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Effects of heat extremes on wheat yields in Australia

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Many agricultural studies have identified that wheat yield is sensitive to seasonal rainfall and extreme high temperatures. We investigate the impact of extreme heat events, in particular on wheat yields in South-East Australia (SEA) and South-West Western Australia (SWWA).

We define a 'heat-day' as a day where the daily maximum temperature exceeds the 1911–2013 90th percentile for the respective calendar month. We find that the number of heat-days has experienced statistically significant increases across most months across much of Australia, particularly in South Australia, Western Australia, the Northern Territory and Tasmania. The trends are especially marked in winter, including in key wheat-growing regions. The temperatures recorded on these hottest days have also shown a statistically significant increase over the last 100 years.

We find that, while wheat yields are more strongly correlated with rainfall than with the number of heat-days, there is substantial evidence to suggest that during drought conditions wheat yields are sensitive to the number of heat-days recorded in August and September in SEA and September and October in SWWA. Extreme heat and rainfall have a stronger association with below-average yields than above-average yields.

Extreme temperatures and rainfall in these regions are related to major Australian climate drivers which form the basis of seasonal prediction models and are important for natural variability and long-term climate change. Here we assess the degree to which wheat yields in both regions can be related to the El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM). We find that positive IOD events and El Niño events are both associated with reductions in wheat yields in SEA, but that the co-incidence of these events have no additional wheat yield reductions than would be expected if either a positive IOD or El Niño event occurs. The average annual wheat yield loss associated with El Niño state and/or positive IOD state in SEA is estimated to around sixteen to twenty one per cent.

This paper provides insights into the historical relationships between wheat yields, extreme heat and climatic modes of variability in Australia, and discusses the possibilities for changes in wheat yields under a future climate change scenario.

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1. Introduction and Background

Wheat and other grains are vital staple foods, and their harvest and sale are an important component of the Australian economy, worth approximately AUD$7bn in 2012-2013 (ABARES 2015). A nationwide harvest of 22,856,000 tonnes grown on 12,979,000 ha was produced over this period, with 80 per cent of this wheat exported (ABARES 2015). Wheat is predominantly grown in South-East Australia (SEA; approximately 60 per cent of national crop) and South-West Western Australia (SWWA; 30 per cent) (ABARES 2014). These regions are illustrated in Figure 1.

Many agricultural studies identify that wheat is negatively affected by high temperatures, especially during spring, using absolute thresholds to identify how high temperatures must be before the wheat is affected. Barlow et al. (2013) and Alexander et al. (2010) suggest that 35°C is an appropriate threshold, whilst Luo (2011) finds that temperatures above 32.7°C during the period of sowing to emergence, and 35.2°C for grain filling (the growth stage where carbohydrates and protein stores increase within the grain), are detrimental to wheat. Asseng et al. (2011) and Lobell et al. (2012) both use a 34°C threshold, with Asseng et al. (2011) finding that this temperature corresponds to a 50 per cent reduction in wheat yields. Talukder et al. (2010) and Alexander et al. (2010) note that a single day of extreme temperature is enough to have a detrimental effect on the wheat yields for that year. Asseng et al. (2011) report a positive correlation between wheat yields and the number of days above 34°C after flowering. Additionally, the effect that rainfall, especially spring rainfall, has on the growth of wheat has long been recognised (Sief and Pederson 1978).

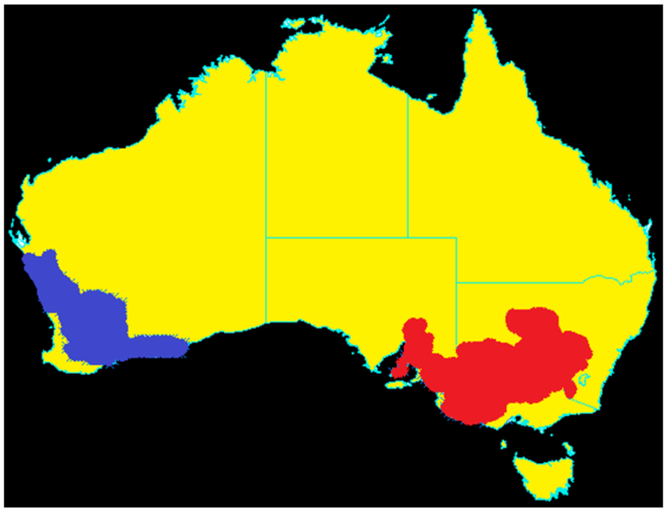

Figure 1 The South-East Australia region (SEA; red; right) and the South-West Western Australia region (SWWA; blue; left) as defined and used in this study (adapted from Jones et al. 2009).

Whilst these results give valuable insights into the susceptibility of wheat crops to heat, defining a percentile-based metric is of interest both agriculturally and meteorologically, allowing the effects of extreme temperatures on wheat yields to be analysed on regional and even national scales. Better understanding of the relationships between wheat, extreme temperatures and rainfall (and the climate regimes that produce these) will assist current and future climate change adaptation efforts.

While wheat is also affected by frost (Barlow et al. 2013), this is not examined in this study since the micro-scale meteorological processes that contribute to frost's occurrence cannot be captured in the gridded data. Nicholls (1997) suggests that 30–50 per cent of observed increases in wheat yields in some regions since 1952 may be due to increases in minimum temperature. This study focuses on the impact of high temperatures and rainfall on wheat yield. There is also some complexity in the time trends of frost occurrences in the wheat regions, with Dittus et al. (2014) noting an overall century-scale decrease but some increases in some months in the last 32 years, however with large spatial variability in these recent trends.

This study aims to catalogue and analyse the occurrence of extreme daily maximum temperatures in Australia's constituent states and territories, and the effects of these on wheat yields. The role of climate modes that drive these weather conditions are considered, as are future wheat yields under a climate change scenario.

2. Data and Methods

2.1 Defining heat-days

Perkins and Alexander (2013) define a heatwave in Australia to be three or more consecutive days where either the minimum or maximum temperatures are above the 90th percentile, however a simplified definition is used here. To assess the impact of extreme heat events on wheat yields, a 'heat-day' is defined as a day where the daily maximum temperature exceeds the 1911–2013 90th percentile for the respective calendar month. This is chosen because a single day of well-above-average temperature can have a detrimental effect on wheat yields (Talukder et al. 2010, Alexander et al. 2010). Monthly averages defined using calendar months, rather than a moving 31-day period as per Perkins and Alexander (2013), are used to simplify analysis. As a result there may be some differences between how heat-days would be classified in the two methods, especially at the start and end of calendar months. The relevance of heat persistence for wheat is also investigated, by comparing the correlations between wheat, heat-days and heatwaves of various lengths.

2.2 Data

Gridded data with 0.25^{o} resolution from the Bureau of Meteorology's Australian Water Availability Project (AWAP) database (Jones et al. 2009) are used to provide daily temperature and rainfall observations. Data are averaged by State (e.g. Victoria, South Australia), and by specially defined areas for wheat (see Figure 1) over the period 1911-2013. As would be expected there are fewer observations in the early part than in the later part of the period, however we note that there is reasonable network stability in the wheat regions with a number of long-lived observational records (Trewin 2013). Trends in both the number of heat-days and the temperatures recorded on these days are analysed. Statistical significance is tested at the five per cent level in all analysis unless stated otherwise and reported as two-tailed p-values throughout. Pearson's product-moment correlation coefficient (r) is used to indicate the strength of association between variables in this study.

Data of annual wheat crops (area planted and weight harvested) from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) spanning 1900 to 2012 are used. The state-based harvest amounts for New South Wales, Victoria and South Australia are combined and divided by the total area planted over the three states to derive the SEA annual yield. For the SWWA yield, the total harvest for Western Australia is divided by the total area planted in Western Australia for each year in the 113-year record.

The correlations between climate drivers and wheat yields in both regions are assessed using common indices to represent the major modes of natural climate variability in the Australian region. The importance and interdependence of the climate drivers are assessed using a multi-regression model. The highest correlations between drivers and wheat yields are found using many averaging periods and start times as per Braganza et al. (2009). We use the Southern Oscillation Index (SOI; Bureau of Meteorology 2015; 1876-2014) to represent the El-Niño Southern Oscillation (ENSO), the Indian Ocean Dipole Mode Index (DMI; Saji et al. 1999; 1900 -2013) for the Indian Ocean Dipole (IOD) and the Thompson and Wallace (2000; 1871-2011) index of the Southern Annular Mode (SAM).

2.3 De-trending the data

To account for technological advances (both in farming practices and changing grain types) being the primary driver of the upward trend exhibited in each state's yields over the 113-year record, it is necessary that both the SEA and SWWA regions' yield data are de-trended (Nicholls 1997). De-trending was achieved by subtracting the linear trend obtained using ordinary least squares. Quadratic and linear trends over time were considered for both SEA and SWWA. The linear trend was the most parsimonious choice for SEA, for SWWA there was some added benefit of including a quadratic term however it was small (R^2=0.66 for quadratic, R^2=0.63 for linear) so linear de-trending was use for both regions as per Nicholls (1997). This approach has the benefit of consistency in methods amongst all variables de-trended in this study.

It should be noted that some component of the advances may be considered successful adaptation measures, and such current and future changes would be relevant to future climate change impacts on wheat yields. The de-trending applied here aims to leave only the year-to-year variability in the wheat yield for both regions, which is analysed for its relationship to rainfall and temperature variability on monthly, seasonal and annual timescales. The SEA and SWWA regions are analysed separately, in order to determine if there are differences in the regions' climatic sensitivities.

As the heat-days data also exhibit a trend, these are de-trended in the same way as the wheat yield data. This makes inference about changes in the wheat yield induced by changes to the frequency of heat extremes difficult. However, it does remove the difficulties associated with determining the proportion of the trend due to technological advances and the proportion due to changes in climate.

The monthly resolved Thompson and Wallace (2000) index datasets, defined using pressure, geopotential height and zonal wind fields, are de-trended on a monthly basis. This allows focus to be placed on the inter-annual variability of the Southern Annular Mode, rather than the documented trend (Abram et al. 2014; Marshall 2003). For similar reasons, the SOI and DMI and temperature data sets are also de-trended.

Rainfall data are not de-trended as only one of the 108 month-region combinations has a statistically significant trend. In this study, all subsequent uses of the climate driver, heat-day or wheat yield datasets are referring to the de-trended datasets, unless noted otherwise.

