess the existence and the significance of the rainfall trend over the years, three statistical test methods are used: Student's t test, the Mann Kendall test and the Sen's slope estimator as non-parametrical tests. The slope was calculated from a linear regression model (lm function in R). The Kendall's Tau was calculated with the MannKendall function in the "Kendall" package (McLeod, 2011). The Kendall's tau is a non-parametrical test, assuming no particular data distribution. The test corroborates whether there is concordance between the variables: a value of 0 means no concordance, and (+/-)1 means perfect concordance. To calculate the significance, the Mann Kendall test is used (MannKendall function). The hypothesis that considers no trend is accepted when the p-value is <= 0.05. The trend is accepted as significant if p-values from the t-test and Mann Kendall test are smaller than 0.05. Finally, when significance was found, the Sen's slope was used to capture the magnitude of the trend, with the function sens.slope form the package "trend" (Thorsten, 2018).

An alternative method for identifying consistent shifts in rainfall is to calculate "rainfall decile ranks" to understand if current rainfall is below average, average or above average compared to the entire rainfall record from 1900. The first decile represents the lowest 10 percent of rainfall totals and decile 10 represents the highest 10 percent of rainfall totals with deciles 4 to 7 representing average rainfall. We calculate rainfall decile ranks for all seventeen stations and for each grid cell in the three study areas.

4. Results

4.1 Trend detection in historical annual and seasonal rainfall 1907-2018

4.1.1 Western Australia Wheat Belt

In the last century, winter rainfall diminished for all the stations selected in the Western Australia - Wheat Belt. For Mingenew, with subtropical climate, and Broomehill with temperate climate we also found a negative trend in the annual rainfall and, for Mingenew only, in the rainfall extreme indices Rx5day and R10mm (

Table **2**). Winter rainfall declined most strongly in Mingenew, by 0.79-0.81 mm/year, and in Broomehill, by 0.51-0.60 mm/year. There is no detectable trend in summer rainfall in Mingenew and Broomehill but a large variability with a coefficient of variation of 86% and summer rainfall totals ranging from 0.8 mm in 1994 and 247 mm in 1982 for the example of Broomehill.

In Merredin, the station with dry grassland climate, we found a positive trend in the summer rainfall but none for annual rainfall or for any of the extreme rainfall indices (**Error! Reference source not found.**6). Summer rainfall has increased by 0.24-0.29 mm per year and winter rainfall has decreased by 0.33-0.34 mm per year. Although there is no trend in the annual rainfall, there is strong year-to-year variability. The deviation of rainfall from long-term average rainfall has been quite extreme in some years with more than 100 mm deviation at a long-term average of 327.24 mm. Nine years have been wetter than average (1917, 1918, 1943, 1953, 1963, 1974, 1978, 1992, 1999) and eight years have been drier than average (1911, 1914, 1940, 1969,1977, 1980, 1994, 2010). In the most recent decades, 2007 (226.2 mm/year) and 2010 (179.2 mm/year) were the driest years.

Figure 6. Rainfall trends and anomaly in Merredin (1907-2018): winter rainfall (a) summer rainfall (b), annual anomaly (c), decadal anomaly (d), number of consecutive dry days (e) and number of days with heavy precipitation (> 10mm) (f). We show here selected results discussed in the main text only. Results for the remaining climate indicators and weather stations in the Western Australia-Wheatbelt can be found at https://shiny.csiro.au/rainfall-trend-explorer/ .

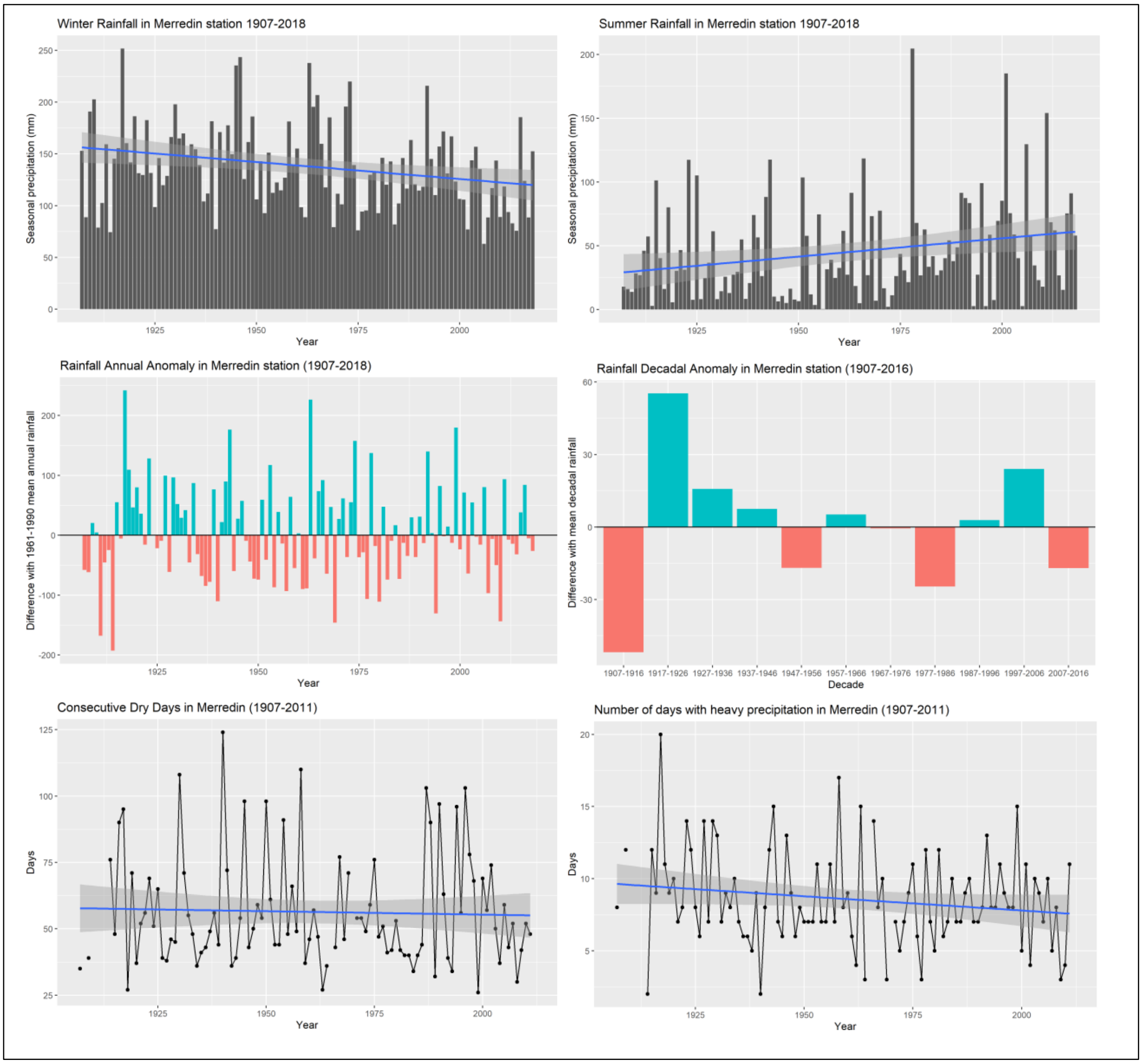


Table 2. Results of trend analysis for the Western Australia Wheat Belt. Yes/No indicates whether the t-test and Mann Kendall test indicate a p-value below (trend detected) or above 0.05 (no trend detected). Number in brackets give the range of the estimated slope of the linear trend line and Sen's slope. All data for 1907-2018 except for extreme rainfall indices from HadEX2 and AWAP-EX (1907-2013).

Location	*Region*	*Merredin*	*Broomehill*	*Mingenew*
Indicator				
Annual (mm/year)	No	No	Yes (-0.67- -0.75)	Yes (-0.91- -0.98)
Summer (mm)	Yes (0.18-0.21)	Yes (0.24-0.29)	No	No
Winter (mm)	Yes (-0.42- -0.43)	Yes (-0.33- -0.34)	Yes (-0.51- -0.59)	Yes (-0.79- -0.81)
Rx5day (mm/year)	No	No	No	No
R10mm (days)	No	No	No	No
CDD (days)	No	No	No	No
CWD (days)	Yes (-0.015- -0.017)	No	No	Yes (0- -0.02)
R95p (mm)	No	No	No	No

In agreement with the results for the three stations, average rainfall in winter across the larger study area shows a statistically significant negative trend. Average winter rainfall in the Western Australia Wheat Belt has decreased by 0.42-0.43 mm/year between 1907 and 2018. Average rainfall in summer has increased by 0.18-0.21 mm per year between 1907 and 2018 (**Error! Reference source not found.**). Annual rainfall varies from year to year and there have been drier than wetter years in the last two decades. However, the last twenty years summer rainfall has been average compared to the entire rainfall record in most places in the Western Australia wheat belt (Fig. 8 A) and there have been more wetter than drier years in the last two decades. In Mingenew, Broomehill and Merredin, the last twenty years summer rainfall has been slightly above average compared to the entire rainfall record since 1907 (Fig. 8 B).

Figure 7. Rainfall trends and anomaly in the Western Australia Wheat Belt (1907-2018): annual rainfall (a), summer rainfall (b) winter rainfall (c), consecutive wet days (d), annual rainfall anomaly (e), summer rainfall anomaly (f).

