Past and future rainfall changes in the Australian midlatitudes and implications for agriculture

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Abstract

Annual rainfall and the seasonality of rainfall during a year are important drivers of agricultural productivity and profitability in Australian agriculture. Historic trend detection can give insights into significant and prolonged changes that might continue in the future and are of relevance to agriculture. Here we complement the analysis of historic data with climate projections from global climate models. We use gridded and station rainfall data for three study areas in the Australian midlatitudes, between 24°S and 35°S. Total summer and winter rainfall, annual total rainfall and annual rainfall extreme indices are calculated for the period 1907 to 2018. Historic trends are analysed with statistical significance tests of linear trends and rainfall deciles. Future trends are analysed for annual, summer and winter rainfall for three time periods, 2020–2039, 2040–2059 and 2060–79, as the ensemble of 25–37 global climate models. Summer rainfall in the Western Australia wheat belt increased by 0.18–0.21 mm per year. Winter rainfall decreased by 0.42–0.43 mm per year. Parts of northern New South Wales (NSW) experienced an exceptionally dry decade, 2011–2020 with summer rainfall 50–200 mm below the long-term average. Future rainfall projections for the wheat belt show a strong declining trend, irrespective of the climate scenario, while in the other two regions, increases and decreases are possible. We confirm previous findings of declines in winter rainfall in the Western Australia wheat Belt but do not detect any such changes in Eastern Australia. Some of the observed long periods of dry summers in northern NSW are rather unprecedented. Future studies should repeat the trend analysis for Eastern Australia as the data becomes available. Apart from climate indices, agrometeorological indices for specific agricultural commodities should be developed and used in trend analysis.

Keywords Seasonal rainfall change · Historic rainfall trend · Future rainfall trends · Drought

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1 Introduction

Australia's climate is highly variable in association with a range of climate drivers. Australia's climate 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 have 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 et al. 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 in recent decades in north-western Australia (Freund et al. 2017; Contractor et al. 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 recent years as largely being absent which increases the risk for agriculture. For example, in Narrabri, NSW, seven out of ten summers between 2012 and 2021 have been dry with rainfall below the long-term average of 216 mm, except for the most recent summers 2019/2020 and 2020/2021. This number of consecutive dry summers has not been observed 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. 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 2019–2020 have been estimated to be worth $24.8 billion, 41% of the national total gross value of production (Australian Bureau of Statistics 2021). 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 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).

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 et al. 1997) with coefficients of variation of 50–80%. The coefficient of variation in summer rainfall between 1926 and 2019, for example in Narrabri, NSW , was 50% 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; Cai et al. 2018). Our study will complement previously undertaken research, and test assumptions used for seasonal and annual rainfall in three study areas that are located between 24°S and 35°S and fall broadly into the midlatitudes. This will support insights into risks 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 specific agricultural commodities but rather on general rainfall changes that are important for agricultural production in the study area.

2 Methods

2.1 Study area

The study areas are in the Australian midlatitudes between 24°S and 35°S and between the tropical and temperate climate zones with associated complexities in the climate system. The study areas 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. 1). The are defined as the Western Australia Wheat Belt ranging from 28°S to 35°S and 114°E to 124°E (map A in Fig. 1), the Northern Murray Darling Basin ranging from 25°S to 34°S and 142°E to 153°E (map B in Fig. 1) and the Coastal Midlatitude New South Wales and Queensland region ranging from 24°S to 34°S and 150°E to 154°E (map C in Fig. 1).

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$ 5.1 billion in 2019–2020 (~ 8% of national total) (Australian Bureau of Statistics 2021). Crop production alone contributes AUD$ 3.5 billion. The WA-wheat belt 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 winter crops is April–June.

In the eastern 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 fourteen 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 cane and cattle. The East Coast is dominated by summer rainfall, receiving 11–84% of its annual rainfall during the austral summer season December–February. One-third of all years in the last 120 years 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 et al. 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