3. Results and Discussion

3.1 Trends in heat-day prevalence and strength in Australia

Trends in the number of days above the 90th percentile ('heat-days') are analysed for each Australian state as an area-averaged quantity - New South Wales includes the Australian Capital Territory observations. Trends in the number of heat-days in the SEA and SWWA regions (defined in Figure 1) are also analysed. The 90th percentile temperatures that are used to define heat-days in each month are provided for all regions in Supplementary Table 1.

Monthly trends in the number of heat-days recorded in each region, over the 1911–2013 period, are shown in Table 1. Notably, there are statistically significant increases in heat-days recorded in every month in Tasmania, South Australia and Western Australia over the 1911–2013 period, with the winter months exhibiting the largest trends. Every region has experienced a statistically significant increase in the incidence of heat-days in July. The regions with the lowest number of statistically significant monthly trends are Victoria and SWWA (two each), and NSW (three). The largest percentage-wise increases in the number of heat-days have occurred in August in Western Australia (26.12 per cent), however this result is not statistically significant in SWWA, indicating that much of the increase in extreme temperature incidence has occurred in that state's vast interior.

Seasonal and annual trends in the number of heat-days are shown in Supplementary Table 2 with the annual trends shown in Figure 2. Winter trends in heat-days are statistically significant in all regions analysed for this study, and annual trends were statistically significant in all regions, including the two wheat regions, except NSW. The largest trends in the number of heat-days annually are in Western Australia (18.01 per cent) and Tasmania (12.76 per cent), with increases in all seasons, especially winter (Western Australia: 22.42 per cent; Tasmania: 14.08 per cent), contributing to this trend. All seasons in Western Australia, Tasmania, South Australia and the Northern Territory experienced statistically significant increases in the number of heat-days over the 1911–2013 period.

Trends in the number of three-day, five-day and seven-day heatwaves (consecutive days above the respective monthly 90th percentile) are also shown in Supplementary Table 2 and Figure 2 (note that the heatwaves are defined in such a way that a six-day heatwave is counted as four three-day heatwaves and two five-day heatwaves). The number of consecutive days used in the definition of a heatwave does not affect the statistical significance of the result, with an increase in three-day, five-day and seven-day heatwaves being statistically significant in all regions except Queensland and SWWA. Generally, on a percentage basis, the incidence of seven-day heatwaves has increased more than five-day heatwaves, which in turn increased more than three-day heatwaves did, over the 1911-2013 period. The largest increases (percentage-wise) are again observed in Western Australia (three-day: 23.33 per cent; five-day: 26.3 per cent; seven-day: 28.92 per cent) and Tasmania (three-day: 20.62 per cent; five-day: 25.66 per cent; seven-day: 28.70 per cent) in all three metrics.

Month	*VIC*	*TAS*	*SA*	*WA*	*NT*	*QLD*	*NSW*	*SWWA*	*SEA*
Jan	0.17 p=0.04 (5.45%)	0.42 p<0.01 (13.65%)	0.37 p<0.01 (11.84%)	0.55 p<0.01 (17.74%)	0.31 p=0.02 (9.97%)	–0.00 p=1.00 (–0.02%)	0.04 p=0.68 (1.37%)	0.16 p=0.03 (5.22%)	0.17 p=0.06 (5.33%)
Feb	0.06 p=0.43 (2.21%)	0.40 p<0.01 (13.65%)	0.22 p=0.02 (7.56%)	0.43 p<0.01 (14.68%)	0.00 p=0.98 (0.08%)	–0.18 p=0.22 (–6.17%)	–0.08 p=0.48 (–2.74%)	0.01 p=0.93 (0.24%)	-0.05 p=0.60 (-1.71%)
Mar	0.10 p=0.27 (3.33%)	0.43 p<0.01 (13.85%)	0.19 p=0.06 (6.21%)	0.44 p<0.01 (14.18%)	0.10 p=0.48 (3.35%)	–0.13 p=0.39 (–4.02%)	–0.07 p=0.55 (–2.34%)	0.15 p=0.07 (4.94%)	0.09 p=0.39 (2.89%)
Apr	0.14 p=0.12 (4.59%)	0.43 p<0.01 (14.38%)	0.41 p<0.01 (13.68%)	0.43 p<0.01 (14.20%)	0.16 p=0.21 (5.39%)	–0.02 p=0.87 (–0.71%)	0.10 p=0.35 (3.18%)	0.15 p=0.09 (5.05%)	0.17 p=0.09 (5.61%)
May	-0.00 p=0.98 (-0.06%)	0.34 p<0.01 (11.01%)	0.22 p<0.01 (7.18%)	0.63 p<0.01 (20.04%)	0.46 p<0.01 (14.79%)	0.24 p=0.06 (7.60%)	0.07 p=0.48 (2.30%)	0.20 p=0.03 (6.41%)	0.05 p=0.64 (1.44%)
Jun	0.17 p=0.07 (5.49%)	0.38 p<0.01 (12.41%)	0.25 p=0.02 (8.35%)	0.47 p<0.01 (15.50%)	0.13 p=0.23 (4.45%)	0.15 p=0.19 (4.88%)	0.24 p=0.02 (7.93%)	0.24 p=0.01 (7.79%)	0.16 p=0.14 (5.33%)
Jul	0.21 p=0.02 (6.69%)	0.51 p<0.01 (16.54%)	0.57 p<0.01 (18.38%)	0.80 p<0.01 (25.43%)	0.43 p<0.01 (13.86%)	0.30 p<0.01 (9.52%)	0.24 p=0.01 (7.59%)	0.30 p<0.01 (9.58%)	0.18 p=0.04 (5.75%)
Aug	0.14 p=0.19 (4.43%)	0.41 p<0.01 (13.08%)	0.41 p<0.01 (13.37%)	0.82 p<0.01 (26.12%)	0.55 p<0.01 (17.83%)	0.34 p<0.01 (10.95%)	0.21 p=0.05 (6.67%)	0.12 p=0.19 (3.86%)	0.14 p=0.24 (4.43%)
Sep	0.09 p=0.24 (3.06%)	0.30 p<0.01 (9.89%)	0.52 p<0.01 (17.25%)	0.59 p<0.01 (19.27%)	0.64 p<0.01 (21.37%)	0.46 p<0.01 (15.31%)	0.25 p=0.02 (8.37%)	–0.10 p=0.20 (–3.15%)	0.17 p=0.05 (5.70%)
Oct	0.03 p=0.71 (0.99%)	0.30 p<0.01 (9.55%)	0.23 p<0.01 (7.44%)	0.63 p<0.01 (20.24%)	0.45 p<0.01 (14.35%)	0.23 p=0.050 (7.27%)	0.04 p=0.67 (1.34%)	0.16 p=0.05 (5.07%)	0.00 p=0.97 (0.12%)
Nov	0.08 p=0.35 (2.61%)	0.401 p<0.01 (13.55%)	0.33 p<0.01 (10.92%)	0.43 p<0.01 (14.34%)	0.24 p=0.026 (8.15%)	0.06 p=0.59 (1.97%)	–0.04 p=0.72 (–1.25%)	0.07 p=0.31 (2.38%)	0.05 p=0.64 (1.52%)
Dec	0.08 p=0.31 (2.63%)	0.37 p<0.01 (12.04%)	0.35 p<0.01 (11.33%)	0.40 p<0.01 (12.87%)	0.32 p=0.009 (10.10%)	0.05 p=0.67 (1.58%)	–0.04 p=0.69 (–1.26%)	0.04 p=0.57 (1.29%)	0.05 p=0.51 (1.68%)

Table 1 Monthly trends in the number of heat-days per decade, the significance of that trend, and the trend expressed as percentage change (per decade) for Victoria, Tasmania, South Australia, Western Australia, the Northern Territory, Queensland, New South Wales (includes Australian Capital Territory) and the two wheat regions defined in Figure 1, calculated over the 1911–2013 period. Underlined results have p-values of 0.05 or less.