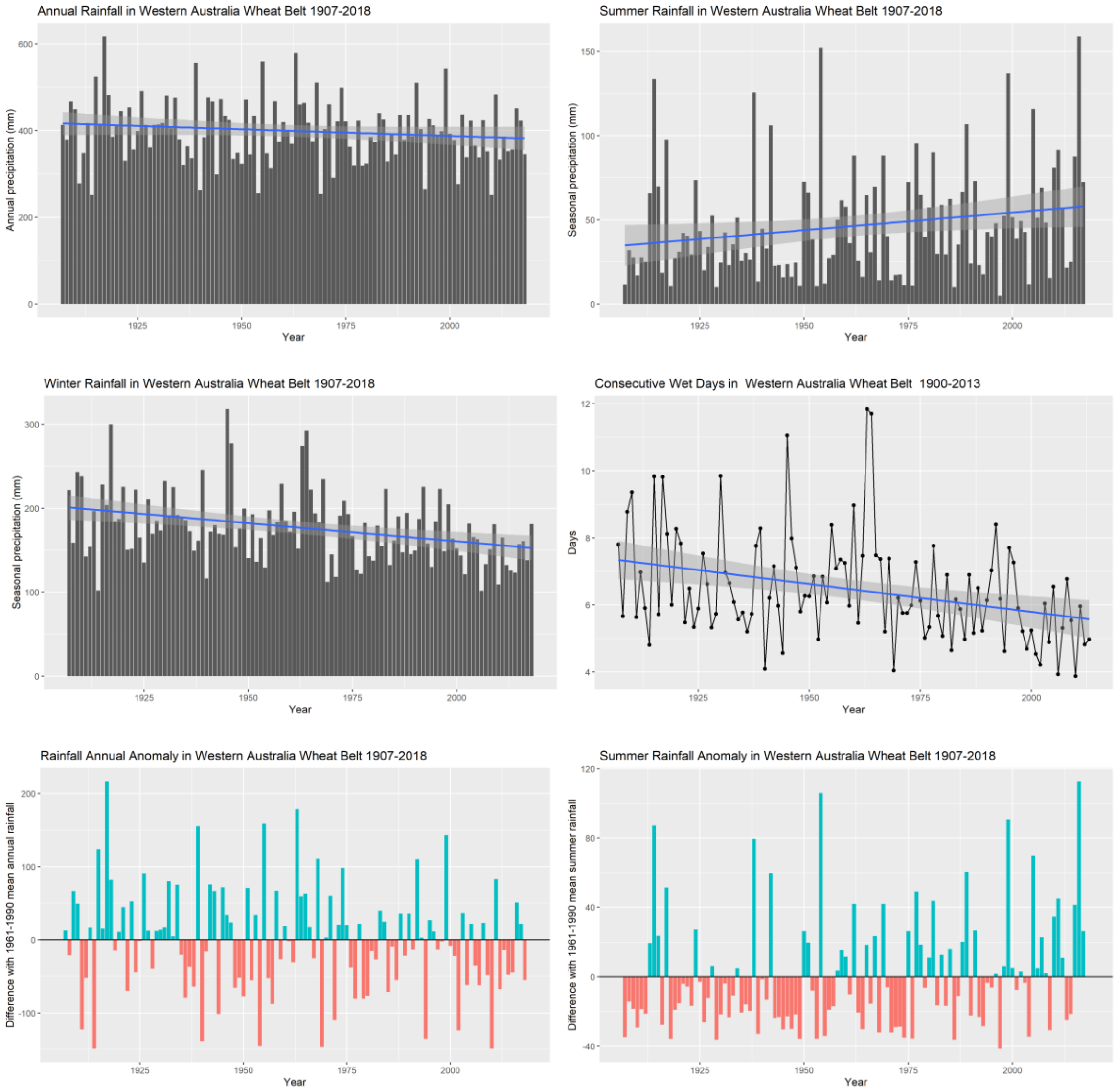
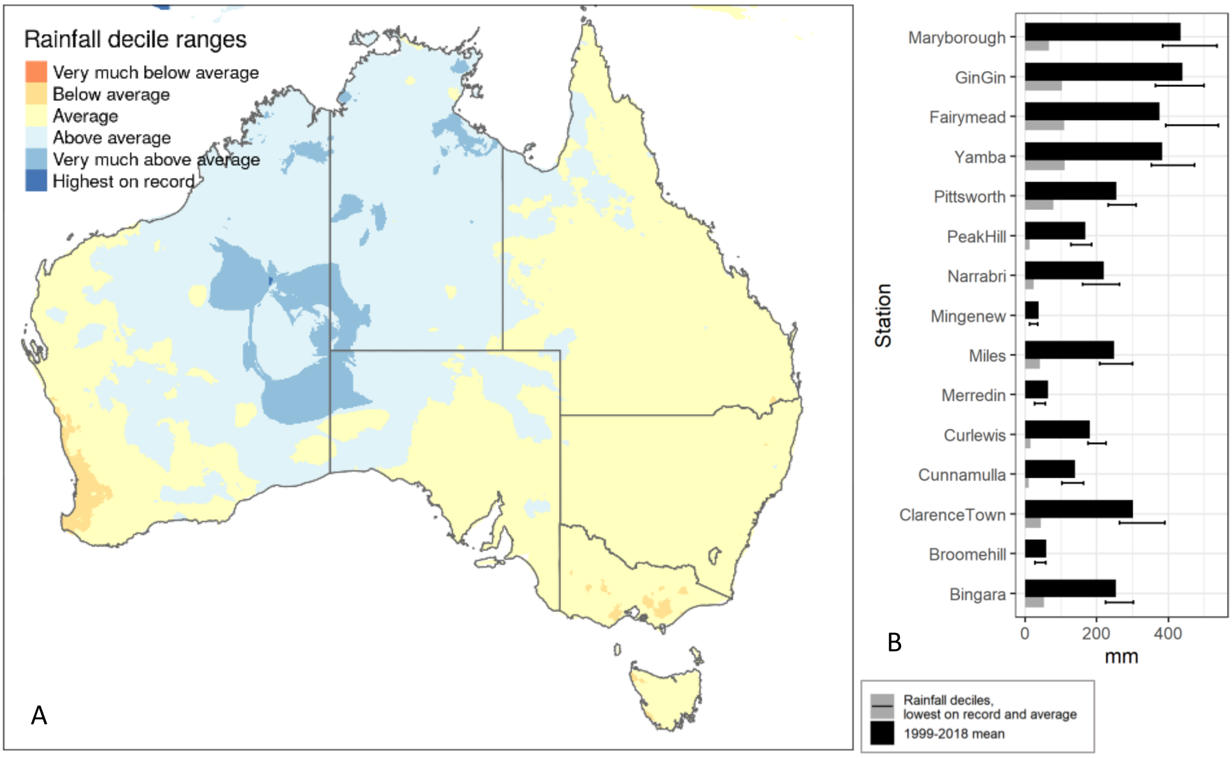


Figure 8. Summer (December-February) rainfall deciles for the last 20 years (1999-2018). A. The map shows where rainfall is above average, average or below average for the recent period, in comparison with the entire rainfall record from 1907. B. The figure shows how the last 20 years summer rainfall at each station compares to the lowest and average summer rainfall in the entire rainfall record from 1907. Murgon and Wallangra are not shown in panel B as the rainfall record for the last twenty years is not complete.



4.1.2 Northern Murray Darling Basin

No linear trend in any of the climate indicators has been found in Bingara, Miles, Narrabri and Peak Hill. The stations with changes in seasonal or annual rainfall are Curlewis, Pittsworth and Wallangra (Table 3). Summer rainfall has increased by 0.67-0.79 mm/year in Wallangra and winter rainfall has decreased by 0.34-0.37 mm/year in Pittsworth with only significant changes in annual rainfall in Curlewis. Although there were strong changes in summer rainfall in the last ten years in Narrabri and Curlewis, this does not constitute a longer-term trend yet.

Three of the five extreme rainfall indices showed a linear trend in Curlewis but only one in Pittsworth (CWD) and in Cunnamulla (R95p). The number of heavy rain days with more than 10mm of rainfall has increased slightly by 0.06-0.07 days/year or approximately by one day per 15 years. The total annual rainfall from heavy rainfall events has increased by 0.76-0.83mm which indicates a change towards more intense rainfall in Curlewis.

In Cunnamulla most years are below the 1961-1990 reference average of 393 mm/year. However, the years having rainfall above average present a bigger deviation (e.g. 1921, 1949, 1950, 1956, 1990, 1998 and 2010 deviate by +250mm from the reference average). In the last 10 years, 2018 (169.1 mm/year) and 2013 (174.8 mm/year) were the driest years. In the last century, the decadal rainfall has increased, starting from a deviation from the average of -52.47 mm in 1907-1916 decade, to +53.64 mm in 2007-2016 decade.

In Miles, three events of El Niño (1957, 1991 and 2009) resulted in a deviation of -250mm from long term average and El Niño year 1919 registered a deviation of +250mm. In the last 10 years the driest years were 2009 (439.3 mm/year) and 2017 (464.6 mm/year). The driest decade of the century was 1997-2006 (-63.89 mm from the decadal average).

Annual and season average rainfall across the study area has not changed significantly. However, the number of days with heavy precipitation (> 10mm) has increased by about 1 day per 30 year and total rainfall from very wet days has increased by 0.48-0.50 mm/year (Table 3. The last twenty years summer rainfall has been average compared to the entire rainfall record in the Northern Murray Darling basin (Fig. 8, A) with an equal number of drier and wetter years in the last twenty years. In all stations the last twenty years summer rainfall has been within the average range compared to the entire rainfall record since 1907 (Fig. 8, B).

Figure 9. Rainfall trends and anomaly in Cunnamulla (1907-2018): annual rainfall (a) summer rainfall (b), annual anomaly (c), decadal anomaly (d), consecutive dry days (e) and very wet days (f). We show here selected results discussed in the main text only. Results for the remaining climate indicators and weather stations in the N-MDB region can be found at https://shiny.csiro.au/rainfall-trend-explorer/.

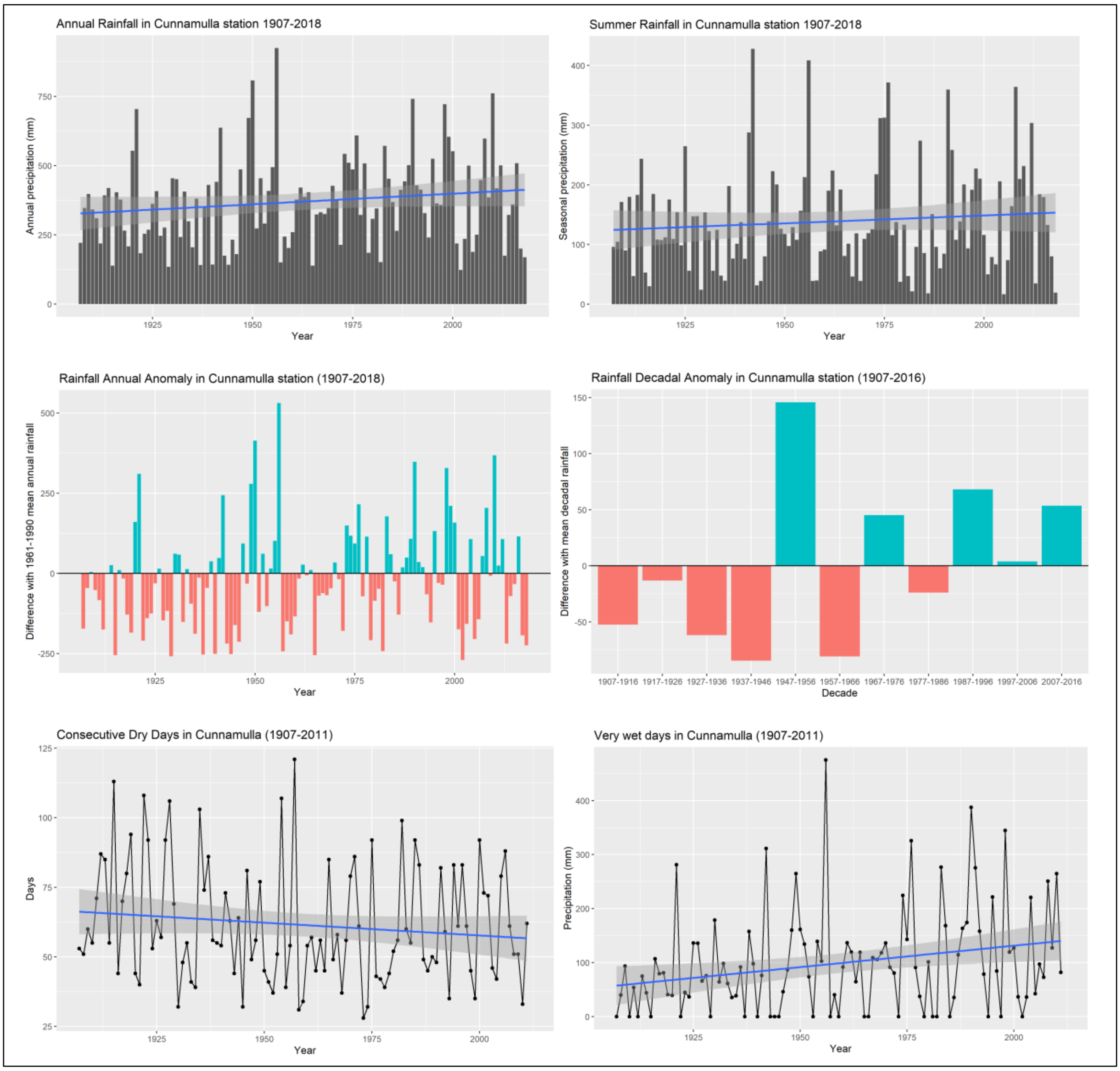


Table 3. Results of trend analysis for the Northern Murray Darling basin. Yes/No indicates whether the t-test and Mann-Kendall test indicate a p-value below (trend detected) or above 0.05 (no trend detected). Number in brackets give the range of the estimated slope of the linear trend line and Sen's slope. There have been no trends detected in any of the climate indicators in Bingara, Miles, Narrabri and Peak Hill. All data for 1907-2018 except for extreme rainfall indices from HadEX2 and AWAP-EX (1907-2013).