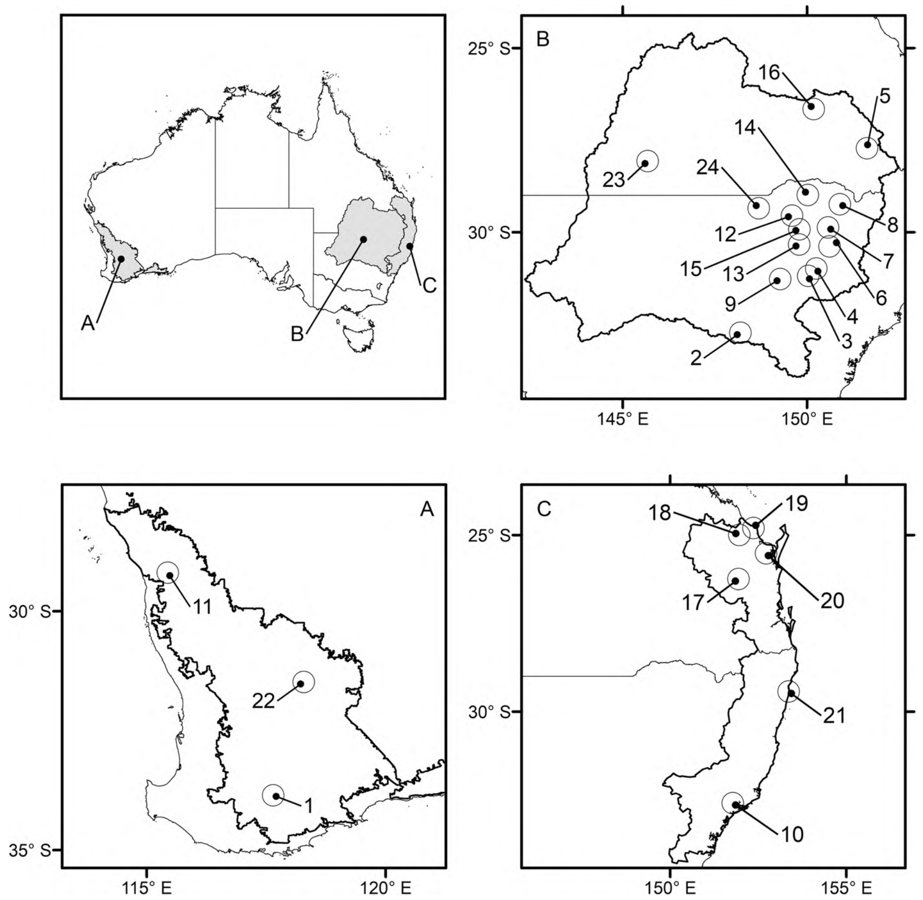

Fig. 1 Study areas and weather stations selected in each study area: the Western Australia Wheat Belt (**A**), the Northern Murray Darling Basin (**B**) and the Coastal areas in southern Queensland and northern New South Wales (**C**). The numbers 1–24 correspond to the ID column in Table 1

subtropical and temperate climate groups correspond to the temperate climate group (C climates) in the original Köppen classification.

2.2 Historical 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) or the Australian climate change site network for high-quality monthly rainfall (HQMR) (Lavery et al. 1997). Both data sets were developed to study climate variability and change as the data spans over more than 100 years, from 1907 to 2018. ACORN-SAT was developed to monitor changes in temperature only, but we assume here that the stations included also report reliable rainfall data. We select twenty-four stations across the three study areas that represent the different climate zones in each area (Table 1). For the N-MDB and East Coast, we

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)

Fig. 1 ID	Station name (state) — BoM 5-digit station ID	Geographic coordinates	Average annual rainfall (1961–1990)
Temperate climate			
1	Broomehill (WA) — 10525	Lat: 33.84° S, Lon: 117.64° E	440 mm/year
2	Peak Hill (NSW) — 50031	Lat: 32.72° S, Lon: 148.19° E	612 mm/year
3	Curlewis (NSW) — 55045	Lat: 31.18° S, Lon: 150.03° E	653 mm/year
4	Gunnedah (NSW) — 55023	Lat: 30.98° S, Lon: 150.25° E	664 mm/year
5	Pittsworth (QLD) — 41082	Lat: 27.72° S, Lon: 151.64° E	731 mm/year
6	Barraba (NSW) — 54003	Lat: 30.38° S, Lon: 150.61° E	732 mm/year
7	Bingara (NSW) —54004	Lat: 29.87° S, Lon: 150.57° E	743 mm/year
8	Wallangra (NSW) — 54036	Lat: 29.24° S, Lon: 150.89° E	771 mm/year
9	Coonabarabran (NSW) — 64008	Lat: 31.28° S, Lon: 149.28° E	812 mm/year
10	Clarence Town (NSW) — 61010	Lat: 32.59° S, Lon: 151.77° E	1077 mm/year
Subtropical climate			
11	Mingenew (WA) — 08088	Lat: 29.19° S, Lon: 115.44° E	393 mm/year
12	Collarenebri (NSW) — 48031	Lat: 29.54° S, Lon: 148.58° E	524 mm/year
13	Narrabri (NSW) — 53026	Lat: 30.26° S, Lon: 149.68° E	602 mm/year
14	Croppa Creek (NSW) — 53018	Lat: 28.99° S, Lon: 150.02° E	602 mm/year
15	Bellata (NSW) — 53003	Lat: 29.92° S, Lon: 149.79° E	630 mm/year
16	Miles (QLD) — 42023	Lat: 26.66° S, Lon: 150.18° E	638 mm/year
17	Murgon (QLD) — 40152	Lat: 26.24° S, Lon: 151.94° E	766 mm/year
18	Gin Gin (QLD) — 39,040	Lat: 24.99° S, Lon: 151.96° E	1033 mm/year
19	Fairymead Sugar Mill (QLD) — 39037	Lat: 24.79° S, Lon: 152.36° E	1094 mm/year
20	Maryborough (QLD) — 40126	Lat: 25.51° S, Lon: 152.72° E	1135 mm/year
21	Yamba (NSW) — 58012	Lat: 29.43° S, Lon: 153.36° E	1468 mm/year
Grassland climate			
22	Merredin (WA) — 10092	Lat: 31.48° S, Lon: 118.28° E	327 mm/year
23	Cunnamulla (QLD) — 44026	Lat: 28.07° S, Lon: 145.68° E	370 mm/year
24	Mogil Mogil (NSW) — 52019	Lat: 29.35° S, Lon: 148.69° E	534 mm/year

use data from multiple stations in the same climate zone to represent locations close to the coast and further inland as they might present different rainfall trends. For the N-MDB, we also select stations in a 200-km radius from Narrabri, NSW, to establish if other locations nearby experienced the same large number of consecutive dry summers in the last decade. Narrabri and Gunnedah in NSW and Maryborough in QLD are the only three stations not included in the ACORN-SAT or HQMR datasets but were selected as being near HQMR station with an uncomplete data record for the last 20 years of rainfall.

For regional analysis, we use the Australian Gridded Climate Data (AGCD v1)/AWAP dataset 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 to 7,000 stations across Australia were 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 is used (Jones et al. 2009).

For every year in the station and the regional data, 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 anomalies are calculated as the deviation from the annual average rainfall of the reference period 1961–1990 and from the decadal average rainfall of the reference period 1907–2018, respectively. For regional data, we calculate annual and seasonal rainfall per grid cell first and then the spatial average over the study region.