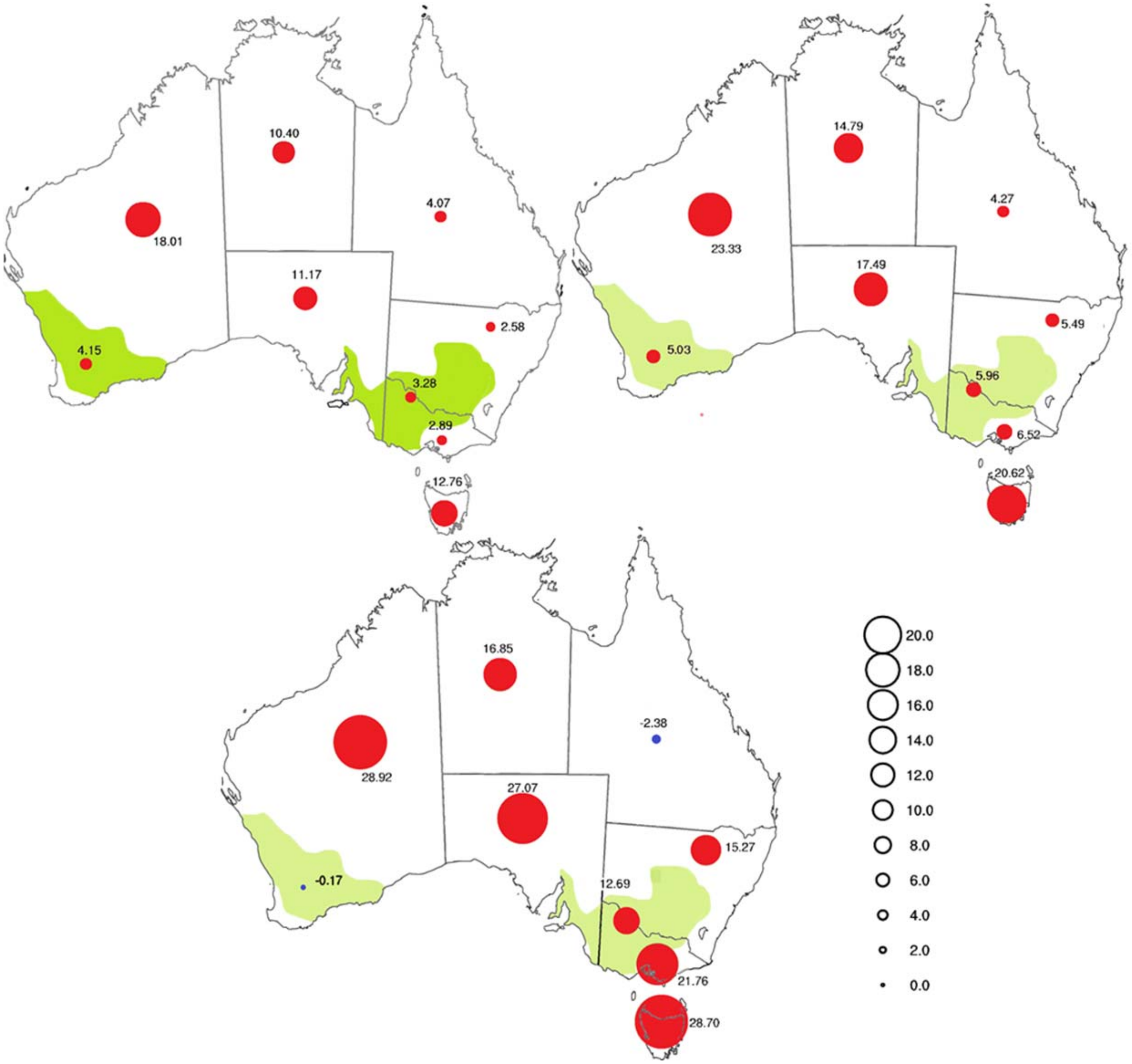

Figure 2 The percentage-wise trends in the number of heat-days (top left), runs of three consecutive heat-days (top right) and runs of seven consecutive heat-days (lower), over the 1911–2013 period. Wheat regions are shaded green, and dots wholly within these regions corresponding to the trend within the region, the other dots correspond to trends within state/territory regions. The radius of each dot is associated with the magnitude of the trend as shown in the key to the right. The shading of the dot denotes whether an increase (red) or decrease (blue) was observed. All results are statistical significant (see Supplementary Table 2), expect for three-day and seven-day heatwaves in SWWA and Queensland.

Month	*VIC*	*TAS*	*SA*	*WA*	*NT*	*QLD*	*NSW*	*SWWA*	*SEA*
Jan	0.00 (p=0.82)	0.10 (p<0.01)	0.06 (p<0.01)	0.05 (p<0.01)	–0.01 (p=0.35)	–0.01 (p=0.10)	0.02 (p=0.06)	0.03 (p=0.01)	0.04 (p<0.01)
Feb	-0.00 (p=0.66)	0.07 (p<0.01)	0.04 (p<0.01)	0.07 (p<0.01)	0.04 (p<0.01)	–0.00 (p=0.30)	0.03 (p<0.01)	–0.00 (p=0.74)	0.00 (p=0.74)
Mar	0.03 (p=0.11)	0.14 (p<0.01)	0.06 (p<0.01)	0.06 (p<0.01)	0.01 (p=0.08)	-0.01 (p=0.50)	0.04 (p<0.01)	-0.01 (p=0.54)	0.04 (p<0.01)
Apr	0.03 (p=0.02)	0.05 (p<0.01)	0.07 (p<0.01)	0.02 (p<0.01)	0.00 (p=0.10)	–0.03 (p<0.01)	0.00 (p=0.62)	0.03 (p<0.01)	–0.00 (p=0.84)
May	0.04 (p<0.01)	0.01 (p=0.35)	0.09 (p<0.01)	0.09 (p<0.01)	0.04 (p<0.01)	0.00 (p=0.34)	0.01 (p=0.38)	0.02 (p=0.05)	-0.01 (p=0.25)
Jun	0.05 (p<0.01)	0.04 (p<0.01)	0.04 (p=0.02)	0.04 (p<0.01)	0.01 (p=0.16)	0.00 (p=0.67)	0.05 (p<0.01)	0.09 (p<0.01)	0.02 (p<0.01)
Jul	0.01 (p=0.01)	0.03 (p<0.01)	0.12 (p<0.01)	0.06 (p<0.01)	0.05 (p<0.01)	0.02 (p<0.01)	0.03 (p<0.01)	0.03 (p<0.01)	0.02 (p<0.01)
Aug	0.03 (p<0.01)	0.06 (p<0.01)	0.12 (p<0.01)	0.08 (p<0.01)	0.07 (p<0.01)	0.05 (p<0.01)	0.05 (p<0.01)	0.07 (p<0.01)	0.01 (p=0.08)
Sep	0.07 (p<0.01)	0.04 (p<0.01)	0.14 (p<0.01)	0.08 (p<0.01)	0.03 (p<0.01)	0.00 (p=0.62)	0.07 (p<0.01)	0.04 (p<0.01)	0.01 (p=0.45)
Oct	0.02 (p=0.07)	0.05 (p<0.01)	0.09 (p<0.01)	0.04 (p<0.01)	0.04 (p<0.01)	0.01 (p=0.03)	–0.03 (p=0.01)	0.02 (p=0.18)	0.05 (p<0.01)
Nov	0.01 (p=0.30)	0.11 (p<0.01)	0.10 (p<0.01)	0.04 (p<0.01)	0.02 (p<0.01)	0.03 (p<0.01)	0.08 (p<0.01)	0.05 (p<0.01)	0.04 (p<0.01)
Dec	–0.01 (p=0.52)	–0.03 (p<0.01)	0.01 (p=0.30)	0.057 (p<0.01)	0.03 (p<0.01)	0.02 (p=0.01)	0.02 (p=0.03)	0.03 (p<0.01)	0.01 (p=0.59)

Table 2 Trends in the temperatures recorded on heat-days in Victoria, Tasmania, South Australia, Western Australia, Northern Territory, Queensland, New South Wales (includes the Australian Capital Territory) and the two wheat regions defined in Figure 1, over the 1911–2013 period. The significance of these trends is shown in parentheses. Underlined results have p-values of 0.05 or less. These trends have been calculated using a ten-year moving mean for each year, so as there was at least one event recorded in each year, and thus a p-value could be calculated. This process results in only 93 observations being used to determine the trends and their significance. The trends were then multiplied by ten so as to be expressed in terms of decades.

Trends in the average temperatures of these heat-days are shown in Table 2. These results show that, broadly, as well as experiencing more frequent extreme temperatures, the temperature of these heat extremes has also increased. All regions experienced a statistically significant increase in July heat-day temperatures, and Western Australia experienced statistically significant increases across all months, over the study period. The largest absolute increase found is the 0.1413 ^{o}C per decade increase in Tasmania's area-averaged March heat-day temperatures. Interestingly, there are more observations of statistically significant increases in the average temperature of heat-days (Table 2) than there are in the number of occurrences of heat-days (Table 1), with the difference mainly coming from New South Wales, Victoria and SEA results. In these regions there were a number of months that experienced statistically significant increases in the temperature of heat-days but no statistically significant increases in the frequency of these heat-days.

3.2 The appropriateness of the heat-days metric

One of the aims of this study is to define a measure of extreme temperatures over a large region that is relevant to wheat. Prior to this study, many varying temperature thresholds have been used. Using heat-days metrics produces correlations that are comparable, if not stronger than, the correlations obtained using absolute threshold-based metrics. The use of de-trended data also strengthens correlations. For example, the correlation between the number of days above 30°C and raw (i.e. not de-trended) wheat yields is –0.35 ($p<0.01$). If the number of heat-days is used instead of the 30°C threshold the correlation becomes –0.39 ($p<0.01$). Using de-trended wheat yield data along with the annual heat-day frequency further strengthens the correlation to –0.51 ($p<0.01$). Results similar to these are obtained for both SEA and SWWA, for many different months and seasons.

Additionally, the heat-day metric is more strongly correlated to wheat-yields than a de-trended mean daily maximum temperature metric. This is especially true when considering annual counts of heat-days and annual means of maximum daily temperatures (SEA - heat-days:-0.51, daily max: -0.19; SWWA- heat-days: -0.3, daily max: -0.14) and October counts and means (SEA – heat-days: -0.44, daily max: -0.15; SWWA – heat-days:-0.35, daily max: -0.26), the two timescales over which wheat yield and heat-days are most significantly-correlated (see 'The Effect of Extreme Heat and Rainfall on Wheat Yields'). This agrees with the assessments of Talukder et al. (2010) and Alexander et al. (2010), which state that single days (i.e. not necessarily reflected in the mean) of extreme heat could be detrimental to wheat crops.

3.3 The effect of extreme heat and rainfall on wheat yields

Extreme heat and total rainfall affect annual wheat yields in both SEA and SWWA, with a negative relationship between the number of heat-days and wheat yield and a positive relationship between total monthly rainfall and annual wheat yield (Figure 3). The number of heat-days exhibits a statistically significant relationship with wheat yield in the months from August to December in SEA, and August to October in SWWA (Supplementary Table 3).The maximum monthly correlations for both regions occur in October. The yearly aggregate of the number of heat-days is also significantly correlated with wheat yields in both regions, especially so in SEA, where the yearly correlation is higher than any of the individual months' relationships.

Correlations between rainfall and wheat yield are significant in the May-November half-year in SEA and in May, August, September and October in SWWA (Supplementary Table 4). However, the effect of rainfall on wheat yield is generally more pronounced when rainfall in the previous twelve months is considered (Supplementary Table 4). This means that as well as being reliant on rainfall while growing, wheat is also dependent on longer-term antecedent rainfall variability, most likely through its impact on soil moisture. The correlations between wheat-yield and longer-term variability appear to be maximised using rainfall in the preceding twelve-month period. Correlations using rainfall in the preceding twenty four months are not as large, however, still statistically significant (Supplementary Table 4).

Years with observed extreme events are associated with poor yields, and SEA is more susceptible to these extreme events than SWWA (Supplementary Table 5). The five lowest (de-trended) yields recorded in SEA occurred in 2006, 1982, 2007, 2002 and 1994, whilst 2002, 1980, 1969, 1914 and 2010 were the lowest (de-trended) yields recorded in SWWA (Supplementary Figures 1 & 2). In SEA, of the years that recorded the ten lowest (de-trended) yields, five are in the highest decile for the number of heat-days recorded and eight are in the lowest decile for annual rainfall recorded (Supplementary Table 5). In SWWA, of the years that recorded the ten lowest (de-trended) yields, four are in the highest decile for heat-day frequency and five are in the lowest decile for annual rainfall totals. As noted previously, correlations between rainfall and wheat yield are higher than those between heat-day frequency and wheat yield (see Figure 3). This analysis suggests that a possible reason for this is that high rainfall promotes a higher wheat yield and low rainfall suppresses yield, but that only a large number of heat-days affects the wheat yield – by reducing the average yield – with years with fewer heat-days having no effect on the yield (Supplementary Table 5).