Location	*Region*	*Cunnamulla*	*Curlewis*	*Pittsworth*	*Wallangra*
Indicator					
Annual (mm/year)	No	No	Yes (1.34-1.64)	No	No
Summer (mm)	No	No	No	No	Yes* (0.67-0.79)
Winter (mm)	No	No	No	Yes (-0.34- -0.37)	No
Rx5day (mm/year)	No	No	No	No	No
R10mm (days)	Yes (0.03)	No	Yes (0.06-0.07)	No	No
CDD (days)	No	No	No	No	No
CWD (days)	No	No	Yes (0-0.01)	Yes (-0.008-0)	No
R95p (mm)	Yes (0.48-0.50)	Yes (0.63-0.81)	Yes (0.76-0.83)	No	No
** Mann Kendall test only, not t-test*					

4.1.3 Coastal midlatitude New South Wales and Queensland region

None of the stations representing the East coast have a statistical significance trend in annual rainfall or summer rainfall (Table 4). For Clarence Town, Fairymead Sugar Mill and Yamba, we find a significant trend in annual total precipitation from days with heavy rainfall (R95p).

The total annual rainfall from heavy rainfall events has increased by 1.16-1.33 mm/year in Yamba which indicates a change towards more intense rainfall. This is confirmed by the results of the trend analysis for the maximum 5-day precipitation (Rx5day) which has increased by 0.52 mm/year. In Yamba more than three quarters of the years were below the long-term average 1961-1990 (1,592 mm/year). Several years deviated from the mean by 750mm: 1915, 1932 and 1968 were below the mean, and 1921, 1950, 1962 and 1999 were above. In the last 10 years, 2016 was the driest year (1,071 mm/year). As for Clarence Town, there is an increase of rainfall after the decade 1937-1946. The last decadal rainfall was above the decadal average.

In Clarence Town and Fairymead, however, annual rainfall from heavy rainfall events has declined by 1.57-1.58 mm/year and 1.9-2 mm/year, respectively. In Clarence Town the number of consecutive wet days has increased by 0.02 days per year or 1 day in 50 years on average. Winter rainfall has declined significantly. Clarence Town presents high year-to-year variability. Several years recorded a difference form the reference average (1077.69 mm/year) of -400mm, i.e. 1935, 1944, 1965, 1979, 1980, 1991. In the last 10 years, the driest year was 2014 (762.7 mm/year).

Annual and season average rainfall across the study area has not changed significantly. However, the number of consecutive wet days has decreased slightly between 1907 and 2013, by about 1 day per 65 years (Table 4). The last twenty years summer rainfall has been average compared to the entire rainfall record in the Coastal Queensland and New South Wales region (Fig 8, A) but there have been more drier than wetter summers in the last twenty years. In Clarence Town, Gin Gin, Maryborough and Yamba the last twenty years summer rainfall has been within the average range compared to the entire rainfall record since 1907 (**Error! Reference source not found.**, B). In Fairymead Sugar

Mill, the last twenty years summer rainfall has been below average compared to the entire rainfall record since 1907.

Figure 20. Rainfall trends and anomaly in Clarence Town (1907-2018): annual rainfall (a) summer rainfall (b), annual anomaly (c), decadal anomaly (d), consecutive wet days (e) and very wet days (f). We show here selected results discussed in the main text only. Results for the remaining climate indicators and weather stations in the East Coast can be found at https://shiny.csiro.au/rainfall-trend-explorer/

Table 4. Results of trend detection tests for the Coastal Queensland and New South Wales region. Yes/No indicates whether the t-test and Mann Kendall test indicate a p-value below (trend detected) or above 0.05 (no trend detected). Number in brackets give the range of the estimated slope of the linear trend line and Sen's slope. All data for 1907-2018 except for extreme rainfall indices from HadEX2 and AWAP-EX (1907-2013).

Location	*Region*	*Clarence Town*	*Yamba*	*Murgon*
Indicator				
Annual (mm/year)	No	No	No	No
Summer (mm)	No	No	No	No
Winter (mm)	No	Yes (-0.63- -0.76)	No	No
Rx5day (mm/year)	No	No	Yes* (0.52)	No
R10mm (days)	No	No	No	No
CDD (days)	No	No	No	No
CWD (days)	Yes (-0.015- -0.016)	Yes (0.02)	No	No
R95p (mm)	No	Yes (-1.57- -1.58)	Yes* (1.16-1.33)	No
** Mann Kendall test only, not t-test*				

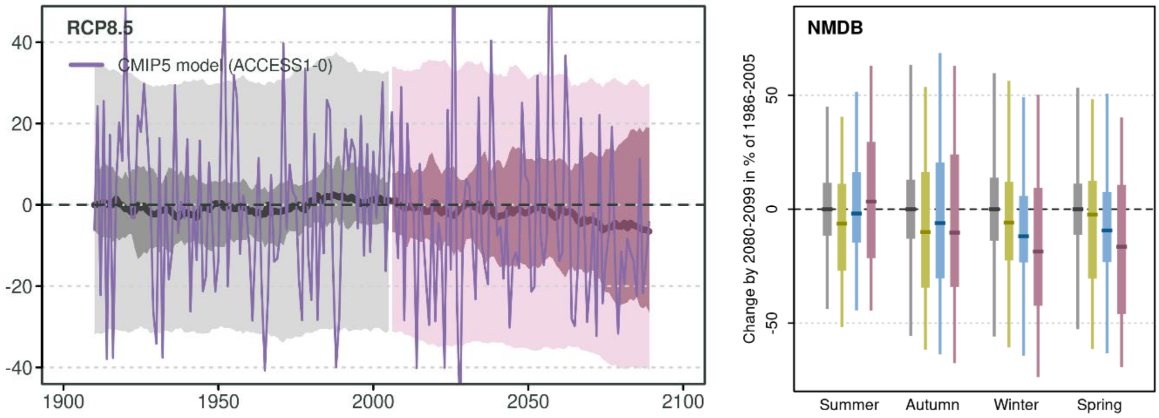
(Continuation of Table 4)

Location	*Fairymead*	*Gin Gin*	*Maryborough*
Indicator			
Annual (mm/year)	No	No	No
Summer (mm)	No	No	No
Winter (mm)	No	No	No
Rx5day (mm/year)	Yes (-0.94 - -0.71)	No	No
R10mm (days)	No	Yes (-0.06 - -0.08)	Yes (-0.04 - -0.05)
CDD (days)	No	No	No
CWD (days)	No	Yes (0.05 - -0.02)	No
R95p (mm)	Yes (-1.9 - -2)	No	No

4.2 Projections of future rainfall changes

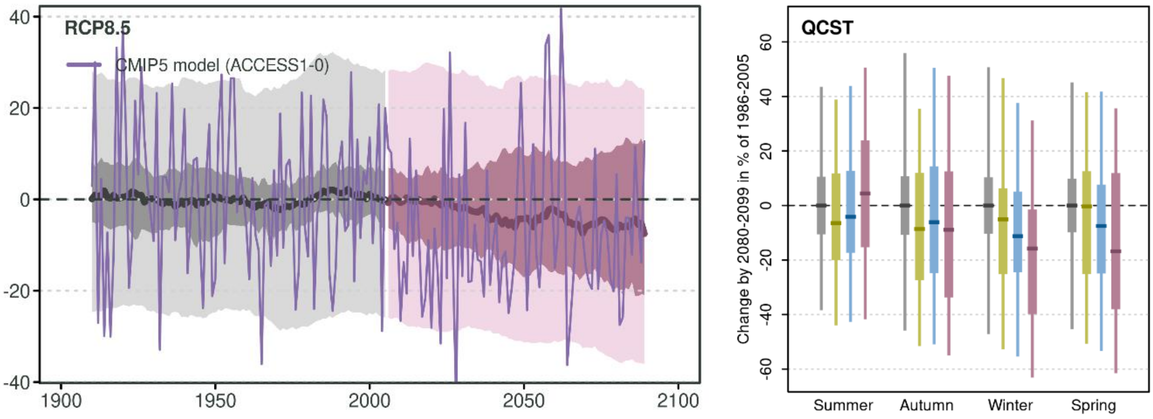
For the Northern Murray Darling basin, rainfall projections show that large increases or decreases are possible, although there is medium model agreement on a decrease in annual rainfall under high emissions towards the end of the century. Over the next decade or so, there is high confidence that natural climate variability will be the main influence on rainfall. Winter (high confidence) and spring (medium confidence) rainfall is expected to decrease by late in the century, irrespective of emissions (Fig. 11). This suggests that by mid-century, while there will continue to be wet and dry years, rainfall is more likely to decline in winter (by up to 35%) and spring (by up to 35%), compared to the period 1986-2005. Climate Futures (Clarke, J. M., Whetton, P. H., and Hennessy, 2011; Whetton *et al.*, 2012) analysis shows that increase and decrease in summer rainfall is plausible but there is insufficient evidence to indicate the direction of change with any confidence (Appendix 9.3).

Figure 31. Projected changes in annual and seasonal regional rainfall for the Northern Murray Darling basin as simulated in CMIP5 for representative concentration pathway (RCP) 8.5. Left panel: time-series of change relative to the 1950-2005 mean, showing historic simulations from all models near-continuously with future as simulated for representative concentration pathway (RCP) 8.5. The central line is the median value of the model simulations while the dark shading shows the 10th and 90th percentile range of 20-year means and the light shading, the 10th to 90th percentile interannual range. The thin purple line shows rainfall as simulated by one illustrative model, ACCESS1-0. Right panel: boxplots summarizing the percent change in seasonal rainfall by 2080-2099 relative to 1986-2005 means for three RCPs, green for RCP 2.6, blue for RCP 4.5 and purple for RCP 8.5. See Appendix for projected rainfall changes by 2020-2039, 2040-2059 and 2060-79.



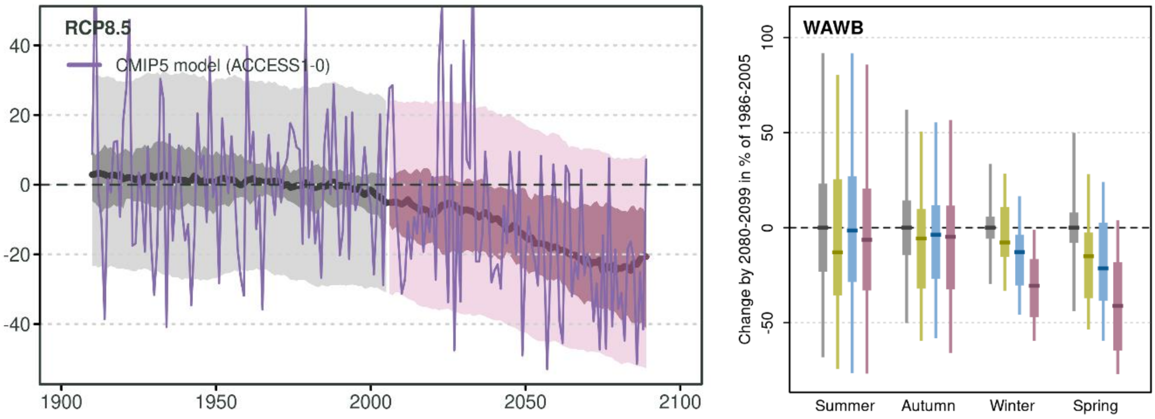
For the Coastal midlatitudes region, rainfall projections show that large increases or decreases are possible, although there is medium model agreement on a decrease in annual rainfall irrespective of emissions towards the end of the century. Over the next decade or so, there is high confidence that natural climate variability will be the main influence on rainfall. Winter rainfall is projected to decrease (medium confidence) by late in the century, irrespective of emissions (Fig. 12). This suggests that, while there will continue to be wetter and drier years, mid-century winter rainfall is more likely to be lower (by up to 30%) than higher, compared to the period 1986-2005. This is further supported by Climate Futures analysis showing a strong clustering of model results in the Drier and Much Drier climate futures around mid-century under high emissions.

Figure 12 As Fig. 11 but for the Coastal midlatitudes New South Wales and Queensland region.