In addition to annual and seasonal rainfall, we describe trends in rainfall extremes for each station and study area as changes in rainfall intensity and rain day frequency for example cannot be detected in seasonal aggregates. We use data for five rainfall extreme indices: the annual count of days when precipitation is larger or equal to 10 mm (R10mm), the amount of rain falling on very wet days defined as days with daily precipitation exceeding the 95th percentile (R95p), precipitation from the five wettest days of the year (Rx5day), the maximum number of consecutive days with rainfall of 1 mm or more (CWD) and the maximum number of consecutive days with rainfall less than 1 mm (CDD). The 95th percentile is calculated for the reference 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 et al. 1999). For stations, we use station data from the HadEX2 dataset for 1901–2010 (Donat et al. 2013), updated to 2013 and if not available also from the Global Historical Climatology Network Daily (GHCNDEX) dataset (Donat et al. 2013). For regional analysis, the five rainfall extreme indices for each grid cell in the study regions from AGCD v1/AWAP are calculated after aggregating from the original 0.05-degree resolution to 0.5-degree resolution. This dataset will hereafter be referred to as AWAP-EX.

2.3 Projections of future rainfall

We use projections from global and regional climate models to describe the range of plausible future climates. The global climate model (GCM) data come from the modelling experiments (CMIP5) that informed the IPCC's Fifth Assessment Report. We used rainfall projections for three representative concentration pathways (RCPs) from 25 to 37 climate models, depending on the RCP (see Supplementary Information, Table ESM1).

Ferguson et al. (2018) describe the historical and RCP8.5 experiments in CMIP5 and evaluate changes in precipitation as simulated by the individual models and the model ensemble. 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 techniques. Downscaled data for RCP4.5 and 8.5 are at 50-km resolution, from CSIRO's Conformal-Cubic Atmospheric Model (CCAM; McGregor and Dix, 2008), downscaled from a selection of five CMIP5 GCMs, MIP-ESM-LR, CNRM-CM5, GFDL-CM3, NorESM1-M, ACCESS1-0. Where relevant, additional insights have been drawn from CMIP6, as reported in the IPCC's Sixth Assessment Report (Douville et al. 2021). Australia-specific analyses of the full suite of CMIP6 projection data were not available at the time of data analysis.

We use the CMIP5 data to assess the direction of changes in projected annual and seasonal rainfall for the three study areas. In addition, we classify seasonal rainfall projections alongside temperature projections into a smaller number of so-called Representative Climate Futures. The classification provides a visual display of the spread, clustering and agreement of climate projections to describe possible climate futures (Whetton et al. 2012). We use projections from 48 climate models for RCP8.5 (see Supplementary Information, Table ESM2). Each climate future is described in terms of seasonal temperature changes as slightly warmer (< 0.5 °C), warmer (0.5–1.5 °C), hotter (1.5–3 °C) or much hotter (> 3 °C) and seasonal rainfall changes as much wetter (> 15%), wetter (5–15%), little change (− 5–5%), drier (− 15 to − 5%) or much drier (< − 15%). The percentage of models agreeing on each climate future can then be interpreted as an indication of relative likelihood. Consensus is defined as being moderate or high if between one-third and two-thirds or more than two-thirds of all models, respectively, agree on a climate future.

2.4 Change detection and trend analysis

We analyse long term trends for 1907 to 2018. To assess the existence and the significance of the rainfall trend over the years, three statistical test methods were 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 2015). 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 trend is accepted as significant if *p*-values from the *t*-test or the 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' (Sen 1968; Pohlert 2020). The linear trend is later discussed in the context of long-term variability to further asses its significance for agriculture.

An alternative method for identifying consistent shifts in rainfall is to calculate so-called rainfall decile ranks to understand if current rainfall is below average, average or above average compared to the entire rainfall record from 1900. This method is used in the biennial State of the Climate report series by the Australian Government Bureau of Meteorology and CSIRO. The first decile represents the lowest 10% of rainfall totals and decile 10 represents the highest 10% of rainfall totals with deciles 4 to 7 representing average rainfall. We calculate rainfall decile ranks for station and regional rainfall data for the three study areas. If annual or seasonal rainfall over the last 20-year period falls into the first or last deciles, we conclude that it is below average or above average, respectively.

3 Results

3.1 Trend detection in historical rainfall

We find statistically significant trends in annual, seasonal and extreme rainfall between 1907 and 2018 in all three study areas, but they differ between locations. The Western Australia wheat belt is the only example of changes in regional average seasonal rainfall. Winter rainfall across the region shows a statistically significant negative trend of 0.42–0.43 mm/year or 4.2–4.3 mm/decade between 1907 and 2018 (Table 2). This trend is stronger than the year-to-year variability in the same time period, with a coefficient of variation of 0.23 mm. Winter rainfall since 1990 was 15% lower than the average between 1907 and 1989. Summer rainfall has increased by 0.18–0.21 mm/year or 1.8–2.1 mm/decade and since 1990 was 28% larger than the average between 1907 and 1989. Summer rainfall in the wheat belt is more variable than winter rainfall and the trend is smaller than the year-to-year variability, with a coefficient of variation of 0.71 mm. In agreement with the regional trend, winter rainfall declined at all the stations in the WA-wheat belt, Merredin, Broomehill and Mingenew (Table 2). Merredin, with grassland climate, is the only station in the WA-wheat belt with a positive trend in summer rainfall with an increase by 0.24–0.29 mm/year (+ 46% since 1990). The number of consecutive wet days has declined slightly in the WA-wheat belt overall and in Mingenew. There is no significant change in average rainfall intensity.