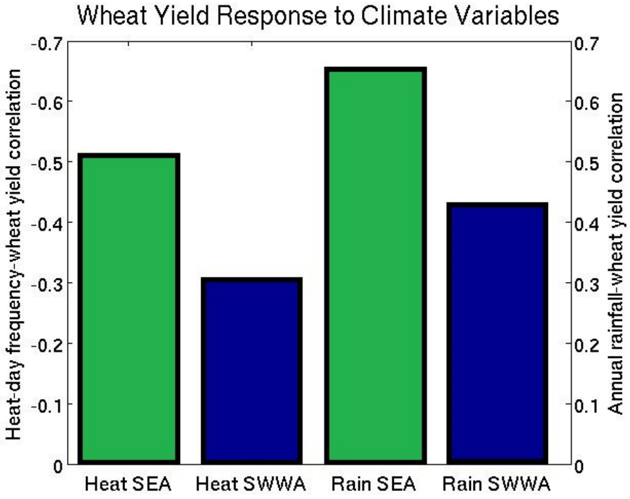

Figure 3 Correlations between wheat yields and annual heat-day frequency ('Heat'; left) and wheat yields and annual rainfall totals ('Rain'; right) in SEA (green) and SWWA (blue) regions using data from 1911 to 2012.

3.4 Interaction between heat-day frequency and rainfall on wheat yields

A large proportion of the correlation between monthly heat-day frequency and annual wheat yields can be explained by the correlations between wheat yields and rainfall. This can be determined by noting the lower number of underlined entries in Supplementary Table 6 compared the number of underlined entries in Supplementary Table 3. Only a small number of months have statistically significant correlations between the number of heat-days and wheat yield once the effect of either contemporaneous (occurring in the same year) or cumulative (occurring over the previous twelve months) rainfall is removed (Figure 4). These results are found by regressing wheat yield against rainfall data and then regressing the residuals from this first regression against the number of heat-days in each month. Correlations between rainfall and wheat yields, where the effect of the number of heat-days on wheat yield has been removed, are compiled in Supplementary Table 7, with the strongest statistically significant correlations being found in September in both regions. These results are very similar to those shown in Supplementary Table 4, indicating that it is rainfall variability that explains some of the correlations between extreme temperatures and wheat yields and not vice versa.

A key result of this analysis is that in SEA the number of heat-days in August and September is negatively correlated with wheat yield, when the rainfall from the previous twelve months is removed. Similarly for SWWA, September and October are the crucial months for the impact of extreme heat on wheat yields.

Furthermore, statistically significant correlations between wheat yields and the number of heat-days in September only occur if rainfall in the preceding twelve months is below median (SEA: $R = -0.40$, $p<0.01$; SWWA: $R = -0.38$, $p<0.01$). If the previous twelve months' rainfall is above median then the correlation between wheat yield and the number of heat-days is not statistically significant at the five per cent level (SEA: $R = -0.17$, $p = 0.22$; SWWA: $R = -0.13$ $p = 0.36$). These results are shown graphically in Figure 5. This means that, on average, during drought or dry conditions, the wheat yield is sensitive to the number of days with temperatures above the September 90^{th} percentile ($24.1^{o}C$ in SEA, $25.2^{o}C$ in SWWA), but if the previous twelve months are wetter than normal, then the impact of extreme temperatures on wheat yields is reduced. This is true in both SEA and SWWA.

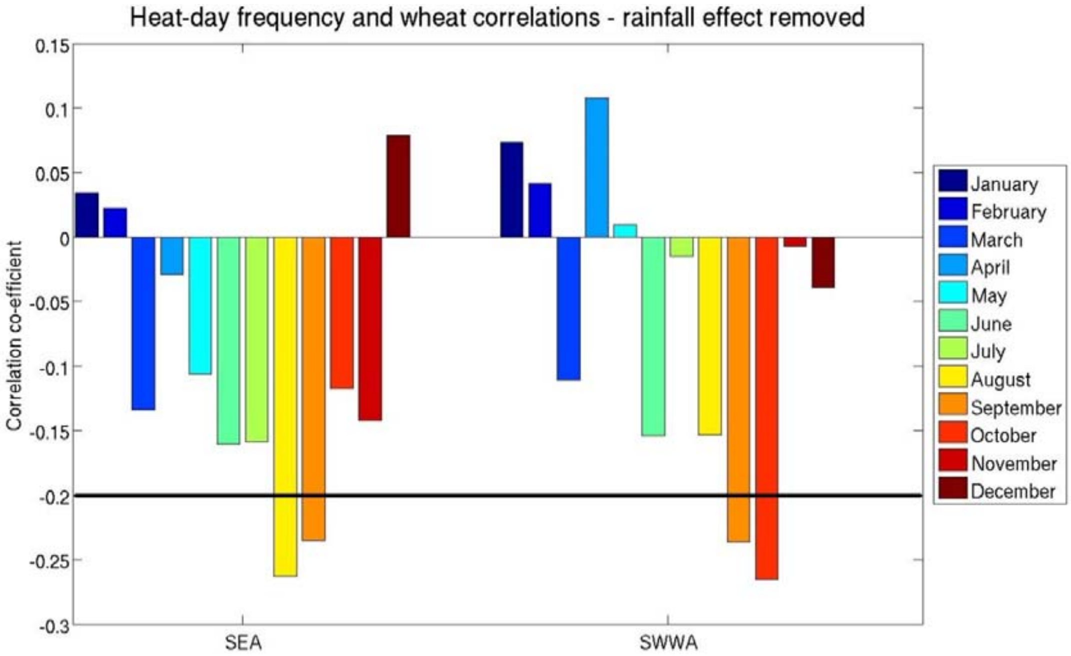

Figure 4 Correlations between heat-day frequency and wheat yield by month in SEA (left) and SWWA (right) regions using data from 1911 to 2012. The black line indicates the minimum magnitude of correlation required for a statistically significant relationship.

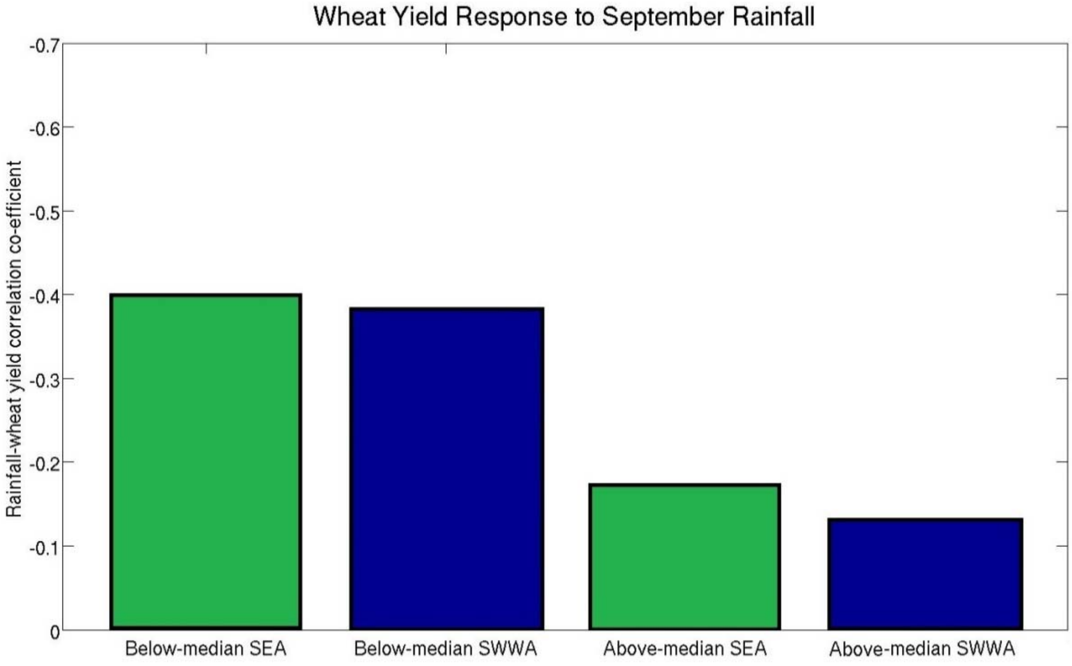

Figure 5 Correlations between below-median (left) and above-median (right) September rainfall and wheat yield in SEA (green) and SWWA (blue) regions using data from 1911 to 2012.

Further analysis finds that if two out of the three seasons (summer, autumn and winter) that precede the spring of the wheat harvest are dry (below 30th percentile) then wheat yield is negatively correlated with the number of heat-days, but there is no correlation if two of the three preceding seasons are wet (above 30th percentile). The statistical significance of these results are diminished compared to the twelve-monthly results because two conditions (e.g. summer rainfall below 30th percentile and autumn rainfall below 30th percentile) are required to select the years rather than one (e.g. summer rainfall below 30th percentile).

3.5 Effects of heatwaves on wheat yields

The effect of the number of consecutive heat-days (i.e. heatwaves) in a month on wheat yields is generally less significant than the effect of the (total) number of heat-days in a month. However, the months for which statistically significant relationships are found differ (Supplementary Table 8).

On an annual basis, the correlations between wheat yields and the number of heatwaves are stronger in SEA than SWWA, and longer heatwaves are generally more weakly correlated to the wheat yields than just the total number of heat days (Figure 6). This provides observational evidence for the experimental results of Talukder et al. (2010) and Alexander et al. (2010) suggest that single days of extreme heat can do just as much damage to the wheat crop as runs of these extreme days.