For the Western Australia wheat belt, rainfall projections show a strong declining trend, irrespective of emissions. Winter, spring and annual rainfall are projected to decrease (high confidence) by late in the century, irrespective of emissions (**Error! Reference source not found.**3). This suggests that by mid-century, while there will continue to be wetter and drier years, rainfall is more likely to decline in winter (by up to 28%) and spring (by up to 39%), compared to the period 1986-2005. This is further supported by Climate Futures analysis showing a strong clustering of model results in the Much Drier climate futures around mid-century under high emissions.

Figure 13 As Fig. 11 but for the Western Australia Wheat Belt.



From analysing the changes in seasonal and annual rainfall in all CMIP5 models we can identify representative models for each direction of change simulated. For the three study areas, the models that represents the least hot and wettest climate future (best case) are NorESMI1-M for the Northern Murray Darling basin and the Coastal midlatitudes region and CNRM-CM5 for the Western Australia Wheat Belt. The models that represent the hottest and driest climate future (worst case) are GFDL-ESM2M for the Northern Murray Darling basin and the Coastal midlatitudes region and CESM1-CAM5 for the Western Australia Wheat Belt. The models that represent the maximum consensus are CESMS1-CAM5 for the Northern Murray Darling basin, and MIROC5 for the Coastal midlatitudes region and the Western Australia Wheat Belt. (Moise *et al.*, 2015; Grose *et al.*, 2020) give more insights into CMIP5 and CMIP6 simulated climate futures and how to evaluate climate model performance.

5. Comparison to previously published studies and review of climatological causes of rainfall changes

The decline in winter rainfall in the Western Australia Wheat Belt has been described before for different time periods and using different rainfall indicators. For example the Indian Ocean Climate Initiative (2013) in one of their reports states that May to July rainfall has decreased by 14% between 1969 and 1999 and by 33% between 2000 and 2009 compared to the 1910 to 1968 average in Nyerilup, WA in the south of the Wheat Belt. For South West Western Australia, including the Wheat Belt Murphy and Timbal (2008) and Smith (2004) found a drying trend since the late 1960s mainly in the late autumn to winter months May to July. Also, Hennessy *et al.* (1999) find a significant negative change in annual rainfall in South West Western Australia during 1910-1995 of - 19% with winter rainfall decreasing even stronger (- 25%). In agreement with that the number of rain days in winter declined by 13% in winter-dominated South West Western Australia (Hennessy, Suppiah and Page, 1999). Haylock and Nicholls (2000) find a significant negative rainfall trend for southwest Western Australia between 1910 and 1992 with a decrease in annual rainfall by 185 mm per 100 years, in the number of rain days by 12.73 days per 100 years and in the number of extreme rainfall events by 1.69 days per 100 years. The number of wet days with more than 1mm rainfall per days in South West Western Australia decreased in all four seasons between 1951 and 2013 but the largest decreases occurred in autumn and winter (Contractor, Donat and Alexander, 2018). (Freund *et al.*, 2017) found a decline in cool season rainfall during the most recent 30- and 50-years periods for the Southern and Southwestern Flatlands region that also includes parts of South Australia.

In contrast to the winter season we find a positive trend in summer rainfall in the Western Australia Wheat Belt overall that is smaller than the trend found for the winter season. The only station with a positive trend in summer rainfall is Merredin, WA (0.24-0.29 mm/year) and this trend is smaller than the trend found before for Peppermint Grove, WA, located about 250km west of Merredin on the Indian Ocean coast, with 0.68 mm/year increase in summer rainfall since 1950 (Indian Ocean Climate Initiative, 2013). We find no change in summer rainfall for the other two locations in the north and south of the WA-Wheat Belt. (Hennessy, Suppiah and Page, 1999) found that heavy rainfall intensity in summer increased by 10-19% in South West Western Australia but we cannot confirm that. In contrast to our results Contractor *et al.* (2018) find some evidence for a drying trend in summer as the number of wet days decreased along parts of the Western Australia coast but the spatial extent of the area affected is quite small compared to the area affected by declines in winter rainfall. In agreement with our results, Ludwig *et al.* (2009) reported declines in annual total and winter rainfall for Mingenew located in the northern part of the Wheat Belt. They found that annual rainfall decreased by 13% in 1975-2004 compared to 1945-1974 with even stronger decrease in June-July rainfall of 27%, all statistically significant.

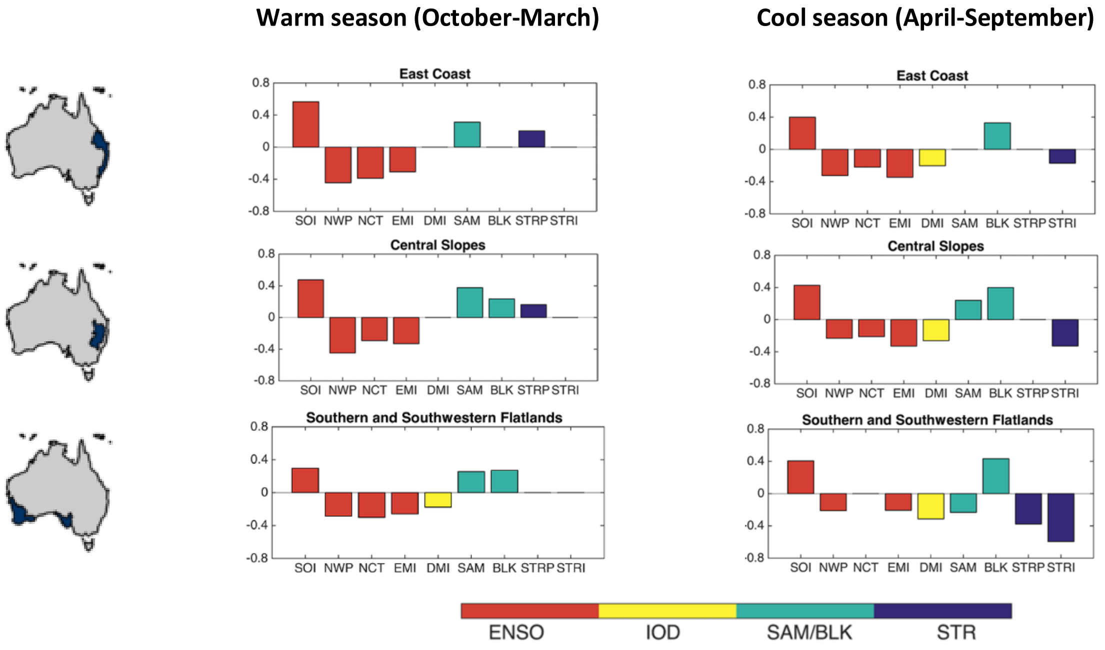
Fewer studies have focused on rainfall trends in Southern Queensland (QLD) and Northern New South Wales (NSW). Hennessy *et al.* (1999) found no statistically significant change in annual or summer rainfall in Queensland and New South Wales. In agreement with that, we find no regional trend in annual and summer rainfall, but we find an increase for specific stations, Wallangra, Queensland and Curlewis, New South Wales. Including more recent data from daily gridded rainfall data sets, Contractor *et al.* (2018) find that the number of wet days in Eastern Australia has decreased in all four seasons between 1951 and 2013, but particularly in the summer season which we cannot confirm. Contractor et al. 2018 found that the number of wet days declined by 1.5% or more but only in regions near the coast and more often in Queensland than in New South Wales.

Dowdy et al. (2015) found a small increase and a small decrease in summer rainfall between 1910 and 2005 in the coastal regions of northern New South Wales and the coastal regions of southern Queensland, respectively, both we cannot confirm for the time period 1907 to 2018.

5.1 Correlation analysis of rainfall with climate drivers

Analysing the influence of different climate drivers on rainfall variability in different seasons can indicate potential causes for long-term trends in seasonal rainfall and some studies have conducted correlation analysis between large-scale climate drivers and rainfall variability (Freund et al., 2017; Risbey et al., 2009; van Dijk et al., 2013). (Freund *et al.*, 2017) found that in the Western Australia Wheat Belt ENSO explains the greatest proportion of rainfall variance during the warm season (~40%), followed by SAM and atmospheric blocking (Fig. 14). There is no influence of the sub-tropical ridge position or intensity (STRP/STRI) in the region in the summer season but a strong influence in the cool season and only a small negative influence of conditions in the Indian Ocean Dipole (IOD) which is less strong than in the cool season. The influence of ENSO on rainfall in the Western Australia Wheat Belt is smaller than in the other two study areas in Eastern Australia.

Figure 4. The dominant climate influence on seasonal rainfall. The correlations shown exceed the 10% significance level. SOI: Southern Oscillation index, NWP: Nino Cold Tongue index, NCT: Nino Warm Pool index, EMI: El Nino Modoki index, DMI: Indian Ocean Dipole, SAM: Southern Annual Mode, BLK: Blocking index, STRP: Subtropical Ridge position, STRI: Subtropical Ridge intensity. Modified from Freund et al. 2017, Figure 2 and Figure 4 that are licensed under a Creative Commons Attribution 4.0 License.



5.2 Influence of individual climate drivers

5.2.1 Western Australia Wheat Belt

Decreased winter rainfall in South West Western Australia has been linked to the Southern Annular Mode, shifts in synoptic systems, land cover changes, anthropogenic forcing, natural multidecadal variability and changes in mean sea level pressure (Ummenhofer *et al.*, 2009).

For example, England *et al.* (2006) established a close relation between interannual rainfall in South West Western Australia and a dipole pattern of Indian Ocean sea surface temperature (SST) anomalies and the Indian Ocean Dipole (IOD) during extreme rainfall years using reanalysis data and a coupled climate model. In dry years, the SST dipole is characterized by cool waters in the tropical/subtropical eastern Indian Ocean extending north-westward to Sumatra next to warm waters near subtropical south-western Western Australia centred at ~30°S, 100°E. The Indian Ocean dipole mode index (DMI), an indicator of the IOD strength is negatively correlated with rainfall and the relationship between IOD and rainfall pattern is strongest during dry years and weaker during wet years (England, Ummenhofer and Santoso, 2006). But even some dry years, e.g. 1992 and 2002 occur without an anomalously positive IOD phase.

Marshall and Hendon (2014) studying the relationship of MJO variability in the Indian Ocean and sea level and currents on the Western Australia coast during the extended summer period November-April and find that sea level at Fremantle, ~32°S are related with MJO zonal wind anomalies in the Indian Ocean with a 4cm amplitude over the MJO lifecycle. This MJO signal in sea level is the result of an increase in sea surface temperature driven by a southward propagating coastal wave, vertical advection and surface heat flux in the early phases of the MJO. Summer rainfall in South West Western Australia is highly sporadic and can sometimes be associated with the breakdown of tropical cyclones in Western Australia but more strongly in northern Western Australia. Between 1970 and 2009, rainfall occurring within 500km of the centre of a tropical cyclone provided ~10-15% of the total extreme rainfall and up to 10% of the annual rainfall in the northern part of the Wheat Belt between 28°-30°S but with large variation between the tropical cyclone seasons (Indian Ocean Climate Initiative, 2012).

The Southern Annular Mode (SAM) has been linked to rainfall variability in southern Australia, south of 30°S (Nicholls, 2010) and subtropical Australia, south of 20°S (Hendon, Lim and Nguyen, 2014). Nicholls (2010) describe SAM as the cause of autumn to winter rainfall decline during 1958-2007 as its year to year variation is correlated with year to year variation in rainfall. The trend in SAM explained 70% of the variation in rainfall over the study area that includes the southern part of the Western Australia Wheat Belt, and the parts of the study areas in Eastern Australia located in Northern NSW. Spring-autumn, but not winter rainfall in the subtropics is influenced by SAM (Hendon, Lim and Nguyen, 2014) and spring-summer rainfall anomaly in subtropical eastern Australia is influenced by SAM during La Nina Events. A midlatitude high mean sea level pressure anomaly (MSLP), a SAM index, reduces rainfall over South West Western Australia (Shi *et al.*, 2008).

Increases in summer rainfall in South West Western Australia, e.g. at Peppermint Grove have been linked to increases in extreme rainfall (Indian Ocean Climate Initiative, 2013) which we cannot confirm for the Wheat Belt located further inland.