In the other two regions, there are significant trends in annual and seasonal rainfall only for individual stations (Fig. 2). Summer rainfall has increased by 0.67–0.79 mm/year in Wallangra, NSW (+ 19% since 1990) and winter rainfall has decreased by 0.34–0.37 mm/year in Pittsworth, QLD (− 31% since 1990) and by 0.63–0.76 mm/year in Clarence Town, NSW (− 17% since 1990) (Table 2). The trend analysis for extreme rainfall indicators suggests changes in the characteristics of heavy or intense rainfall, an increase in rainfall intensity in Cunnamulla, QLD, and Curlewis and Yamba in NSW and a decrease in Clarence Town, NSW, and Fairymead, Gin Gin and Maryborough in QLD (Table 3). Precipitation from very wet days (R95p) and the number of days with more than 10 mm of precipitation (R10mm) has increased in Curlewis between 1907 and 2009 by 0.76–0.83 mm/year and 0.06–0.07 days/year, respectively. This means that there are about eight more days with more than 10 mm of precipitation in 2009 than in 1907 and precipitation on very wet days has increased by 85 mm on average over the whole time period. The number of consecutive

Table 2 Selected results of trend analysis for annual and seasonal rainfall 1907 to 2018. 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). Numbers in brackets give the range of the estimated slope of the linear trend line and Sen's slope. The table shows results for selected regions and weather stations. Results for other weather stations and rainfall indicators can be found at https://shiny.csiro.au/rainfall-trend-explorer/

Indicator	Trend in annual rainfall (mm/year)	Trend in summer rainfall (mm/year)	Trend in winter rainfall (mm/year)
Region			
WA-wheat belt	No	Yes (0.18–0.21)	Yes (− 0.42 to − 0.43)
East Coast	No	No	No
N-MDB	No	No	No
Weather station			
Merredin	No	Yes (0.24–0.29)	Yes (− 0.33 to − 0.34)
Broomehill	Yes (− 0.67 to − 0.75)	No	Yes (− 0.51 to − 0.59)
Mingenew	Yes (− 0.91 to − 0.98)	No	Yes (− 0.79 to − 0.81)
Curlewis	Yes (1.34–1.64)	No	No
Pittsworth	No	No	Yes (− 0.34 to − 0.37)
Wallangra	No	Yes* (0.67–0.79)	No
Clarence Town	No	No	Yes (− 0.63 to − 0.76)

*Mann–Kendall test only, not *t*-test.

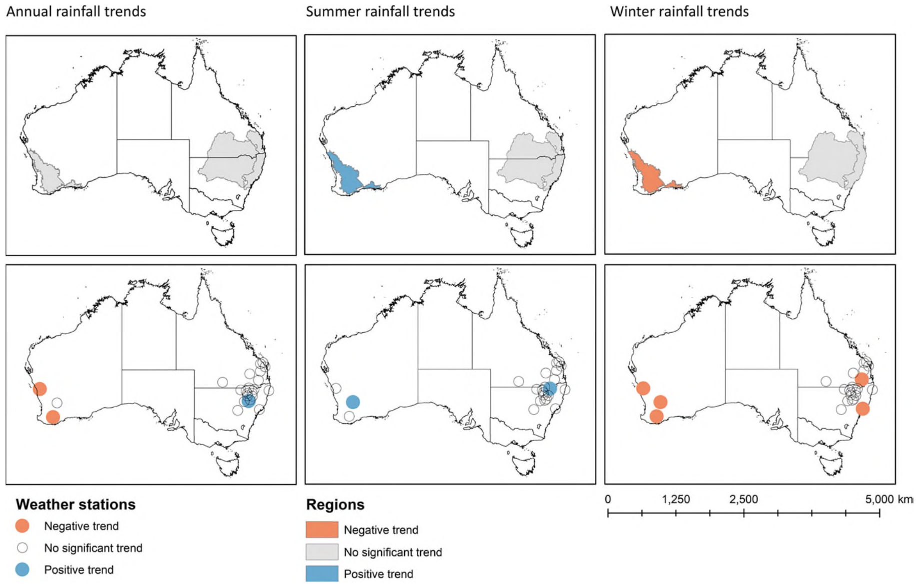

Fig. 2 Long-term trends (1907–2018) in annual, summer and winter rainfall in three study areas and twenty-four weather stations

Table 3 Selected results of trend analysis for extreme rainfall 1907 to 2013. 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 gives the range of the estimated slope of the linear trend line and Sen's slope. The table shows results for selected regions and weather stations. Results for other weather stations and rainfall indicators can be found at https://shiny.csiro.au/rainfall-trend-explorer/

Indicator	Trend in Rx5day (mm/year)	Trend in R10mm (days/year)	Trend in CWD (days/year)	Trend in R95p (mm/year)
Region				
WA-wheat belt	No	No	Yes (– 0.015 to – 0.017)	No
East coast	No	No	Yes (– 0.015 to – 0.016)	No
N-MDB	No	Yes (0.03)	No	Yes (0.48–0.50)
Weather station				
Mingenew	No	No	Yes (0 to – 0.02)	No
Cunnamulla	No	No	No	Yes (0.63–0.81)
Curlewis	No	Yes (0.06–0.07)	Yes (0–0.01)	Yes (0.76–0.83)
Pittsworth	No	No	Yes (– 0.008–0)	No
Clarence Town	No	No	Yes (0.02)	Yes (– 1.57 to – 1.58)
Yamba	Yes* (0.52)	No	No	Yes* (1.16–1.33)
Fairymead	Yes (– 0.94 to – 0.71)	No	No	Yes (– 1.9 to – 2)
Gin Gin	No	Yes (– 0.06 to – 0.08)	Yes (0.05 to – 0.02)	No
Maryborough	No	Yes (– 0.04 to – 0.05)	No	No

*Mann–Kendall test only, not *t*-test.