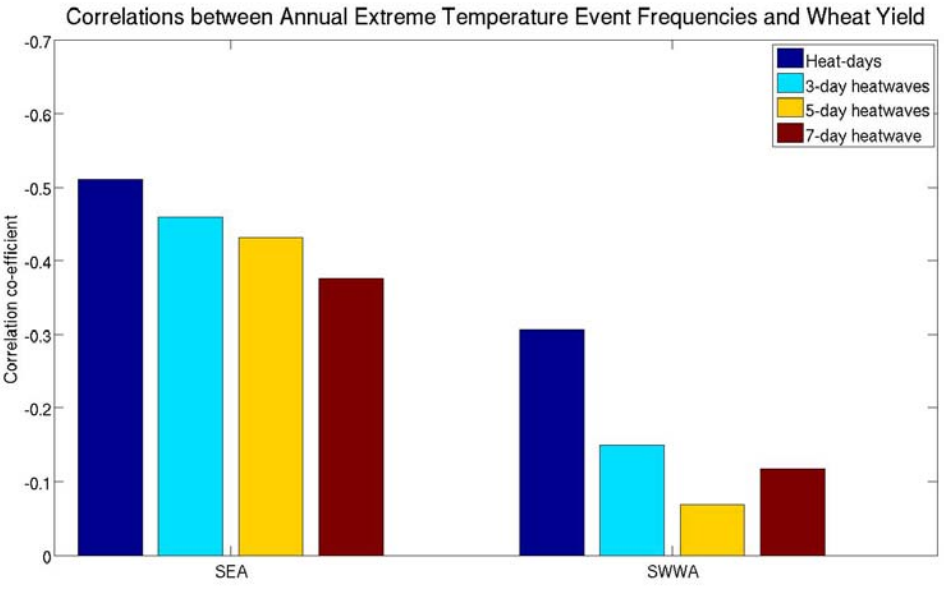

Figure 6 Correlations between heat-day and heatwave frequency and wheat yield in SEA (left) and SWWA (right) regions using data from 1911 to 2012.

3.6 The effect of climate drivers on wheat yields

Climate modes or drivers are potentially useful predictors of wheat yields as seasonal climate prediction is largely based upon climate modes of variability. This analysis uses indices for the IOD, ENSO and SAM climatic modes of variability. Regressions using a variety of starting months and averaging period lengths for each variable are conducted. These regressions aim to establish the temporal nature and relative strengths of the relationships between climate drivers and wheat yields. This includes identifying the time periods where driver-yield correlations are maximised and whether any time lags exist between the two variables. The full results are shown in Supplementary Tables 9-14. This analysis shows that the DMI is the driver best-correlated to wheat yields in SEA (largest magnitude R = –0.46) and is also significantly correlated to SWWA yields (largest magnitude R= –0.26). SAM is best correlated driver in SWWA largest magnitude R=+0.27), and is significantly correlated to SEA yields (largest magnitude R=+0.23). The SOI is significantly correlated to SEA yields (largest magnitude R=+0.38) but there were no statistically significant correlations over tested periods in SWWA.

Mann Whitney U-Tests were conducted for the SEA and SWWA regions to test if there is a difference in the mean detrended wheat yield in years where certain IOD conditions and certain ENSO conditions prevail. For this analysis, the classifications of the years 1887 to 1998 by Meyers et al. (2007) into IOD states: 'positive', 'no event' or 'negative ' and ENSO states: 'El Niño', 'no event' or 'La Niña' are used. These classifications have subsequently been extended to 2008, as used by Ummenhoffer et al. (2009). Analysis of years between 1900 and 2008 finds that the occurrence of a positive IOD and/or an El Niño corresponds to a statistically significant reduction in wheat yield compared to years where other IOD or ENSO states occurred. The results for SEA wheat yields are shown in Table 3, SWWA results are not shown as none were statistically significant.

	'La Niña'	*'Neg. IOD'*	*'La Niña' + 'Neg. IOD'*	*'No ENSO'*	*'No IOD'*	*'No IOD' + 'No ENSO'*	*'El Niño' + 'Pos. IOD'*
'El Niño'	**p=0.007**	**p=0.011**	**p=0.023**	**p=0.042**	**p=0.018**	**p=0.010**	p=0.712
'Pos. IOD'	**p=0.004**	**p=0.001**	**p=0.020**	**p=0.032**	**p=0.011**	**p=0.008**	p=0.721

Table 3 Statistical significance (using Mann-Whitney U-tests), denoted by underlined text, of changes in mean wheat yields in El Niño years (first row) or Positive IOD years (second row) compared to years where other ENSO and IOD states prevailed (the various columns). Each year was classified for both ENSO and IOD states. Bold text indicates that the climatic conditions described in the row title (i.e. El Niño or Positive IOD) were associated with a reduction in wheat yield when compared to the climatic conditions described in the column title. Non-bold text indicates that the climatic conditions described in the row title were associated with an increase in wheat yield when compared to the climatic conditions described in the column title.

Risbey et al. (2009) find that years in which El Niño and positive IOD events occur concurrently are much drier than the years in which just an El Niño event occurs or just a positive IOD event occurs. Here it is found that there was no statistically significant 'added loss' resulting from simultaneously occurring positive IOD and El Niño states meaning that this additional dryness does not appear to produce lower wheat yields (Table 3).

The average annual wheat yield loss associated with El Niño state and/or positive IOD state in SEA is estimated to around sixteen to twenty one per cent using the aforementioned extended IOD/ENSO classification data set. This estimate is obtained using two separate methods. In the first method, the overall mean wheat yield is added to the de-trended SEA wheat yield values thus creating an anomaly. The percentage difference between the overall mean and the mean yields in both El Niño and positive IOD years is then calculated. The second method is identical to the first, except that raw SEA wheat yield data (i.e. including technological advances and other factors) are used instead of the anomaly value. The first method produces estimates of sixteen per cent loss in El Niño years and eighteen per cent loss in positive IOD years. The second method produces estimates of twenty one per cent loss in El Niño years and nineteen per cent loss in positive IOD years.

3.7 Future projections of wheat yields under climate change

It has been noted that wheat yields have been increasing in the southern grain growing regions in recent decades, and that this is a consequence of agricultural advances (e.g. farming technology, fertilisers and cultivars) as well as potentially due to warming minimum temperatures (Nicholls 2007). Whilst further agricultural advances are possible and likely (Zhang et al. 2012), removal of these influences still shows a sensitivity of wheat yields to natural climate variability.

The sensitivity of wheat to warmer and drier conditions is potentially important for yields in a changing climate, and especially changes in the frequency of extreme weather and climate events. There has been a ten to twenty per cent observed reduction in April to September rainfall since the 1970s in SWWA and since the mid-1990s in SEA (Braganza et al. 2011). These reductions have been associated with circulation changes in the southern hemisphere that are in turn partly attributable to climate change (Braganza et al. 2015). Arblaster et al. (2014) estimate that fifteen per cent of the above-average temperatures in the record-breaking heat of September 2011 in Australia could be attributed to global-mean temperature increases due to climate change.

Under climate change, rainfall across large parts of Australia is expected to decrease in winter and spring, while temperatures are expected to increase. Given their strong dependence on rainfall especially, but also the incidence of extreme heat in spring, future wheat yields may be expected to be adversely impacted by projected future climate change, in the absence of suitable adaptation practices. For SWWA, the most severe climate change scenario (RCP8.5), projects annual rainfall to be 5 per cent to 37 per cent less in 2090 relative to 1985-2005, with the largest decreases in winter (–44 per cent to –15 per cent) and spring (–59 per cent to –14 per cent) (Hope et al. 2015). There is high confidence of increased frequency and severity of droughts. The same study, under the same high emissions scenario, projects there to be an increase in annual daytime maximum temperatures of between 2.7oC and 4.5oC in SWWA by 2090, with even greater (between 3.1oC and 5.1oC) increases in spring. This means that projected temperature increases in September and October may exacerbate the effect of drought and cause further declines in wheat yields than would be expected from just rainfall decline alone. This is because it would be expected that increasing average temperatures cause more exceedances of the 1911-2013 monthly 90th percentiles used to measure heat-day frequency in this study.

In SEA, there is less certainty of decrease in rainfall with Timbal et al. (2015) projecting a slight annual decrease most likely, under the RCP8.5 climate change scenario for 2090. They note, however, that larger decreases in winter and spring are possible and they have medium confidence that drought frequency and severity will increase. The same study, under the same high emissions scenario used by Hope et al. (2015), projects there to be an increase in annual daytime maximum temperatures of between 2.9°C and 5.0°C in SEA by 2090, with even greater (between 3.1°C and 5.8°C) increases in spring. Asseng et al. (2015) estimate that under a scenario equivalent to RCP8.5 (IPCC 2013), reductions in average yield of twenty four to twenty eight per cent at Kojonup in SWWA, and twelve to sixteen per cent at Griffith in SEA, are possible by the end of the 21st century.

4. Conclusion

Overall, the number of days with maximum temperatures above the monthly 90th percentile (i.e. heat-days) has experienced statistically significant increases across most months across much of Australia, particularly in SA, WA, NT and Tasmania, especially in winter. The temperatures recorded on these heat-days have also exhibited significant increases over the last 100 years. In many cases the increases in temperatures have been more statistically significant than the increases in the number of heat-days.

We find that wheat yields are correlated to rainfall more strongly than to the number of heat-days. However, antecedent low rainfall leads to the number of heat days recorded (in August and September in SEA and September and October in SWWA) having a strong influence on wheat yields. Additionally, the effect of extreme weather and climate events appears to more strongly influence the occurrence of below-average yields than above-average yields. Future work could focus on building a framework for operational seasonal predictions of wheat growing conditions using the relationships between the Indian Ocean Dipole, El Niño Southern Oscillation and Southern Annular Mode and wheat yields identified in the study. We find that positive IOD events and El Niño events are associated with wheat crop losses, typically about sixteen to twenty one per cent below average.

Whilst this study is general in its discussion of future wheat yields under climate change scenarios, projected decreases in rainfall, especially in SWWA, and increases in daytime maximum temperatures in both regions could be expected to negatively impact wheat yields in the future. Future work extending the predictions of Asseng et al. (2015) to the full SEA and SWWA regions would be beneficial to inform policy and practices for adaptation to these future climate changes.

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7. Supplementary Section

	VIC	*TAS*	*SA*	*WA*	*NT*	*QLD*	*NSW/ACT*	*SWWA*	*SEA*
Jan	34.61	24.29	39.70	39.06	39.47	37.85	37.02	37.72	37.17
Feb	33.77	24.08	38.76	38.36	38.67	36.77	35.89	37.42	36.21
Mar	30.81	22.15	35.89	36.56	37.26	35.09	32.95	34.99	32.96
Apr	25.56	18.59	31.22	33.19	34.98	32.66	28.36	30.34	28.05
May	20.17	14.98	26.01	28.57	31.54	29.06	23.65	25.05	22.60
Jun	15.51	12.31	21.53	24.40	29.03	26.50	19.10	20.68	17.66
Jul	14.69	11.49	21.09	23.99	28.65	26.12	18.46	19.34	16.85
Aug	17.28	12.62	24.30	26.57	31.28	28.38	21.32	21.34	19.75
Sep	21.13	14.90	29.02	30.70	34.96	32.20	26.19	25.23	24.07
Oct	25.38	17.70	33.33	34.35	37.98	35.19	30.02	29.49	28.60
Nov	29.69	20.08	36.60	36.73	39.35	37.03	33.78	33.52	33.04
Dec	32.42	22.03	38.26	38.24	39.67	38.05	35.82	36.20	35.44

Supplementary Table 1: 90th percentiles for area-averaged daily maximum temperature in all study regions calculated over the 1911–2013 period. The calculations are stratified by calendar month.