5.2.2. Northern Murray Darling Basin and Coastal Midlatitude Queensland and New South Wales

For New South Wales, Duc *et al.* (2017) finds that that annual rainfall at Yamba, Branxton and Port Macquarie in coastal New South Wales is dominated by the Southern Annular Mode, SAM, and El Niño–Southern Oscillation, ENSO and with little influence from the Indian Ocean Dipole, IOD, and the ENSO-IOD interaction although the ENSO-IOD interaction is the second most important driver at Port Macquarie. Annual rainfall at Bathurst, Nyngan, Coonabarabran and Bingara located in the Northern Murray Darling Basin is dominated by ENSO, SAM, followed by the ENSO-IOD interaction. Overall, the rainfall pattern in the coastal areas is dominated by SAM and ENSO while further inland the influence of ENSO and ENSO-IOD interactions increase. Others identified teleconnections in regional seasonal rainfall in eastern Australia and related them to large scale climatic drivers. The DJF teleconnection describing rainfall variation in coastal southern Queensland was not correlated with any of the large-scale drivers considered in Klingaman *et al.* (2013): ENSO, the Inter-decadal Pacific Oscillation index, IPO and SAM, but with coastal cyclones and onshore winds that explain around 8% of the rainfall variability in the region. The Queensland state-wide DJF teleconnection is related to ENSO but has smaller influence on the study areas in the Northern Murray Darling Basin and Coastal Queensland. Blocking likely plays a small role as Queensland receives most of its rainfall from tropical, not from extra-tropical systems (Klingaman, Woolnough and Syktus, 2013). Verdon *et al.* (2004) investigates the magnitude of the impacts of ENSO on eastern Australia by identifying the rainfall stations with a significant difference in rainfall during La Nina and El Nino years and find that ENSO impacts rainfall between the spring and summer months of September to January. The rainfall in La Nina years is statistically significant larger compared to El Nino years in northern New South Wales and Queensland, between 50-100%. The stations selected for Queensland fall within the Northern Murray Darling Basin and Coastal Queensland and New South Wales but some are also located further north and inland. The IPO also plays an important role with the negative phase being associated with an increase in magnitude of rainfall compared to the positive phase, irrespective of ENSO. The contrasting findings in Duc et al. 2017, Verdon et al. 2004 and Klingaman et al. 2013 are examples of how ENSO impacts on eastern Australian rainfall differ between years and sites. An example of different impacts of similarly strong El Nino events on east Australia spring rainfall were the events in 1982, 1997 and 2015 which in this case can be explained by differences in the strength of the meridional wind component of the regional circulation (van Rensch *et al.*, 2019).

The Madden-Julian Oscillation (MJO) impacts Australian and Queensland summer rainfall as well, but mostly at locations north of 20°S in the Northern Territory and Western Australia and the Cape York Peninsula in Queensland, with high rainfall probability in phases 5 and 6 and low rainfall probability in phases 1 and 2 (Wheeler *et al.*, 2009). Wheeler *et al.* 2009 also studied a region in Central-South Queensland more closely that is located in the northern Murray Darling Basin between 24°-28°S and 144°-148°E. They find a reduced probability of high weekly rainfall in summer during phases 5 and 6 and a maximum probability in phase 4. In contrast the daily rainfall anomaly showed a maximum in phase 8 which might happen as a results of outlier rainfall events that lead to noisier daily rainfall anomaly curves than weekly probabilities which most likely occurred by chance and is not indicating a robust MJO signal (Wheeler *et al.*, 2009)

5.3 Potential implications for agriculture in the study area

Consistent declines in rainfall and increases in temperature over a large part of an important agricultural area can have strong implications for food and feed production, productivity, and farm profitability as crops in Australia are almost entirely grown under rain-fed conditions. There are two main research methods to study the relationship between rainfall and agriculture: i) studying the relationship between past climate conditions and agricultural output and ii) using statistical or process-based crop models coupled with climate models to project impacts of changes in climate.

The first method can help gain an understanding of the magnitude of impact past adverse climate events have had on agriculture and the importance of climatic drivers for year-to-year variability compared to changes in technology or management. Previous studies have shown that two thirds of the variance in crop yields in Australia between 1961 and 2008, for example for wheat, can be attributed solely to climate variability which is the highest ratio globally (Vogel *et al.*, 2019). Climate conditions between 2018 and 2020 were also the dominant influence on financial performance of Australian broadacre farms which includes cereals, oilseeds, lupins, sugar cane, legumes, hops, cotton, hay and silage. Average farm business profit was down AUD 88,0000 in the agricultural season 2019-20 compared to 2017-18 due to drought (Martin and Topp, 2020) but with marked regional differences. Queensland and New South Wales had the strongest declines. This is overall twice as much as the longer-term average of AUD 43,000 per farm (Martin and Topp, 2020) and makes it the lowest average farm profit since the end of the millennium drought in 2009-10. The dry conditions also resulted in low farm business profits in dairy farms in all states except for South Australia.

The second method helps gain an understanding of how the system reacts to fluctuations in climate under different management scenarios without having to alter the actual system and to identify adaptation options. Several simulation studies have been conducted for Australian agriculture in the past and (Hochman and Lilley, 2020) give an overview of the development of simulation models in Australia and their application with long-term climate projections for estimating impacts on agriculture.

For Eastern Australia, Reyenga *et al.* (1999) estimates wheat yield changes with increases in atmospheric CO2 concentrations and under stylized temperature and rainfall scenarios at *Gayndah* in the North Burnett region in the Northern Murray Darling basin. Modelled yield increased by 26-37% with increases in atmospheric CO2 concentration to 700 ppm depending on the variety, increased by 9-23% in a scenario with a 2.76°C increase of maximum and minimum temperatures and by 21-33% in a scenario with the same temperature increases and 12% in winter rainfall. Wheat yields decreased by 3% in a scenario with temperature increases as described above and reduction in summer and winter rainfall by 24% and 12%, respectively. Increases in atmospheric CO2 concentrations are typically expected to increase crop yields because of reduced water losses at similar photosynthesis rates whereas higher temperatures can have positive or negative effects depending on the current mean temperatures, heat and frost tolerance of the plants and magnitude of change. In this study the potential risk of heat shock to wheat during grain filling with temperatures above 32°C was almost doubled. It can be expected that climate variability contributes to crop yield variability. The coefficient of variation in the wheat yields between 1922-2000 in the eastern slopes and the northern plains of the New South Wales wheat belt was 45-48% and increased in the late 20th century indicating a mean yield only double the standard deviation and an increasing adverse effect on wheat yields caused by climate variability that may continue during the 21st century. Wheat yield variability was largely associated with rainfall extremes, in particular the standardized precipitation index calculated for June-August which reflects dry and wet conditions during winter (Feng *et al.*, 2018). The study region in Feng *et al.* 2018 is located in the southern part of the Northern Murray Darling basin.

For Western Australia, Ludwig and Asseng (2006) by modelling climate change impacts on wheat using APSIM-Nwheat, find that a reduction in rainfall and increase in temperature can lead to different changes in wheat yields in the Wheat Belt, depending on the current climate of the site, the magnitude of the change and the soil type which is associated with water holding capacity and plant available water in the soil. In *Binnu*, in the northern Wheat Belt at ~28°S, a 30% lower winter rainfall reduced yields by 67% on clay soils but on sandy loam soils it was only reduced by 25% as the water holding capacity and plant available water of clay soils is very low. In *Kojonup*, in the southern Wheat Belt at ~34°S, yields increased at the sandy loam and duplex soils despite a reduction in rainfall of 15–30%. On clay soils, reduced rainfall had a negative effect on grain yield also at Kojonup, however, the effects of 15% reduction in rainfall were relatively small. A temperature increase of 2-3°C reduced yields in the two warmest and driest sites in the Wheat Belt studied irrespective of the soil and atmospheric CO2 concentration but only a temperature increase of 6°C reduced wheat yield at the coolest and wettest site in the southern Wheat Belt. Lower rainfall can increase average grain protein concentrations as with lower grain production the nutrient content per grain produced can increase. The gross margin ($/ha) variability increased for the future climate scenario for 2050, 2100 in this study. Also for wheat, van Ittersum *et al.* (2003) have estimated a 14-8% reduction in yield with a 20% increase in summer/autumn rainfall and a 35% decrease in winter/spring rainfall for three locations across the Wheat Belt. A temperature increase by 3°C lead to an increase in wheat yield modelled as grown in a clay soil as anthesis and maturity dates were advanced to a significantly wetter period of the year which outweighs the shortage of the growing season. The same effect occurred for a sandy soil but the increased moisture availability during grain filling was not as efficient because of low biomass at the start of the grain filling and lower photosynthetic capacity which resulted in slightly negative effect on sandy soils. Any higher changes in temperature had negative effects on wheat yield irrespective of the soil type. In a multi-model simulation study, 27 different crop models simulated wheat yield under climate change in *Wongan Hills* located in the northern wheat belt (Asseng *et al.*, 2013). The median wheat yield change with a 6°C temperature increase was -20% and +18% and +25% with an increase in atmospheric CO2 concentration to 540ppm and 720ppm. At a 3°C temperature increase the models did not agree on the direction of yield changes but at 6°C ~65% of the models simulated a decline in wheat yield. In a similar study with thirty-two crop models simulating wheat yield in Kojonup and Merredin, wheat yield declined by 10-15% at the low rainfall site Merredin and increased by more than 15% at the high-rainfall site Kojonup in 2036-2065 compared to 1981-2010 for a high-emissions climate change scenario RCP8.5 (Asseng *et al.*, 2019).

Changes in temperature and rainfall can have direct consequences such as when heat or frost stress during flowering leads to reduced yield e.g. in canola, Lilley *et al.* (2019) but also indirect consequences by delaying the flowering period and shortening the overall time for crop development and biomass production. At *Kojonup*, for example the flowering period was long, 52 days, and canola yield high at 4.1 t/ha with little risk of stress during flowering whereas in *Merredin* with lower rainfall, the flower period was reduced to 32 days and canola yield reduced to 2.5 t/ha. On the other hand, some negative impacts of changes in average climate or consistent declines in rainfall can be mitigated by sowing earlier or sowing different cultivars with faster development such as studied by Flohr *et al.* (2018). They find a trend toward sowing wheat earlier with different rates of change in all four locations studied in southern and western Australia wheat belts already between 2008 and 2015. In Western Australia the rate of change was 1.3 days/year and in Southern New South Wales the rate of change was 1.1 days/year.

Studying the entire Australian Wheat Belt, in the southwest of Western Australia and in the East extending into the northern Murray Darling basin, Watson *et al.* (2017) find that some of the 33 climate models used project an increase in the frequency of severe water stress conditions in the southwest and fewer severe water stresses in the other regions. Water stress is defined as the ratio of crop-available soil water to the amount of water that the crop could use for potential transpiration so accounts for leaf and root development of the crop, weather and soil conditions. Ssing a crop model coupled with projections from the climate models did not find consistent evidence for an increase in yield variation due to the imposed changes in CO2, temperature and rainfall. The number of years with sowing opportunities was projected to decrease slightly in the coming decades, by 1.8, 2.1, and 3.7% for 2030, 2050, and 2070, respectively, with greater impact in the West than in the rest of the Wheat Belt. The average sowing date was projected not to change substantially, but tended to be slightly delayed, around 1 day. When considering a 200 kg/ha threshold as crop failure, crop viability did not change much across the Wheat Belt but with a 500 kg/ha threshold crop viability was impacted more but not in a consistent way across different climate model projections

The results from these individual studies are difficult to summarize as they use different crop models and climate change scenarios. As a general trend a conclusion is that crop yield, most often studied are wheat and canola, decline quite substantially with temperature increases and rainfall decline but when the magnitude of change is small, the shift in timing of sensitive crop development stages can actually be beneficial for biomass accumulation. The rate of change further depends on the soil type and some will store water for plants more efficiently than others, and the assumed level of atmospheric CO_2 concentration which can benefit crop yields. Potentially positive implication for agriculture resulting from increases in atmospheric CO_2 concentration need to be discussed in the context of global and local warming levels and changes in rainfall patterns that are projected to occur alongside them. The emission scenario with 700ppm considered in Reyenga *et al.* (1999) for example is a very strong emission scenario, for comparison, the global average atmospheric CO_2 concentration in 2018 was 407.4 ppm ± 0.1ppm (Blunden and Arndt, 2019). This corresponds to emissions and warming levels as projected under RCP8.5 for 2070 (Meinshausen *et al.*, 2011) resulting in global warming of 3.9°C in 2080-2100 compared to 1980-2000 a local warming of 3.5-4°C in Eastern Australia. Manipulating a historic climate record for a side in such a manner has the risk of decoupling these effects and underestimating the impacts from warming and drying trends potentially.