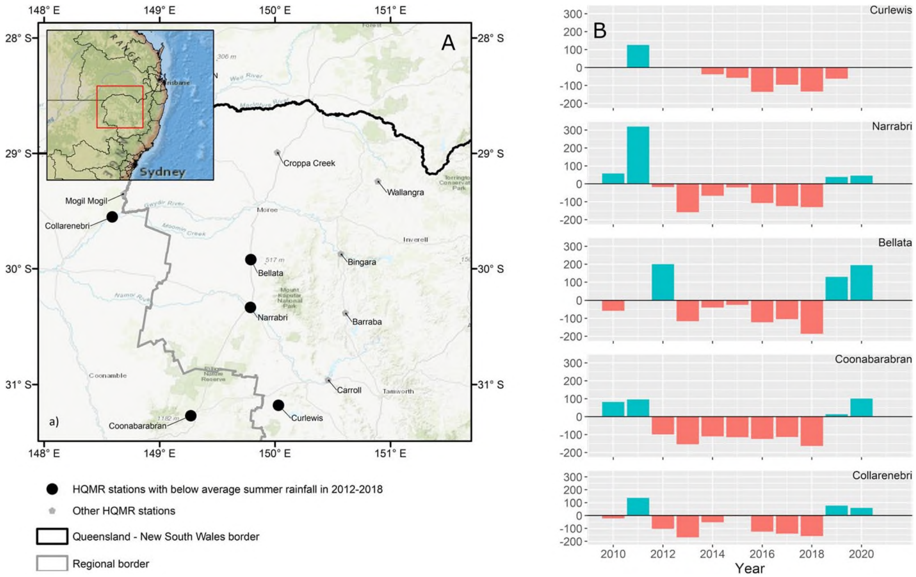

Fig. 3 The New England and North West region in northern New South Wales with selected weather stations showing a high number of consecutive dry summers in the last 10 years, 2010 to 2020. (**A**) Map showing locations of weather stations and (**B**) showing summer rainfall anomaly as the difference of each summer rainfall and the 1961–1990 average in mm

wet days has increased slightly by one day to five days per 100 years in Mingenew, Curlewis, Clarence Town and Gin Gin. No linear trend in any of the rainfall indicators has been found in Bingara, Narrabri and Peak Hill in NSW and Miles and Murgon in QLD. Across the N-MDB the number of days with precipitation of more than 10 mm has increased by about one day per 30 years. Since 1990, precipitation from very wet days across the region is 27% larger than the average in 1907 to 1989.

We found four stations in a 200-km radius from Narrabri, NSW, that also experienced a long period of below average summer rainfall between 2012 and 2019 (Fig. 3). In Curlewis, for example located 120 km southeast of Narrabri, six consecutive summers have been dry with below average rainfall which is however not unprecedented as the entire rainfall record indicates a similarly long dry period in the early twentieth century. The summer 2013/2014 has been very dry with only 20 to 60 mm falling over the entire three months in Narrabri, Curlewis and Collarenebri. The location of these five weather stations seems to indicate an area between 148°E to 150°E and 29.5°S to 31.5°S with below average decadal summer rain as the weather stations east of 150°E (Bingara, Barraba, Carroll Ranch, Wallangra) and north of 29.5°S (Mogil Mogil, Croppa Creek) do not show the same trend (Fig. 3A).

3.2 Rainfall deciles

The rainfall decile analysis suggests that the last 20-year (1999–2018) summer rainfall has been average compared to the entire rainfall record in most places in the Western Australia wheat belt, with the exemption of the southwest corner of the wheat belt (Fig. 4A). The

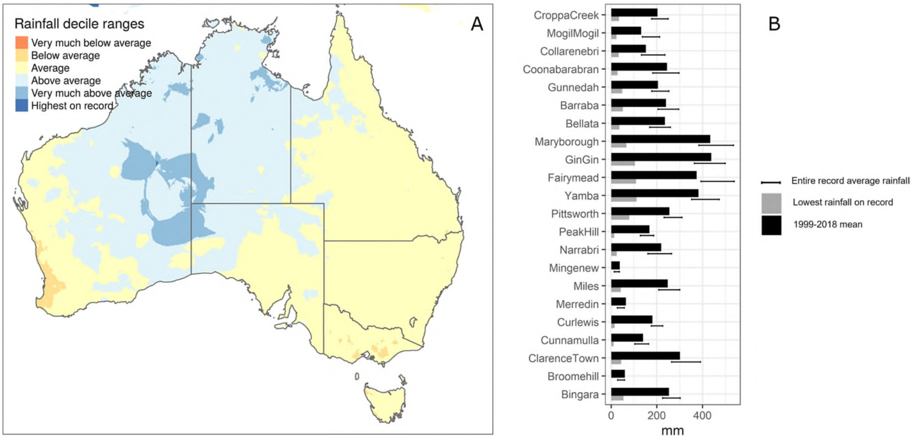

Fig. 4 Summer rainfall deciles for the last 20 years (1999–2018). (**A**) The map shows where rainfall is above average, average or below average, in comparison with the entire rainfall record from 1907. (**B**) The figure shows how the last 20-year summer rainfall (black bar) at each station compares to the lowest (grey bar) and average (black line) 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 20 years is not complete

last 20-year summer rainfall has been average compared to the entire rainfall record in the Northern Murray Darling basin and the Coastal QLD and NSW region. Fairymead Sugar Mill in Queensland is the only station with 1999–2018 summer rainfall average below average compared to the entire rainfall record since 1907 (Fig. 4B) although there is no long-term trend in summer rainfall.