Metric	*VIC*	*TAS*	*SA*	*WA*	*NT*	*QLD*	*NSW*	*SWWA*	*SEA*
Yearly	1.24 p<0.01 (2.89%)	4.67 p<0.01 (12.76%)	4.08 p<0.01 (11.17%)	6.61 p<0.01 (18.01%)	3.81 p<0.01 (10.40%)	1.49 p<0.01 (4.07%)	0.94 p<0.01 (2.58%)	1.50 p<0.01 (4.15%)	1.19 p=0.01 (3.28%)
Summer	0.28 p=0.08 (3.10%)	1.14 p<0.01 (12.64%)	0.91 p<0.01 (10.03%)	1.37 p<0.01 (15.13%)	0.61 p=0.02 (6.73%)	–0.18 p=0.51 (–2.0%)	–0.14 p=0.52 (–1.59%)	0.16 p=0.26 (1.77%)	0.14 p=0.41 (1.61%)
Autumn	0.24 p=0.132 (2.62%)	1.20 p<0.01 (13.07%)	0.83 p<0.01 (8.97%)	1.49 p<0.01 (16.17%)	0.73 p=0.03 (7.86%)	0.09 p=0.77 (0.98%)	0.10 p=0.63 (1.03%)	0.50 p<0.01 (5.48%)	0.29 p=0.08 (3.21%)
Winter	0.34 p=0.04 (2.78%)	1.29 p<0.01 (14.08%)	1.23 p<0.01 (13.42%)	2.08 p<0.01 (22.42%)	1.12 p<0.01 (12.13%)	0.78 p<0.01 (8.49%)	0.68 p<0.01 (7.38%)	0.65 p<0.01 (7.09%)	0.47 p=0.012 (5.04%)
Spring	0.34 p=0.086 (2.74%)	1.00 p<0.01 (10.97%)	1.08 p<0.01 (11.82%)	1.65 p<0.01 (17.97%)	1.33 p<0.01 (14.62%)	0.75 p<0.01 (8.19%)	0.26 p=0.265 (2.80%)	0.14 p=0.344 (1.52%)	0.24 p=0.223 (2.65%)
3-day	0.59 p<0.01 (6.52%)	1.47 p<0.01 (20.62%)	1.70 p<0.01 (17.49%)	2.91 p<0.01 (23.33%)	2.02 p<0.01 (14.79%)	0.61 p=0.142 (4.27%)	0.61 p=0.017 (5.49%)	0.29 p=0.052 (5.03%)	0.58 p<0.01 (5.96%)
5-day	0.29 p<0.01 (12.8%)	0.45 p<0.01 (25.66%)	0.73 p<0.01 (22.17%)	1.22 p<0.01 (26.31%)	0.94 p<0.01 (17.39%)	0.17 p=0.484 (2.84%)	0.37 p<0.01 (9.71%)	0.02 p=0.732 (1.74%)	0.22 p=0.052 (7.30%)
7-day	0.17 p<0.01 (21.8%)	0.14 p<0.01 (28.70%)	0.36 p<0.01 (27.07%)	0.51 p<0.01 (28.92%)	0.37 p<0.01 (16.85%)	–0.06 p=0.681 (–2.38%)	0.22 p<0.01 (15.27%)	–0.00 p=0.988 (–0.17%)	0.13 p<0.01 (12.69%)

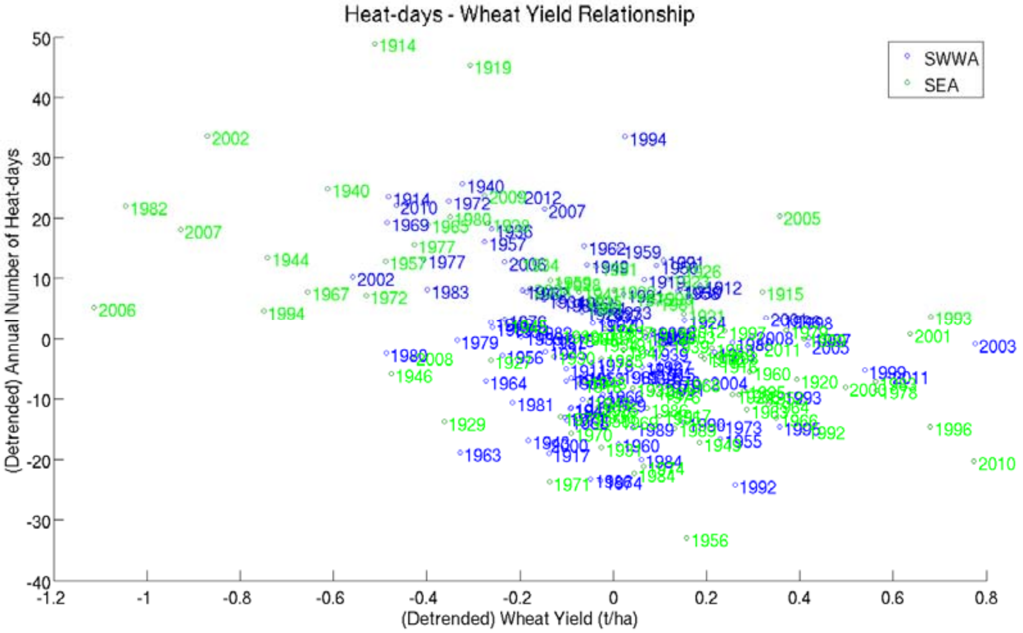
Supplementary Table 2: Trends in the number of yearly and seasonally aggregated heat-days and 3-day, 5-day and 7-day heatwaves per decade, the significance of those trends, and the trends expressed as the percentage change (per decade) for Victoria, Tasmania, South Australia, Western Australia, the Northern Territory, Queensland, New South Wales (includes Australian Capital Territory) and the two wheat regions defined in Figure 1, calculated over the 1911–2013 period. Underlined results have p-values of 0.05 or less. The heatwaves are defined in such a way that a 6-day heatwave is counted as four 3-day heatwaves and two 5-day heatwaves.

Accumulation Period	*SEA Heat-days – Wheat Correlation*	*SWWA Heat-days – Wheat Correlation*
January	0.02 (p=0.83)	-0.07 (p=0.49)
February	0.00 (p=1.00)	0.05 (p=0.65)
March	-0.17 (p=0.09)	-0.09 (p=0.37)
April	-0.06 (p=0.57)	0.13 (p=0.20)
May	-0.12 (p=0.22)	-0.01 (p=0.91)
June	-0.19 (p=0.06)	-0.19 (p=0.06)
July	-0.17 (p=0.10)	-0.09 (p=0.36)
August	-0.32 (p<0.01)	-0.26 (p<0.01)
September	-0.31 (p<0.01)	-0.32 (p<0.01)
October	-0.44 (p<0.01)	-0.35 (p<0.01)
November	-0.43 (p<0.01)	-0.14 (p=0.18)
December	-0.24 (p<0.01)	-0.17(p=0.09)
Yearly	-0.51 (p<0.01)	-0.31 (p<0.01)

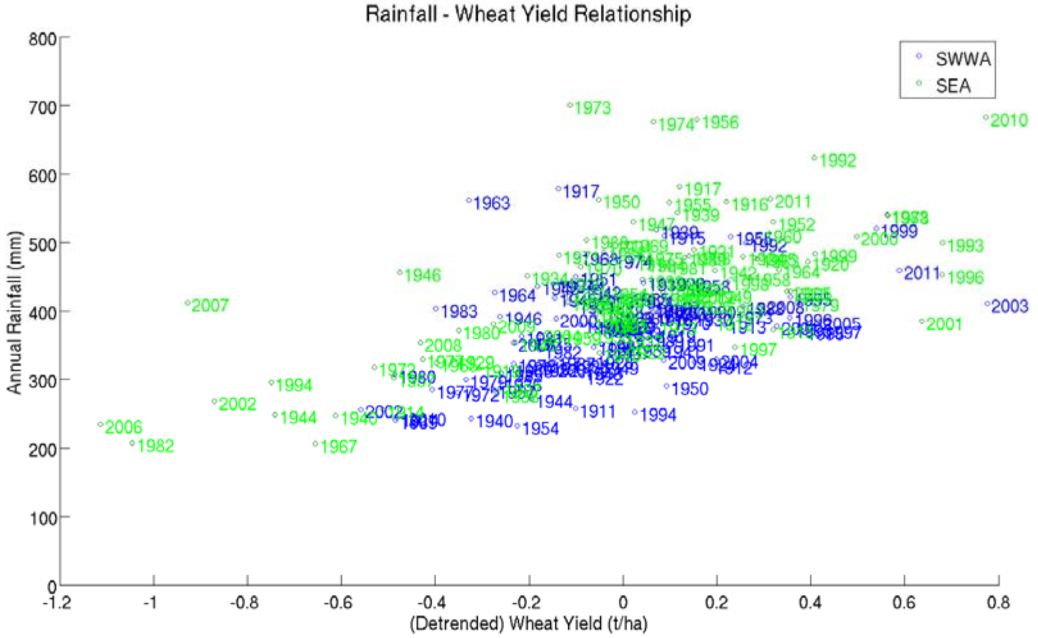
Supplementary Table 3: Correlations between the number of heat-days and wheat yields in each month and annually, using de-trended wheat and heat-days data for the two wheat regions defined in Figure 1, calculated over the 1911–2012 period. Underlined results have p-values of 0.05 or less.