6. Conclusion

6.1 Key findings

1. Statistically significant trends in summer rainfall between 1907 and 2018 were found:
    - for two out of the seventeen stations studied, Merredin, Western Australia and Wallangra, Queensland. Summer rainfall has increased by 0.67-0.79 mm/year in Wallangra and by 0.24-0.29mm per year in Merredin.
    - for the Western Australia Wheat Belt. Average rainfall in summer has increased by 0.18-0.21 mm per year.
2. Statistically significant trends in winter rainfall between 1907 and 2019 were found:
    - for all three WA stations and the Western Australia Wheat Belt overall. This agrees with previous studies that have used different rainfall indicators and studied different time periods. Winter rainfall declined between 0.33-0.81mm per year with the weakest trend in Merredin and the strongest in Mingenew.
    - for Pittsworth, Queensland (0.34-0.37mm per year) and Clarence Town, New South Wales (0.67-0.76mm per year).
3. The number of consecutive wet days in the Western Australia Wheat Belt and the Coastal midlatitudes region has decreased slightly. The annual rainfall from very wet days and the number of days with more than 10mm have increased in the Northern Murray Darling basin.
4. For the remaining combinations of station, regions and seasons we did not find any statistically significant trends for 1907-2018, so any observed changes in seasonal rainfall are most likely part of natural variability.
5. Spatial heterogeneity in rainfall is high leading to different trends in annual, seasonal and extreme rainfall for stations in the same region and different trends for stations and the region overall.
6. In Narrabri, New South Wales and Curlewis, New South Wales, seven out of ten summers between 2010/11 and 2019/20 have been dry with rainfall below the long-term average. This number of consecutive dry summers in Narrabri is unprecedented since 1926 as even during the World War II drought (1935-1945) with six consecutive years of below average summer rainfall the seventh year had above average summer rainfall.
7. Robust statements of climate change and trends in any climate variable require a reference period of at least 20 years. Although there have been unprecedented changes in seasonal rainfall, for example in Narrabri in the last eight summers, the average 20 years summer rainfall has not been below average compared with the entire summer rainfall record from 1907.
8. Summer rainfall in the Western Australia Wheat Belt is mainly influenced by the El Nino-Southern Oscillation, the Southern Annual Mode and atmospheric blocking. Although no change in annual and seasonal rainfall has been found for Eastern Australia, the year-to-year variability remains high and poses a challenge to agriculture. The main drivers of summer rainfall variability are the El Nino-Southern Oscillation, the Southern Annual Mode and the position of the subtropical ridge.

9. Summer rainfall is projected to change under the climate change scenario most closely aligned with current cumulative CO2 emissions:
    - in the Northern Murray Darling basin by -13 to +27% in 2020-39 and by -21 to +30% in 2080-2099. For 2080-99, 46% of all models simulate only little change (medium agreement) but 35% of models simulate a substantial increase and 19% of models simulate a substantial decrease.
    - in the Western Australia Wheat Belt by -23 to +19% in 2020-2039 and by -33 to +21% in 2080-2099 with 70% of all models agreeing on little change (high agreement). In contrast to summer rainfall all models simulate a continuing substantial decrease in winter rainfall by 2080-2099.
    - in the Coastal midlatitudes by -14 to +14% in 2020-2039 and by -15 to +24% in 2080-2099 with low agreement among models on the direction of change.

6.2 Benefits to industry

The results of this study are expected to provide insights into past, current and future rainfall and rainfall changes that have occurred and might occur in the future in selected locations and across larger production areas. As producers take climate information into consideration when making management decisions this can assist in climate related risk assessments for producers. The results of this study can assist in understanding if recently observed changes are part of a longer-term trend that can be expected to continue and would require transformational, system-wide adaptation. As our results are as localized as possible with the weather station data available, they can assist in increasing climate knowledge and help make effective decisions toward a more resilient agricultural sector.

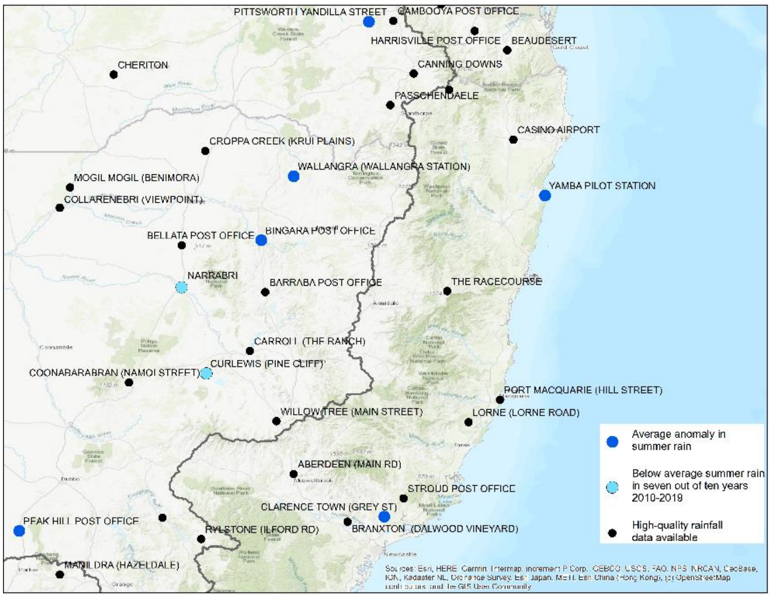
Our results from the trend and correlation analysis do not suggest a shift in the rainfall distribution or long-term trend in seasonal rainfall in the Northern Murray Darling basin and the Coastal midlatitudes of New South Wales and Queensland that would justify the need for transformational changes. The changes in rainfall distribution towards more intense rainfall (R95p in N-MDB) and shorter consecutive wet periods (CWD, East coast) are too small and it is unclear how this trend will continue in the future. However, rainfall variability in these areas is high and strongly associated with variability in crop yields even in the absence of long-term trends which will continue to challenge farmers.

On the other hand, the consistent decline in winter rainfall observed and projected to continue into the future in the Western Australia Wheat Belt might require more transformational changes to industries in the region where possible, such as changes in farm management practices, increased focus on flexibility of production, diversification of crops, varieties and rotations, adjustments to livestock breeds and size of the herd.

7. Future research and recommendations

Spatial correlation of rainfall is low which makes the identification of consistent, regional trends challenging. For example, while for the region overall we find a positive trend in the annual precipitation from heavy precipitation days in the Northern Murray Darling basin overall but only in two of the eight weather stations used. Site-specific trends will differ from regional trends and are often smaller than year-to-year variability. One way to identify large-scale trends in rainfall in future R&D can be to work with the Bureau of Meteorology's rainfall district systems[1] which groups sites with relatively similar rainfall climates. Narrabri, Bingara and Wallangra in northern New South Wales are for example located in the rainfall district 'Northwest Slopes'. These units are smaller than agricultural production zones and need to be related to the main agricultural commodities produced in them.

It remains a challenge to establish regional and longer-term trends in rainfall from observed trends at specific locations which is however required to try and explain the causes of such changes. One way forward from the current findings could be to define an area of observed strong anomalies in summer rainfall between 2010-2019 around the towns of Narrabri and Curlewis in New South Wales and to extend the area outwards to include nearby stations with high-quality long-term rainfall records, e.g. Barraba, Bellata, Collarenebri, Carroll Ranch, Coonanarabran. The current findings suggest that the area does not extend into a northeast direction and does not extend as far south as Peak Hill as we do not find strong anomalies in summer rain for Peak Hill, Bingara or Wallangra.



Climate change and agricultural impact studies can use the material presented here to inform (i) the choice of climate models as the model needs to be able to simulate the relevant large-scale climate drivers associated with rainfall in the three study areas and need to be representative of best case, worst case and maximum consensus climate futures and (ii) the choice of rainfall indicators as the ones presenting a positive or negative trend continuing into the future might be specifically relevant to agricultural impact studies.

A more methodological consideration for future R&D is to define an extended set of rainfall variables beyond growing season rainfall in summer or winter. The list should be as short and general as possible but relevant and validated by primary producers to use for a range of industries, dry and irrigated cropping, horticulture, sugar industry, cotton industry, dairy and meat industries. Rainfall variables can be defined with specific events in mind, such as the time of planting or sensitive growth stages for dryland cropping or with the aim to identify adverse climate and weather events,

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[1] http://www.bom.gov.au/climate/cdo/about/rain-districts.shtml

such as drought. The rainfall variables used for statistical analysis should align as closely as possible with statements on rainfall changes from primary producers and the larger community.

Any generated climate and other data that can potentially benefit decision making for farmers in the locations and regions studied should be made publicly available if possible and disseminated as widely as possible to assist farmers.

8. References

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9. Appendix

9.1 Outputs related to this project

9.1.1 Research article

Waha K, Dayal K, Vogel E, Alexander L, Clarke J, Heady C (in prep): Past and future rainfall changes in the Australian midlatitudes and implications for agriculture.

9.1.2 Conferences and seminars

Waha K, Parisi I, Freund M, Alexander L, Vogel E, Müller C, Coumou D (2020): Past rainfall changes in Australia and implications for agriculture. A Forewarned is Forearmed Community of Practice seminar. 28 July 2020. (this presentation was done instead of the conference presentation for Climate and Carbon in Agriculture 2020 conference which was cancelled due to COVID-19).

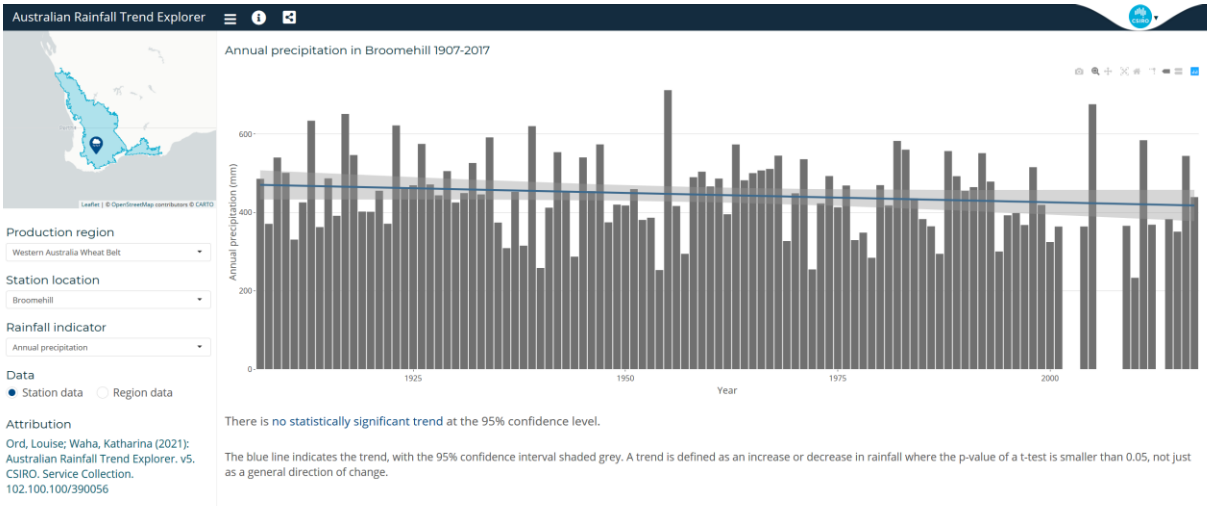
Waha K, Alexander L, Coumou D, Mueller C, Vogel E (2019): Extreme events and agriculture. A statistical analysis of historic changes in extreme events and crop yields in Australia. Australian Meteorological and Oceanographic Society Annual Meeting and the International Conference on Tropical Meteorology and Oceanography (AMOS-ICTMO 2019), 11-15 June 2019. Darwin, Australia

Parisi I (2019) Are Australian agricultural sites getting drier? Food Systems and Global Change Seminar, 3 December 2019. Brisbane, Australia.