3.3 Projections of future rainfall change

For the N-MDB, 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 , 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. 5). 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.For the summer season, Climate Futures analysis shows 24 models that simulate increased summer rainfall while 14 models give summer rainfall reductions (10 show little change). Among these, the maximum consensus future, represented by 18 models (38%), is hotter (1.5–3 °C) and wetter to slightly drier (−5 to + 15%) summers by mid-century under RCP8.5. Thus, both increase and decrease in summer rainfall are plausible, but there is insufficient evidence to indicate the direction of change with any confidence (see Supplementary Information, Fig. ESM1).

For the coastal midlatitude 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

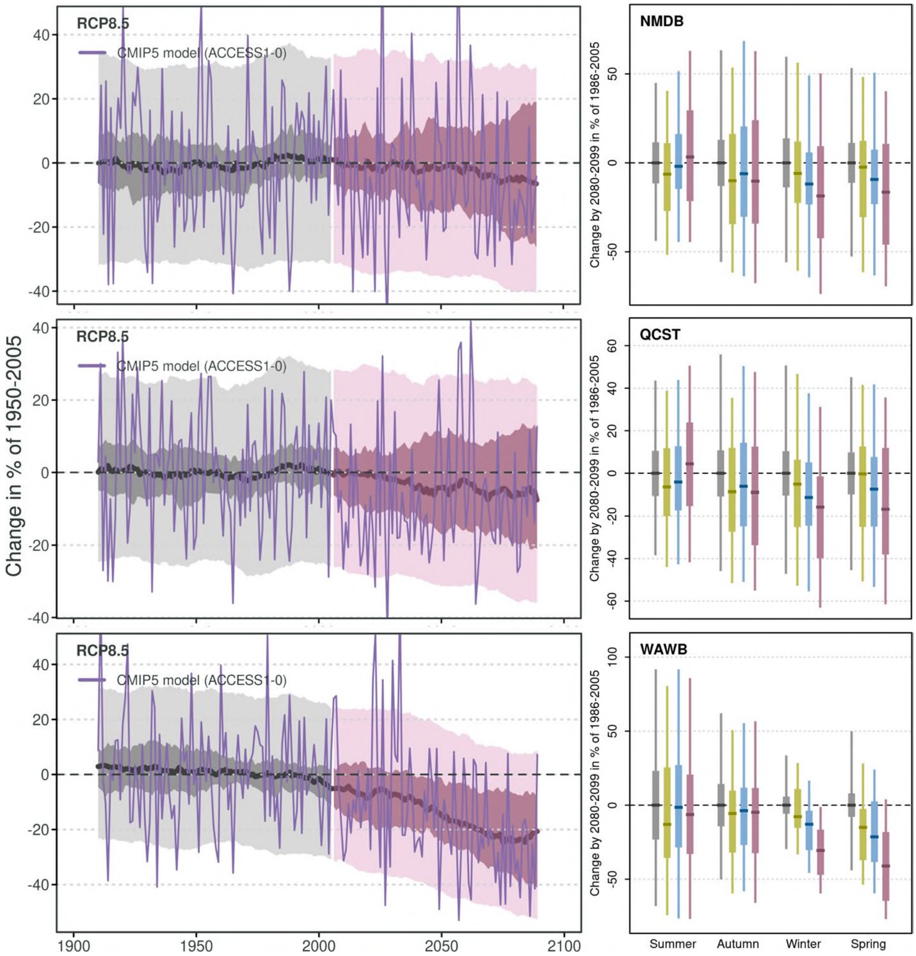

Fig. 5 Projected changes in annual (left) and seasonal (right) regional rainfall as simulated in CMIP5 for different representative concentration pathways and three study areas: the Northern Murray Darling basin (top, NMDB), Coastal QLD and NSW region (middle, QCST) and Western Australia wheat belt (bottom, WAWB). Left panels show time-series of annual change relative to the 1950–2005 mean for historic simulations from all models with future as simulated for 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 the 20-year running 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 panels show 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. Boxes indicate the 10th and 90th percentile range of 20-year means, and whiskers show the 10th to 90th percentile interannual range. See Supplementary Information, Tables ESM3–5 for data plotted in boxplots for 2080–2099 and three other time periods (2020–2039, 2040–2059, 2060–2079)

rainfall. Winter rainfall is projected to decrease (medium confidence) by late in the century, irrespective of emissions (Fig. 5). 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 supported by Climate Futures analysis showing a strong clustering of model results in the drier and much drier climate futures (-5 to $> -15\%$) around mid-century under high emissions (see Supplementary Information, Fig. ESM2).

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 (Fig. 5). 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 for winter rainfall ($< -15\%$) around mid-century under high emissions (see Supplementary Information, Fig. ESM3). Further evidence substantiating these declines comes from the newest global climate modelling (CMIP6) reported in the IPCC's Sixth Climate Change Assessment Report (Working Group 1). The authors report stronger annual drying in southwest Australia than previous modelling (Douville et al. 2021).

4 Discussion

4.1 Comparison to previously published studies

The decline in winter rainfall in the WA-wheat belt has been described before for different time periods and using different rainfall indicators (Hennessy et al. 1999; Haylock and Nicholls 2000; Smith 2004; Murphy and Timbal 2008; Delworth and Zeng 2014; Freund et al. 2017; Contractor et al. 2018). For example, Hennessy et al. (1999) find a significant negative change in annual rainfall in southwest 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 southwest Western Australia (Hennessy et al. 1999). The Indian Ocean Climate Initiative (2013) 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 the south of the wheat belt. Freund et al. (2017) find a decline in cool season rainfall during the most recent 30- and 50-year 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 Merredin and in the WA-wheat belt overall that is smaller than the trend for the winter season. The positive trend in summer rainfall in Merredin, WA (0.24–0.29 mm/year) is smaller than the trend found before for Peppermint Grove, WA, located about 250 km west of Merredin on the Indian Ocean coast, with 0.68 mm/year increase in summer rainfall since 1950 (Indian Ocean Climate Initiative 2013). Hennessy et al. (1999) find that heavy rainfall intensity in summer increased by 10–19% in southwest 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) report declines in annual total and winter rainfall for Mingenew located in the northern part of the wheat belt.