Accumulation Period	*SEA Rainfall – Wheat Correlation Contemporaneous*	*SWWA Rainfall – Wheat Correlation Contemporaneous*	*SEA Rainfall – Wheat Correlation Cumulative*	*SWWA Rainfall – Wheat Correlation Cumulative*
January	0.11 (p=0.29)	0.03 (p=0.80)	0.04 (p=0.66)	-0.24 (p=0.02)
February	0.05 (p=0.61)	0.17 (p=0.09)	0.07 (p=0.48)	-0.16 (p=0.11)
March	0.17 (p=0.09)	0.12 (p=0.24)	0.12 (p=0.22)	-0.09 (p=0.37)
April	0.04 (p=0.66)	0.16 (p=0.10)	0.12 (p=0.20)	-0.05 (p=0.61)
May	0.28 (p<0.01)	0.24 (p=0.02)	0.16 (p=0.01)	0.09 (p=0.38)
June	0.26 (p<0.01)	0.02 (p=0.78)	0.21 (p=0.03)	0.13 (p=0.20)
July	0.39 (p<0.01)	0.16 (p=0.11)	0.30 (p<0.01)	0.17 (p=0.09)
August	0.51 (p<0.01)	0.21 (p=0.03)	0.42 (p<0.01)	0.25 (p<0.01)
September	0.61 (p<0.01)	0.48 (p<0.01)	0.52 (p<0.01)	0.33 (p<0.01)
October	0.48 (p<0.01)	0.25 (p=0.01)	0.62 (p<0.01)	0.39 (p<0.01)
November	0.31 (p<0.01)	0.09 (p=0.34)	0.66 (p<0.01)	0.42 (p<0.01)
December	0.13 (p=0.19)	0.04 (p=0.70)	0.65 (p<0.01)	0.43 (p<0.01)

Supplementary Table 4: Correlations between the amount of rainfall and wheat yield in each month, using de-trended wheat data for the two wheat regions defined in Figure 1, calculated over the 1911–2012 period. The 'Contemporaneous' correlations use rainfall totals from only the month in the accumulation period, whereas the 'Cumulative' correlations use rainfall totals from the 12 months up-to-and-including the month stated in the accumulation period (thus the December correlations in the cumulative column represent the correlations between annual rainfall and wheat yield). Underlined results have p-values of 0.05 or less.



Supplementary Figure 1: Scatter plot showing the relationship between the number of (de-trended) heat-days and the (de-trended) wheat yield in a given year in the 1911–2012 period. Values and years labelled for SWWA are shown in blue, and values and years labelled for SEA are shown in green.



Supplementary Figure 2: Scatter plot showing the relationship between the yearly rainfall totals and the (de-trended) wheat yield in a given year in the 1911–2012 period. Values and years labelled for SWWA are shown in blue, and values and years labelled for SEA are shown in green.

SEA		*SWWA*	
Years with lowest yields	Years with highest yields	Years with lowest yields	Years with highest yields
2006^{R}, 1982^{RT}, 2007^{T}, 2002^{RT}, 1994^{R}, 1944^{R}, 1967^{RT}, 1940^{RT}, 1972, 1914^{RT}.	2010^{R}, 1993, 1996, 2001, 1978, 1983, 2000, 1999, 1992^{R}, 1920.	2002^{RT}, 1980, 1969^{RT}, 1914^{R}, 2010^{RT}, 1977, 1983, 1972^{RT}, 1979, 1963.	2003, 2011, 1999^{R}, 1997, 2005, 1998, 1993, 1995, 1996, 2001

Supplementary Table 5: Table with the years with highest and lowest de-trended yields in the SEA and SWWA wheat regions over the 1911–2012 period. Years are listed in order of decreasing anomaly. R superscript denotes that the annual yearly rainfall of the noted year was in either the lowest decile (for 'lowest yields' columns) or highest decile (for 'highest yields' columns). T superscript denotes that the number of heat-days recorded in the noted year was either in the highest decile (for 'lowest yields' columns) or lowest decile (for 'highest yields' columns).

Accumulation Period	*SEA Contemporaneous*	*SWWA Contemporaneous*	*SEA Cumulative*	*SWWA Cumulative*
January	0.06 (p=0.57)	–0.08 (p=0.45)	0.03 (p=0.73)	0.07 (p=0.47)
February	0.01 (p=0.88)	0.05 (p=0.64)	0.02 (p=0.82)	0.04 (p=0.68)
March	–0.13 (p=0.18)	0.12 (p=0.24)	–0.13 (p=0.19)	–0.11 (p=0.27)
April	–0.05 (p=0.63)	0.18 (p=0.07)	–0.03 (p=0.77)	0.11 (p=0.28)
May	–0.07 (p=0.51)	0.04 (p=0.66)	–0.11 (p=0.29)	0.01 (p=0.93)
June	–0.17 (p=0.08)	–0.20 (p=0.05)	–0.16 (p=0.11)	–0.15 (p=0.12)
July	–0.04 (p=0.07)	–0.03 (p=0.79)	–0.16 (p=0.11)	–0.01 (p=0.88)
August	–0.03 (p=0.74)	–0.20 (p=0.04)	–0.26 (p<0.01)	–0.15 (p=0.12)
September	–0.11 (p=0.28)	0.05 (p=0.59)	–0.24 (p=0.02)	–0.24 (p=0.02)
October	–0.18 (p=0.07)	–0.27 (p<0.01)	–0.12 (p=0.24)	–0.27 (p<0.01)
November	–0.32 (p<0.01)	–0.09 (p=0.35)	–0.14 (p=0.16)	–0.01 (p=0.94)
December	–0.20 (p=0.05)	–0.16 (p=0.10)	0.08 (p=0.43)	–0.04 (p=0.70)
Yearly	–0.11 (p=0.25)	–0.02 (p=0.80)		

Supplementary Table 6: Correlations between the number of heat-days and wheat yields, in each month and annually, once the effect of rainfall is removed, using de-trended wheat data for the two wheat regions defined in Figure 1, calculated over the 1911–2012 period. The 'Contemporaneous' correlations use rainfall totals from only the month in the accumulation, whereas the 'Cumulative' correlations use rainfall totals from the 12 months up-to-and-including the month stated in the accumulation period. Both periods however use the contemporaneous number of heat-days not the number of heat-days over the last 12 months. This is to test the effect that extreme temperatures have on wheat yield in tandem with prolonged dry conditions. Underlined results have p-values of 0.05 or less.

Accumulation Period	*SEA*	*SWWA*
January	0.11 (p=0.26)	-0.04 (p=0.68)
February	0.06 (p=0.61)	0.17 (p=0.09)
March	0.14 (p=0.18)	0.09 (p=0.36)
April	0.03 (p=0.76)	0.20 (p=0.04)
May	0.26 (p<0.01)	0.24 (p=0.02)
June	0.25 (p=0.01)	-0.08 (p=0.42)
July	0.34 (p<0.01)	0.12 (p=0.23)
August	0.34 (p<0.01)	0.14 (p=0.16)
September	0.52 (p<0.01)	0.31 (p<0.01)
October	0.24 (p=0.02)	0.13 (p=0.18)
November	0.14 (p=0.15)	0.04 (p=0.72)
December	0.04 (p=0.65)	0.02 (p=0.87)
Yearly	0.37 (p<0.01)	0.24 (p=0.01)

Supplementary Table 7: Correlations between contemporaneous rainfall and wheat yields, in each month and annually, once the effect of the number of heat-days is removed, using de-trended wheat data for the two wheat regions defined in Figure 1, calculated over the 1911–2012 period.

	SEA		*SWWA*	
	Contemporaneous	*Cumulative*	*Contemporaneous*	*Cumulative*
3-day heatwaves	November (R=-0.21)	August (R=-0.23) July (R=-0.20)	November (R=-0.21)	-
5-day heatwaves	-	July (R=-0.20)	December (R=+0.25)	December (R=+0.20)

Supplementary Table 8: Statistically-significant correlations between de-trended wheat yields and the de-trended numbers of heatwaves of varying lengths in different months of the year, once the effect of either contemporaneous or cumulative rainfall is removed, are shown. Note that by definition of heatwaves one 5-day heatwave is equivalent to three 3-day heatwaves. 3-day and 5-day heatwaves for both SEA and SWWA regions defined in Figure 1 for each month were calculated over the 1911–2012 period, however only the results statistically significant to the 5% level are shown.

Start Month	*1*	*2*	*3*	*4*	*5*	*Averaging 6*	*Period 7*	*Length 8*	*9*	*10*	*11*	*12*
Sep*	-0.07	-0.10	-0.11	-0.10	-0.13	-0.16	-0.16	-0.14	-0.10	-0.06	-0.01	0.03
Oct*	-0.1	-0.13	-0.11	-0.14	-0.17	-0.18	-0.15	-0.10	-0.06	-0.00	0.04	0.09
Nov*	-0.12	-0.10	-0.14	-0.18	-0.18	-0.14	-0.10	-0.05	0.02	0.06	0.11	0.14
Dec*	-0.05	-0.14	-0.18	-0.18	-0.14	-0.08	-0.03	0.04	0.09	0.13	0.16	0.18
Jan	-0.19	-0.24	-0.22	-0.15	-0.09	-0.02	0.06	0.11	0.15	0.18	0.20	0.21
Feb	-0.22	-0.20	-0.12	-0.04	0.02	0.11	0.15	0.20	0.22	0.24	0.25	
Mar	-0.13	-0.05	0.03	0.10	0.18	0.22	0.26	0.28	0.29	0.29		
Apr	0.02	0.12	0.18	0.25	0.28	0.32	0.33	0.33	0.33			
May	0.20	0.25	0.31	0.33	0.36	0.36	0.36	0.36				
Jun	0.22	0.32	0.34	0.37	0.37	0.37	0.36					
Jul	0.38	0.37	**0.38**	**0.38**	0.37	0.37						
Aug	0.31	0.35	0.36	0.35	0.34							
Sep	0.36	0.35	0.34	0.34								
Oct	0.30	0.30	0.31									
Nov	0.25	0.28										
Dec	0.25											

Supplementary Table 9: Correlations between de-trended wheat yields and the de-trended Southern Oscillation Index (SOI), where the monthly SOI values were averaged over different periods with varying starting months and averaging period lengths, for the SEA region defined in Figure 1, calculated over the 1900–2012 period, were obtained. Underlined results have p-values of 0.05 or less. The triangular structure is due to correlations that do not exhibit the correct temporal relationship being removed (e.g. Hill 1965). The maximum absolute correlation is shown in red. Asterisked months indicate a one year lag in the driver data.