9.1.3 Research data collection and data visualization tool

Waha K, Ord L, Alexander L, Parisi I (2021): Australian Midlatitudes Rainfall. v14. CSIRO. Data Collection. https://doi.org/10.25919/qdk0-ys13

Ord L, Waha K (2021): Australian Rainfall Trend Explorer. v5. CSIRO. Service Collection. 102.100.100/390056: https://shiny.csiro.au/rainfall-trend-explorer/



Production region: Western Australia Wheat Belt

Station location: Broomehill

Rainfall indicator: Annual precipitation

Data

● Station data ○ Region data

Attribution

Ord, Louise; Waha, Katharina (2021): Australian Rainfall Trend Explorer. v5. CSIRO. Service Collection. 102.100.100/390056

There is no statistically significant trend at the 95% confidence level.

The blue line indicates the trend, with the 95% confidence interval shaded grey. A trend is defined as an increase or decrease in rainfall where the p-value of a t-test is smaller than 0.05, not just as a general direction of change.

9.2 Projected rainfall changes as simulated in CMIP5

Figure A 1 Projected changes in seasonal regional rainfall for the Northern Murray Darling basin as simulated in CMIP5 relative to the 1986-2005 mean for RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (purple). Greys bars represent the expected range of change due to natural internal climate variability.

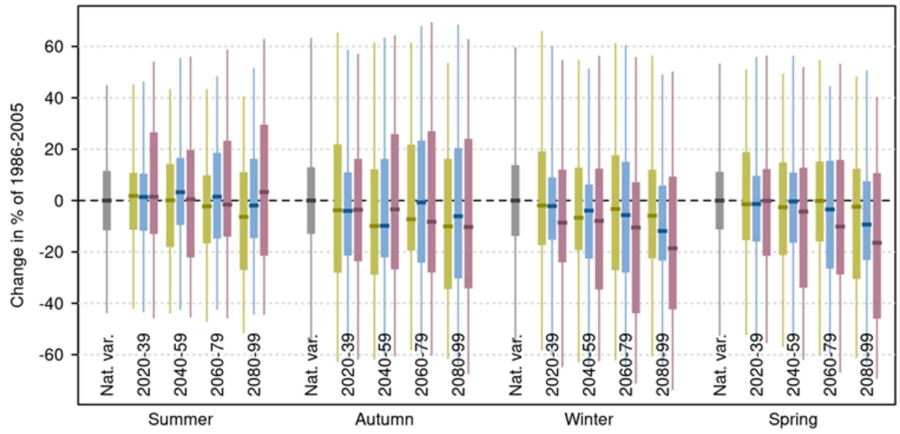


Figure A 1 As Fig. A 1 but for the Coastal midlatitudes New South Wales and Queensland region.

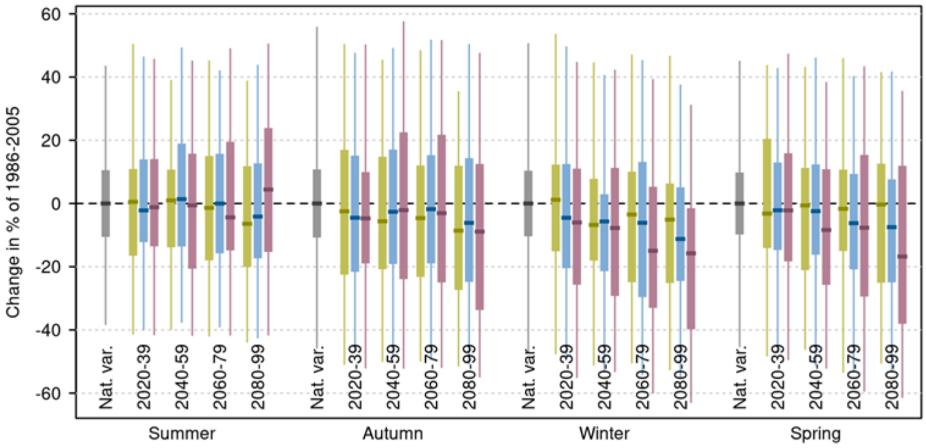


Figure A 2 As Fig. A 1 but for the Western Australia Wheat Belt.

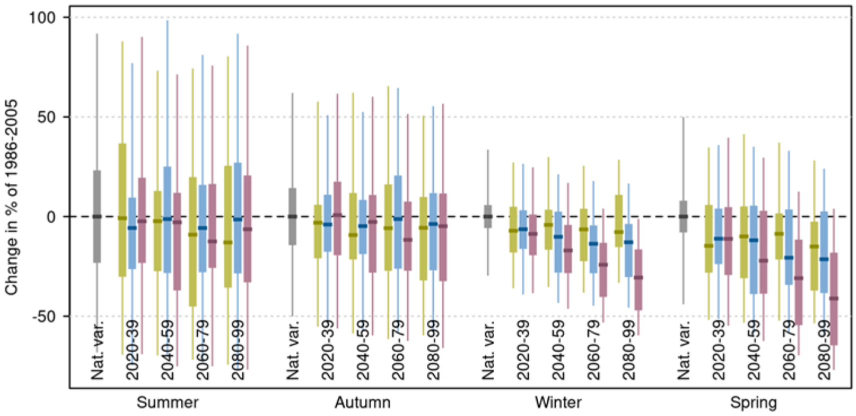


Table A 1 Projected changes in annual and seasonal rainfall in the Northern Murray Darling basin.

Time period	Emissions scenario	Annual	Summer (DJF)	Winter (JJA)
2020-2039	RCP2.6	-10 to +8.5	-11 to +11	-17 to +19
	RCP4.5	-12 to +5.5	-12 to +10	-15 to +9
	RCP8.5	-11 to +6.4	-13 to +27	-24 to +12
2040-2059	RCP2.6	-19 to +8.7	-18 to +14	-19 to +13
	RCP4.5	-14 to +11	-9.5 to +17	-23 to +6.3
	RCP8.5	-16 to +10	-22 to +20	-35 to +12
2060-2079	RCP2.6	-16 to +11	-17 to +9.8	-27 to +18
	RCP4.5	-15 to +8.1	-15 to +19	-28 to +15
	RCP8.5	-20 to +14	-14 to +23	-44 to +7.2
2080-2099	RCP2.6	-24 to +6.1	-27 to +11	-23 to +12
	RCP4.5	-19 to +6.1	-15 to +16	-23 to +5.8
	RCP8.5	-27 to +16	-21 to +30	-42 to +9.4

Table A 1 As Table A 1 but for the Coastal midlatitudes New South Wales and Queensland region.

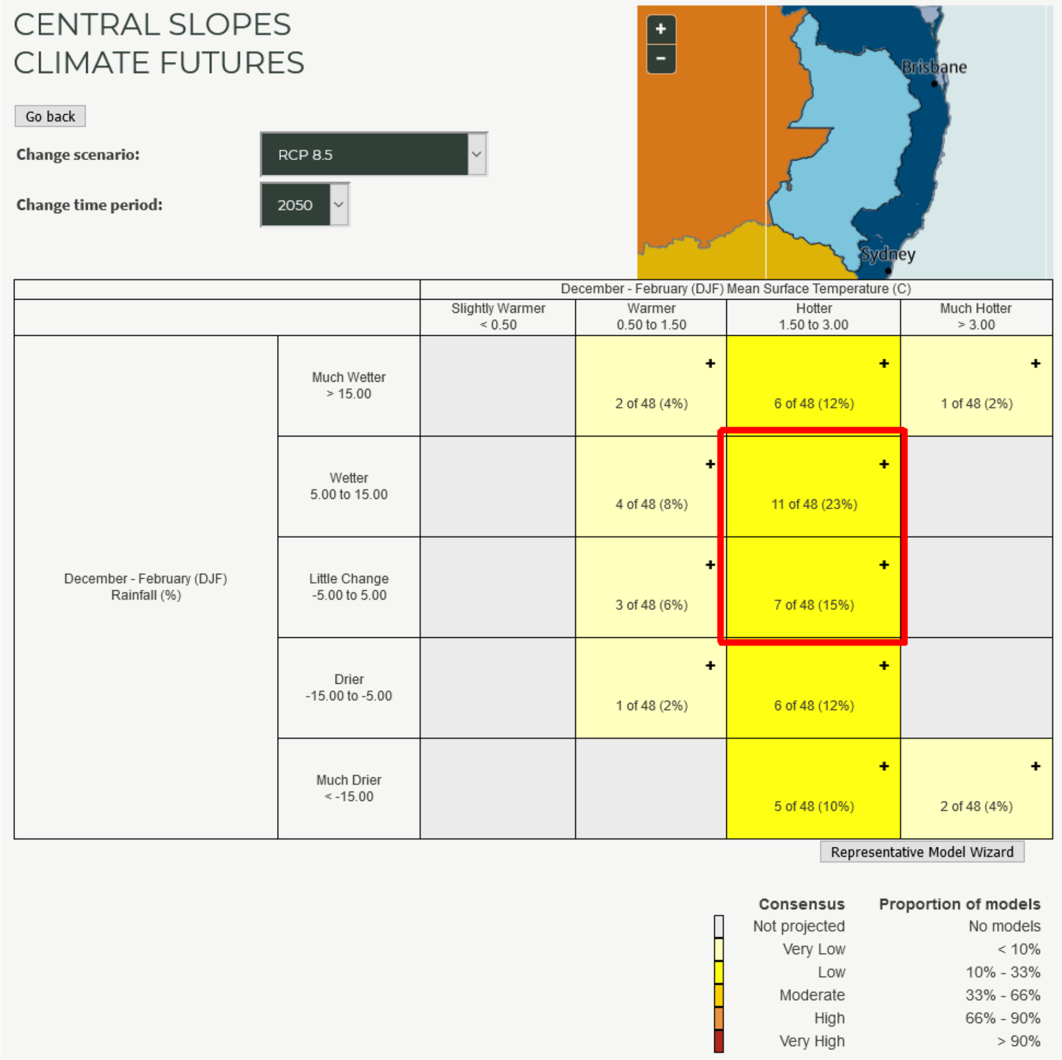
Year	Emissions scenario	Annual	Summer (DJF)	Winter (JJA)
2020-2039	RCP2.6	-8.3 to +5.9	-17 to +11	-15 to +12
	RCP4.5	-11 to +6	-12 to +14	-20 to +12
	RCP8.5	-13 to +6.6	-14 to +14	-26 to +11
2040-2059	RCP2.6	-15 to +7.5	-14 to +11	-18 to +7.8
	RCP4.5	-11 to +6.1	-14 to +19	-21 to +2.9
	RCP8.5	-17 to +5.9	-21 to +16	-29 to +11
2060-2079	RCP2.6	-14 to +9	-18 to +15	-25 to +10
	RCP4.5	-16 to +6.5	-16 to +16	-30 to +13
	RCP8.5	-19 to +9.9	-15 to +20	-33 to +5.3
2080-2099	RCP2.6	-19 to +7.9	-20 to +12	-25 to +6.3
	RCP4.5	-18 to +5.2	-17 to +13	-25 to +5.1
	RCP8.5	-24 to +11	-15 to +24	-40 to -1.5

Table A 2 As Table A 1 but for the Western Australia Wheat Belt.