Fewer studies have focused on rainfall trends in southern Queensland (QLD) and northern New South Wales (NSW). In agreement with our results, Hennessy et al. (1999) find no statistically significant change in annual or summer rainfall in Queensland and 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) also find that the number of wet days declined by 1.5% or more but only in regions near the coast and more often in QLD than in NSW. Dowdy et al. (2015) find a small increase and a small decrease in summer rainfall between 1910 and 2005 in the coastal regions of northern NSW and the coastal regions of southern QLD, respectively, but we cannot confirm this trend for the time period 1907 to 2018. Potter et al. (2010) study changes in rainfall and runoff in the Murray Darling basin between 1895 and 2006 and find that only small parts of the basin in the extreme northwest, southwest and south have experienced a significant downward trend and step change in rainfall. The trends in runoff are similar but the area with statistically significant downward trends in runoff is larger than that for rainfall.

4.2 Climate drivers of rainfall changes

Analysing the influence of different climate drivers on rainfall variability in different seasons can indicate potential causes of long-term trends in rainfall and potential future changes. 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. 6). There is no influence of the sub-tropical ridge position or intensity (STRP/STRI) in the region in the warm 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. We discuss the individual drivers of rainfall in the three study areas further in supplementary Cite ESM.material 1.

4.3 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. We here discuss two main research methods to study the relationship between rainfall and agriculture: (i) empirical methods studying the relationship between past climate conditions and agricultural output and (ii) modelling 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 climate events have had on agriculture and the importance of climatic drivers for

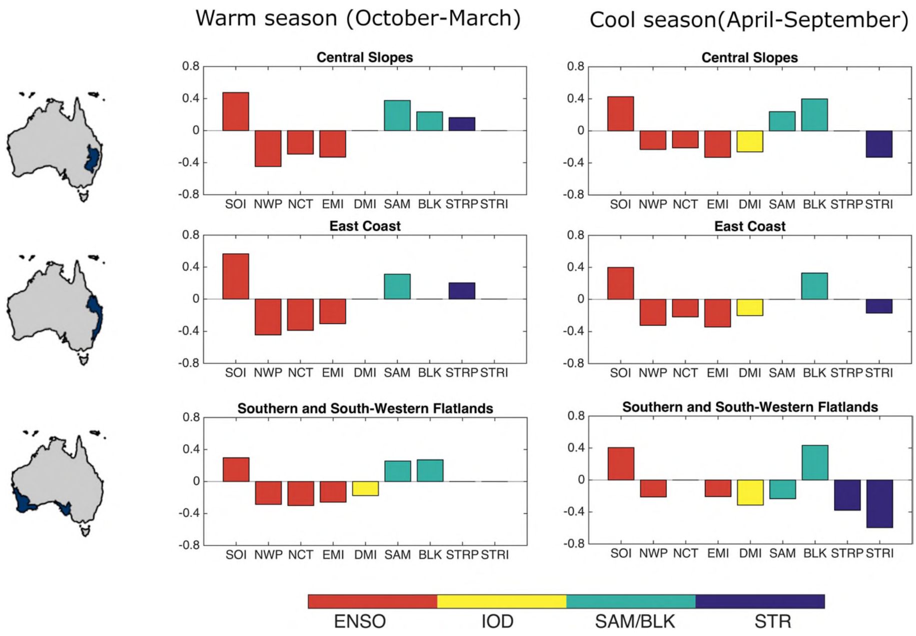

Fig. 6 The dominant climate influence on seasonal rainfall. The correlations shown in the bar plots exceed the 10% significance level. SOI, Southern Oscillation index; NWP, Nino Cold Tongue index; NCT, Nino Warm Pool index; EMI, El Nino Modoki index; DMI, Indian Ocean Dipole; SAM, Southern Annual Mode; BLK, Blocking index; STRP, Subtropical Ridge position; STRI, Subtropical Ridge intensity. Modified from Freund et al. (2017), Fig. 2 and Fig. 4 that are licensed under a Creative Commons Attribution 4.0 License

year-to-year variability compared to changes in technology or management. Not every change in rainfall, even if statistically significant will have an impact on agricultural production. Previous studies have shown, however, that two-thirds of the temporal 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). In the northern plains of the NSW wheat belt, the fluctuation range of wheat yields amplified in the late twentieth century, 1980–2000, indicating an increasing adverse effect on wheat yields caused by climate variability that may continue during the twenty-first century (Feng et al. 2018). Wheat yield variability in this region is largely associated with rainfall extremes, in particular the 3-month standardized precipitation index of June–August, September–November and the number of consecutive dry days (Feng et al. 2018). 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 2019–2020 compared to 2017–2018 due to drought (Martin and Topp 2020) but with marked regional differences. This is overall twice as much as the long-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 2009–2010. 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 such simulation studies have been conducted for Australian agriculture in the past. Hochman and Lilley (2020) give an overview of the development of simulation models in Australia and their coupling with long-term climate projections for estimating impacts on agriculture. Climate change impacts on crops for example depend on the magnitude of temperature, rainfall and atmospheric CO_2 concentration changes, crop and soil management, the soil type and crop cultivar. Sowing earlier or sowing different cultivars with faster development for example can mitigate some negative effects of increased temperature in southern and western Australia (Ludwig and Asseng 2010; Flohr et al. 2018). Wang et al. (2018) found in a simulation experiment that bringing the wheat sowing date forward and using a cultivar with a longer growth period compensated for the negative impacts of climate change on yields. Adaptation in other agronomic practices to manage changes in water availability include increasing the row spacing and decreasing the frequency of irrigation (Williams et al. 2018), and changes to row configuration, crop duration and plant density (Hammer et al. 2014).