Start						*Averaging*	*Period*	*Length*				
Month	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Sep*	-0.07	-0.07	-0.06	-0.04	-0.03	-0.04	-0.03	-0.04	-0.04	-0.02	0.01	0.02
Oct*	-0.07	-0.05	-0.02	-0.02	-0.03	-0.02	-0.03	-0.04	-0.01	0.02	0.03	0.05
Nov*	-0.02	0.00	0.01	-0.02	-0.01	-0.03	-0.03	-0.00	0.03	0.05	0.06	0.07
Dec*	0.02	0.02	-0.01	-0.01	-0.03	-0.03	-0.00	0.04	0.05	0.07	0.07	0.09
Jan	0.01	-0.03	-0.02	-0.04	-0.04	-0.01	0.04	0.06	0.07	0.07	0.09	0.11
Feb	-0.07	-0.03	-0.05	-0.05	-0.01	0.04	0.06	0.07	0.08	0.09	0.11	
Mar	0.01	-0.04	-0.04	0.01	0.07	0.08	0.09	0.09	0.11	0.12		
Apr	-0.07	-0.05	0.01	0.08	0.09	0.10	0.10	0.11	0.13			
May	-0.02	0.06	0.13	0.13	0.13	0.13	0.14	0.16				
Jun	0.12	0.18	0.17	0.16	0.15	0.16	0.18					
Jul	0.23	0.18	0.17	0.15	0.16	0.18						
Aug	0.10	0.12	0.11	0.13	0.16							
Sep	0.12	0.11	0.13	0.16								
Oct	0.08	0.13	0.17									
Nov	0.14	0.20										
Dec	**0.22**											

Supplementary Table 10: Correlations between de-trended wheat yields and the de-trended Southern Oscillation Index (SOI), where the monthly SOI values were averaged over different periods with varying starting months and averaging period lengths, for the SWWA region defined in Figure 1, calculated over the 1900–2012 period, were obtained. Bolded results have p-values of 0.05 or less. The triangular structure is due to correlations that do not exhibit the correct temporal relationship being removed (e.g. Hill 1965). The maximum absolute correlation is shown in red. Asterisked months indicate a one year lag in the driver data.

Start						*Averaging*	*Period*	*Length*				
Month	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Sep*	0.11	0.11	0.11	0.10	0.09	0.10	0.08	0.06	0.01	-0.04	-0.10	-0.15
Oct*	0.10	0.11	0.09	0.07	0.08	0.07	0.04	-0.02	-0.07	-0.14	-0.19	-0.25
Nov*	0.11	0.07	0.04	0.06	0.03	0.00	-0.06	-0.12	-0.19	-0.23	-0.29	-0.34
Dec*	-0.00	-0.02	0.02	-0.01	-0.04	-0.10	-0.16	-0.22	-0.27	-0.32	-0.36	-0.38
Jan	-0.03	0.02	-0.01	-0.04	-0.11	-0.17	-0.23	-0.27	-0.32	-0.37	-0.38	-0.37
Feb	0.07	0.01	-0.04	-0.12	-0.18	-0.24	-0.28	-0.33	-0.38	-0.39	-0.37	
Mar	-0.05	-0.09	-0.17	-0.23	-0.28	-0.31	-0.36	-0.40	-0.41	-0.39		
Apr	-0.12	-0.20	-0.26	-0.31	-0.34	-0.38	-0.42	-0.42	-0.40			
May	-0.24	-0.29	-0.33	-0.35	-0.39	-0.42	**-0.43**	-0.41				
Jun	-0.28	-0.33	-0.35	-0.39	-0.42	**-0.43**	-0.40					
Jul	-0.34	-0.35	-0.39	-0.42	-0.43	-0.40						
Aug	-0.33	-0.38	-0.43	-0.43	-0.40							
Sep	-0.41	-0.45	-0.44	-0.39								
Oct	-0.46	-0.43	-0.37									
Nov	-0.35	-0.25										
Dec	-0.04											

Supplementary Table 11: Correlations between de-trended wheat yields and the de-trended Dipole Mode Index (DMI), where the monthly DMI values were averaged over different periods with varying starting months and averaging period lengths, for the SEA region defined in Figure 1, calculated over the 1900–2012 period, were obtained. Underlined results have p-values of 0.05 or less. The triangular structure is due to correlations that do not exhibit the correct temporal relationship being removed (e.g. Hill 1965). The maximum absolute correlation is bolded. Asterisked months indicate a one year lag in the driver data.

Start						*Averaging*	*Period*	*Length*				
Month	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Sep*	0.03	0.04	0.02	-0.01	-0.06	-0.09	-0.10	-0.10	-0.12	-0.14	-0.17	-0.18
Oct*	0.04	0.01	-0.03	-0.10	-0.12	-0.14	-0.13	-0.15	-0.17	-0.20	-0.21	-0.23
Nov*	-0.04	-0.09	-0.17	-0.20	-0.19	-0.18	-0.19	-0.21	-0.23	-0.24	-0.25	-0.26
Dec*	-0.14	-0.23	-0.24	-0.21	-0.19	-0.20	-0.22	-0.24	-0.24	-0.25	**-0.26**	**-0.26**
Jan	-0.25	-0.23	-0.20	-0.18	-0.19	-0.21	-0.22	-0.23	-0.2	-0.25	**-0.26**	**-0.26**
Feb	-0.16	-0.13	-0.12	-0.14	-0.17	-0.19	-0.20	-0.22	-0.23	-0.24	-0.24	
Mar	-0.08	-0.07	-0.10	-0.14	-0.17	-0.19	-0.20	-0.21	-0.22	-0.23		
Apr	-0.05	-0.10	-0.15	-0.17	-0.19	-0.20	-0.22	-0.23	-0.23			
May	-0.12	-0.17	-0.19	-0.20	-0.21	-0.22	-0.23	-0.23				
Jun	-0.17	-0.20	-0.20	-0.21	-0.22	-0.23	-0.23					
Jul	-0.18	-0.19	-0.20	-0.21	-0.23	-0.23						
Aug	-0.18	-0.20	-0.21	-0.22	-0.22							
Sep	-0.20	-0.21	-0.23	-0.22								
Oct	-0.21	-0.23	-0.22									
Nov	-0.23	-0.21										
Dec	-0.13											

Supplementary Table 12: Correlations between de-trended wheat yields and the de-trended Dipole Mode Index (DMI), where the monthly DMI values were averaged over different periods with varying starting months and averaging period lengths, for the SWWA region defined in Figure 1, calculated over the 1900–2012 period, were obtained. Underlined results have p-values of 0.05 or less. The triangular structure is due to correlations that do not exhibit the correct temporal relationship being removed (e.g. Hill 1965). The maximum absolute correlation is bolded. Asterisked months indicate a one year lag in the driver data.

Start						*Averaging*	*Period*	*Length*				
Month	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Sep*	0.03	-0.04	-0.06	-0.06	-0.06	-0.05	-0.04	0.00	0.04	0.05	0.08	0.09
Oct*	-0.10	-0.10	-0.09	-0.07	-0.06	-0.05	-0.00	0.04	0.04	0.08	0.09	0.09
Nov*	-0.06	-0.05	-0.04	-0.03	-0.02	0.03	0.07	0.07	0.11	0.12	0.12	0.14
Dec*	-0.03	-0.00	0.00	0.02	0.06	0.11	0.10	0.14	0.15	0.14	0.17	0.19
Jan	0.03	0.03	0.04	0.09	0.15	0.14	0.16	0.17	0.16	0.18	0.20	0.21
Feb	0.02	0.04	0.11	0.16	0.16	0.17	0.17	0.16	0.19	0.21	0.21	
Mar	0.04	0.13	0.19	0.16	0.18	0.18	0.16	0.19	0.21	0.22		
Apr	0.17	0.21	0.17	0.19	0.19	0.17	0.20	0.22	0.22			
May	0.18	0.13	0.17	0.17	0.15	0.18	0.20	0.20				
Jun	0.04	0.11	0.12	0.11	0.15	0.17	0.18					
Jul	0.14	0.14	0.11	0.17	0.20	0.19						
Aug	0.08	0.06	0.14	0.17	0.17							
Sep	0.02	0.14	0.18	0.17								
Oct	0.21	**0.23**	0.19									
Nov	0.17	0.13										
Dec	0.06											

Supplementary Table 13: Correlations between de-trended wheat yields and the de-trended Southern Annular Mode (SAM) index, where the de-trended monthly SAM values were averaged over different periods with varying starting months and averaging period lengths, for the SEA region defined in Figure 1, calculated over the 1900–2012 period, were obtained. Underlined results have p-values of 0.05 or less. The triangular structure is due to correlations that do not exhibit the correct temporal relationship being removed (e.g. Hill 1965). The maximum absolute correlation is bolded. Asterisked months indicate a one year lag in the driver data.

Start						*Averaging*	*Period*	*Length*				
Month	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Sep*	0.03	0.01	0.08	0.10	0.12	0.14	0.16	0.19	0.22	0.20	0.21	0.23
Oct*	-0.00	0.09	0.11	0.13	0.15	0.17	0.20	0.22	0.21	0.21	0.24	0.24
Nov*	0.15	0.14	0.17	0.19	0.21	0.24	0.26	0.23	0.23	0.26	0.26	0.26
Dec*	0.09	0.18	0.19	0.22	0.24	0.26	0.23	0.23	0.26	0.25	0.26	0.26
Jan	0.19	0.20	0.22	0.24	**0.27**	0.24	0.22	0.24	0.23	0.24	0.24	0.26
Feb	0.15	0.17	0.21	0.25	0.21	0.20	0.22	0.20	0.21	0.22	0.24	
Mar	0.14	0.18	0.24	0.19	0.17	0.20	0.18	0.19	0.20	0.22		
Apr	0.16	0.23	0.17	0.16	0.18	0.17	0.18	0.19	0.21			
May	0.21	0.13	0.13	0.17	0.15	0.17	0.17	0.20				
Jun	0.01	0.05	0.11	0.10	0.13	0.14	0.16					
Jul	0.06	0.14	0.12	0.15	0.16	0.18						
Aug	0.15	0.12	0.15	0.16	0.19							
Sep	0.03	0.11	0.12	0.16								
Oct	0.14	0.14	0.17									
Nov	0.10	0.14										
Dec	0.14											

Supplementary Table 14: Correlations between de-trended wheat yields and the de-trended Southern Annular Mode (SAM) index, where the de-trended monthly SAM values were averaged over different periods with varying starting months and averaging period lengths, for the SWWA region defined in Figure 1, calculated over the 1900–2012 period, were obtained. Underlined results have p-values of 0.05 or less. The triangular structure is due to correlations that do not exhibit the correct temporal relationship being removed (e.g. Hill 1965). The maximum absolute correlation is bolded. Asterisked months indicate a one year lag in the driver data.