Year	Emissions scenario	Annual	Summer (DJF)	Winter (JJA)
2020-2039	RCP2.6	-18 to +3.3	-30 to +37	-18 to +4.9
	RCP4.5	-14 to -1.4	-26 to +9.5	-16 to +3.2
	RCP8.5	-15 to +1.3	-23 to +19	-19 to +1
2040-2059	RCP2.6	-18 to +2.2	-27 to +13	-17 to +3.4
	RCP4.5	-19 to +0.75	-28 to +25	-28 to +2.5
	RCP8.5	-25 to +1.3	-37 to +12	-28 to -4.2
2060-2079	RCP2.6	-24 to +6.6	-45 to +20	-22 to +3.9
	RCP4.5	-19 to +1.9	-28 to +16	-28 to -4.4
	RCP8.5	-34 to -8.1	-26 to +16	-40 to -13
2080-2099	RCP2.6	-24 to +2.4	-36 to +25	-15 to +11
	RCP4.5	-24 to +2.3	-29 to +27	-30 to -3.7
	RCP8.5	-39 to -8.1	-33 to +21	-47 to -16

9.3 Climate Futures

Figure A4. Rainfall projections can be classified alongside temperature projections into a smaller number of so-called Representative Climate Futures to describe possible climate changes in a colour-coded matrix (Whetton *et al.*, 2012). The classification provides a visual display of the spread, clustering, and agreement of climate projections.



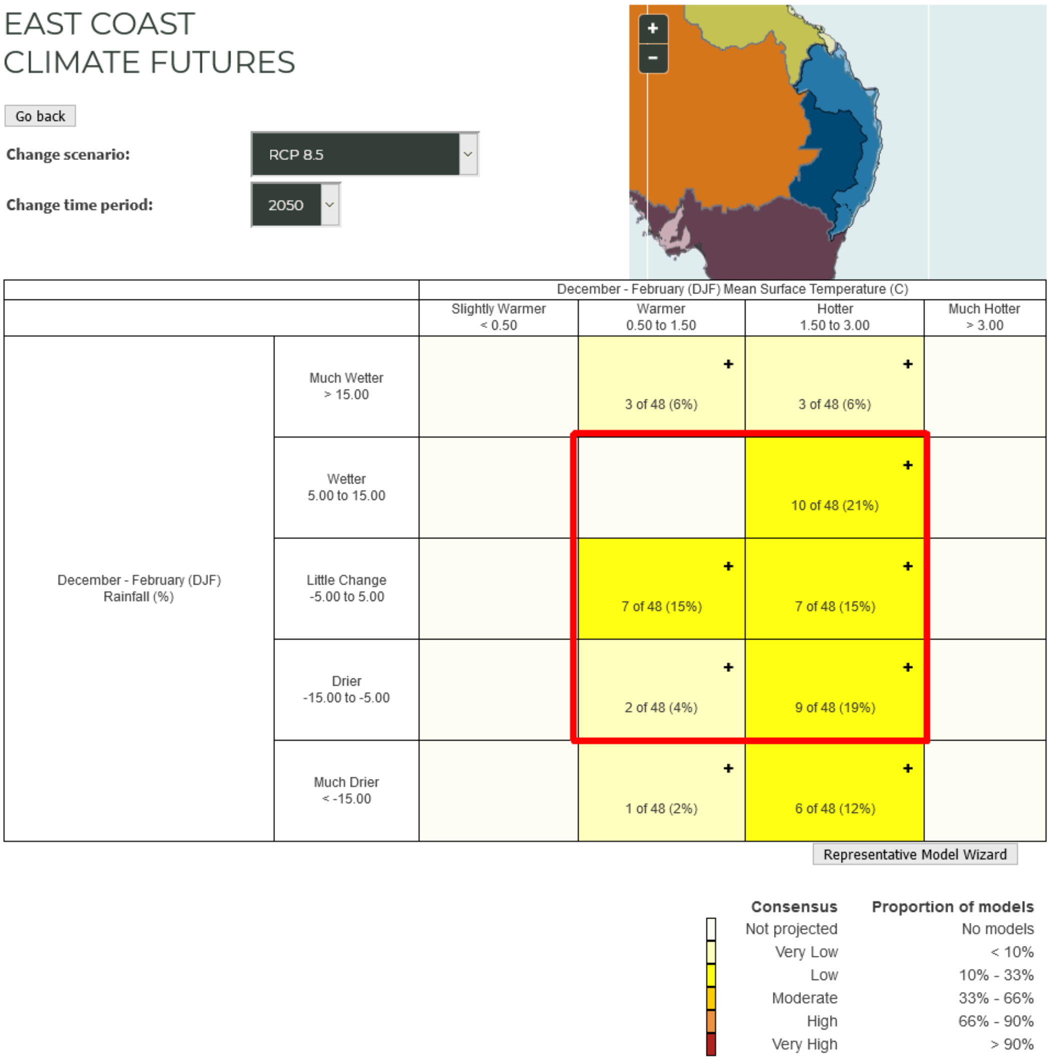
CENTRAL SLOPES
CLIMATE FUTURES

Change scenario: RCP 8.5

Change time period: 2050

		December - February (DJF) Mean Surface Temperature (C)			
		Slightly Warmer < 0.50	Warmer 0.50 to 1.50	Hotter 1.50 to 3.00	Much Hotter > 3.00
December - February (DJF) Rainfall (%)	Much Wetter > 15.00		+ 2 of 48 (4%)	+ 6 of 48 (12%)	+ 1 of 48 (2%)
	Wetter 5.00 to 15.00		+ 4 of 48 (8%)	+ 11 of 48 (23%)	
	Little Change -5.00 to 5.00		+ 3 of 48 (6%)	+ 7 of 48 (15%)	
	Drier -15.00 to -5.00		+ 1 of 48 (2%)	+ 6 of 48 (12%)	
	Much Drier < -15.00			+ 5 of 48 (10%)	+ 2 of 48 (4%)

	Consensus	Proportion of models
⬜	Not projected	No models
🟨	Very Low	< 10%
🟨	Low	10% - 33%
🟧	Moderate	33% - 66%
🟧	High	66% - 90%
🟥	Very High	> 90%



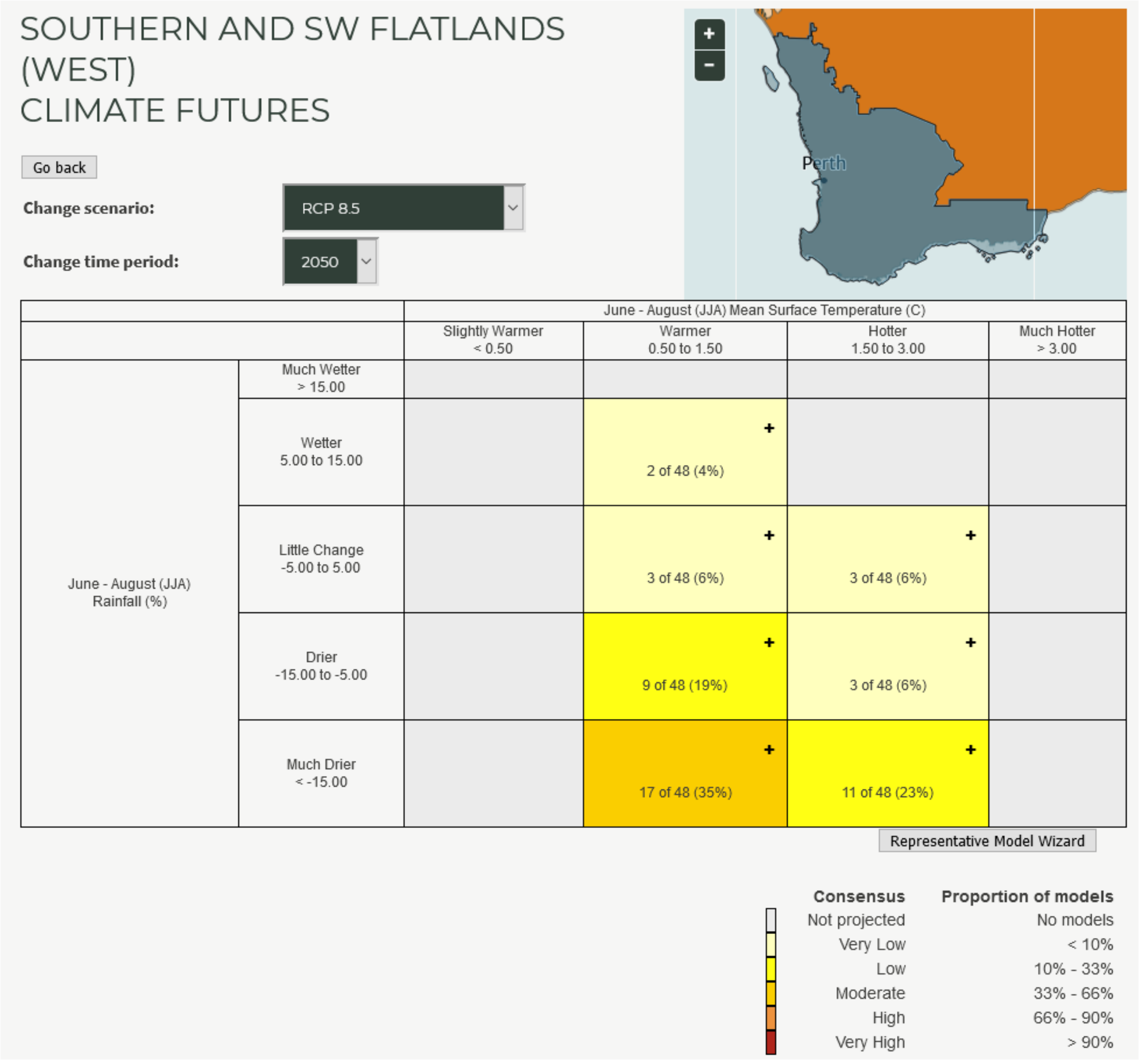
EAST COAST CLIMATE FUTURES

Change scenario: RCP 8.5

Change time period: 2050

		December - February (DJF) Mean Surface Temperature (C)			
		Slightly Warmer < 0.50	Warmer 0.50 to 1.50	Hotter 1.50 to 3.00	Much Hotter > 3.00
December - February (DJF) Rainfall (%)	Much Wetter > 15.00		+ 3 of 48 (6%)	+ 3 of 48 (6%)	
	Wetter 5.00 to 15.00			+ 10 of 48 (21%)	
	Little Change -5.00 to 5.00		+ 7 of 48 (15%)	+ 7 of 48 (15%)	
	Drier -15.00 to -5.00		+ 2 of 48 (4%)	+ 9 of 48 (19%)	
	Much Drier < -15.00		+ 1 of 48 (2%)	+ 6 of 48 (12%)	

	Consensus	Proportion of models
□	Not projected	No models
🟨	Very Low	< 10%
🟨	Low	10% - 33%
🟧	Moderate	33% - 66%
🟧	High	66% - 90%
🟥	Very High	> 90%



SOUTHERN AND SW FLATLANDS (WEST) CLIMATE FUTURES

Change scenario: RCP 8.5

Change time period: 2050

		June - August (JJA) Mean Surface Temperature (C)			
		Slightly Warmer < 0.50	Warmer 0.50 to 1.50	Hotter 1.50 to 3.00	Much Hotter > 3.00
June - August (JJA) Rainfall (%)	Much Wetter > 15.00				
	Wetter 5.00 to 15.00		+ 2 of 48 (4%)		
	Little Change -5.00 to 5.00		+ 3 of 48 (6%)	+ 3 of 48 (6%)	
	Drier -15.00 to -5.00		+ 9 of 48 (19%)	+ 3 of 48 (6%)	
	Much Drier < -15.00		+ 17 of 48 (35%)	+ 11 of 48 (23%)	

Consensus	Proportion of models
Not projected	No models
Very Low	< 10%
Low	10% - 33%
Moderate	33% - 66%
High	66% - 90%
Very High	> 90%