Without any adaptation, wheat yields are projected to decline, on average, by 2 to 19% in the East Coast, by 3% to 5% in the N-MDB and by 22% to 34% in the WA-wheat belt with strongest declines for 2°C to 3°C local warming levels (Fig. 7). Taylor et al. (2018) also found an increase in wheat yields in the N-MDB (Moree, Peak Hill) with local warming levels of 1.5 °C. These changes are relative to wheat yields in 2005. All studies consider

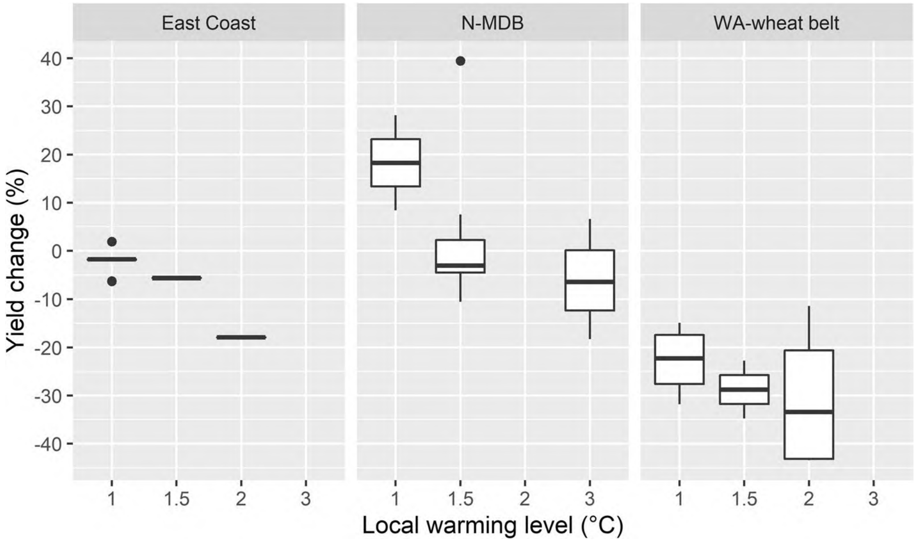

Fig. 7 Projected wheat yield changes for different local warming levels relative to the baseline period (2001-2005) . The data shown is from thirty observations, four studies and eight sites: Bellata, Peak Hill and Moree in the N-MDB (Taylor et al. 2018; Feng et al. 2019), Gayndah and Maitland in the East Coast (Reyenga et al. 1999; Taylor et al. 2018) and Kellerberrin, Mingenew and Wongan Hills in the WA-wheat belt (Cammarano et al. 2016; Taylor et al. 2018). The box shows the interquartile range and the middle line in the box represents the median. The upper and lower end of the lines extending from the box show the largest value no further than 1.5 times the interquartile range from the 75th percentile and the 25th percentile, respectively. The filled dots show values larger or smaller than 1.5 the interquartile range. Data source: (Hasegawa et al. 2021)

the CO_2 fertilization effect in modelling climate change impacts with CO_2 concentrations of 486.5 to 844.8 ppm. Increases in atmospheric CO_2 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.

4.4 Methodological remarks for future studies

Future studies could define an extended set of rainfall variables beyond seasonal rainfall. 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, such as drought. The rainfall variables used for statistical analysis should align as closely as possible with local observations on rainfall changes from primary producers and the larger community. Another methodological issue is that spatial correlation of rainfall is low which makes the identification of consistent, regional trends challenging. For example, for the N-MDB, overall we find a positive trend in the annual precipitation from heavy precipitation days but only in two of the eight weather stations in the region. 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 might be to work with the Bureau of Meteorology's rainfall district systems (http://www.bom.gov.au/climate/cdo/about/raindistricts.shtml) which groups sites with relatively similar rainfall types. Narrabri, Bingara and Wallangra in northern New South Wales are for example located in the rainfall district 'Northwest Slopes'.

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.

5 Conclusions

The results of this study 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 towards a more resilient agricultural sector. For this, it is crucial to make climate data and knowledge of climate changes that can potentially benefit decision-making publicly available if possible and disseminated as widely as possible to assist producers.

Our results 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 yet. Some of the observed long periods of dry summers in northern New South Wales are rather unprecedented, for example for Narrabri but it is too soon to know if this is part of a longer-term trend and projected changes are equivocal. The changes in rainfall distribution towards more intense rainfall and shorter consecutive wet periods are 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.

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Author contribution KW designed the study and research questions and selected the study areas. KW, MF and IP collected secondary data for historic rainfall and rainfall drivers and KW, IP and MP did the data analysis for historic rainfall trends. IP summarized the first results of the analyses and KW wrote the manuscript based on that. JC and CH analysed future rainfall projections and prepared the respective plots and text describing the results. EV and KD discussed the initial study design and focus with KW. All authors contributed to internal review and discussion of the results multiple times.

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Data availability Waha, Katharina; Ord, Louise; Alexander, Lisa; Parisi, Irene (2021): Australian Midlatitudes Rainfall. v15. CSIRO. Data Collection. https://doi.org/10.25919/qdk0-ys13.

Materials availability An interactive web application to query and view the rainfall data for selected locations is available at https://shiny.csiro.au/rainfall-trend-explorer/. Please cite the tool as Ord, Louise; Waha, Katharina (2021): Australian Rainfall Trend Explorer. v5. CSIRO. Service Collection. http://hdl.handle.net/102.100.100/390056?index=1.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

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