Theoretical and Applied Climatology
https://doi.org/10.1007/s00704-022-03936-6

ORIGINAL PAPER

Climate change in the temperature and precipitation at two contrasting sites of the Argentinean wheat region

Silvana Marisol Luján Basile[1] · **Jorge Alberto Tognetti**[2,3] · **Marcelo Luciano Gandini**[4] · **William John Rogers**[1,5]

Received: 19 April 2021 / Accepted: 8 January 2022

Abstract

Global climate change is shifting temperature and precipitation regimes, which is modifying the environments that define wheat yield and quality. The current work characterises the changes that have occurred in the thermal and hydric environment in two contrasting sites of the wheat-growing region of Argentina, allowing comparison between sites for these changes and for how the changes are accelerating. Temperature and precipitation variables were analysed by regression and trend testing (Mann Kendall), and future projections were made based upon significant relationships. The two sites compared were in the zones around the cities of Azul in the Province of Buenos Aires and Marcos Juárez in the Province of Córdoba, located approximately 500 km apart. The climate data analysed covered the period 1931–2014 for Azul and 1952–2014 for Marcos Juárez. At both sites, temperatures increased significantly in mean and extreme values over these periods, where the rate of change accelerated during the first years of the twenty-first century. The changes observed were in general more pronounced in Marcos Juárez than in Azul. Furthermore, in Marcos Juárez, mean precipitation increased from September to December and there was a higher frequency of extremes of precipitation greater than 100 mm in September and October during the early twenty-first century. Evidence was found for temperature rise and the occurrence of extreme temperature and precipitation events occurring differently between sites, as well as for its acceleration rate in the early twenty-first century. The projected future changes made implied that wheat yield is expected to suffer losses over the coming century.

1 Introduction

The burgeoning global demand for food, feedstuff and biocombustible, will require dramatic increases in wheat and other staple crop yields. According to Reynolds et al. (2009), increases of 50% in wheat yield are feasible, principally by improving potential yield (Hall and Richards 2013); however, to achieve this, it will be indispensable to reduce climate change and attenuate its effects upon crop yield (Asseng et al. 2015; IPCC 2018), many of them deleterious (World Bank 2013; Asseng et al. 2015; Zhao et al. 2017; IPCC 2018). In many areas of the world, climate change represents 32–39% of the annual global variability of yield for wheat, corn, soybeans, and rice (Ray et al. 2015). Furthermore, countries where increasing temperature causes negative impacts are typically the most food insecure (Agnolucci et al. 2020).

Mean earth surface temperature has risen constantly since the twentieth century, with the 2000s being the hottest to date. Also, the number and period of sub-zero temperature days have reduced almost without exception in each country where the variable has been examined (Stocker et al. 2013);

✉ Silvana Marisol Luján Basile
marisol_basile@yahoo.com.ar

[1] Laboratorio de Biología Funcional y Biotecnología (BIOLAB)-INBIOTEC-CONICET-CIC, Facultad de Agronomía, CIISAS, Universidad Nacional del Centro de la Provincia de Buenos Aires, Av. República de Italia 780, 7300 Azul, Argentina

[2] Laboratorio de Fisiología Vegetal, Facultad de Ciencias Agrarias, Universidad Nacional de Mar del Plata, Ruta 226 km 73,5, 7620 Balcarce, Argentina

[3] Comisión de Investigaciones Científicas de la Provincia de Buenos Aires (CIC), Buenos Aires, Argentina

[4] Laboratorio de Investigación y Servicios en Teledetección, Facultad de Agronomía, CIISAS, Universidad Nacional del Centro de la Provincia de Buenos Aires, Av. República de Italia 780, 7300 Azul, Argentina

[5] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina

this is despite the hiatus reported by Chen and Tung (2014) though refuted by De Saedeleer (2016). Also, since 1980, increases have been observed in temperature and precipitation for the main wheat crop regions, amongst other crop regions (maize, rice, and soybean) (Lobell et al. 2011).

The 2015 Paris Agreement includes the long-term global goal of promoting measures aimed at holding the increase in the global average temperature to well below 2 °C (1.5 °C, if possible) above pre-industrial levels (UNFCCC 2016). Future emissions are uncertain since they depend upon complex dynamic systems determined by demographic change, socio-economic development, technological advance, and political will. IPCC scenarios project mean global temperature rise of between 1.8 and 4 °C for the decade 2090–2099 compared to 1980–1999, with ranges between 1.1 and 6.4 °C (Nakicenovic et al. 2007; IPCC 2007a) and increments of 1 °C in mean global temperatures in the period 2016–2035 versus 1850–1900, under high greenhouse gas emission scenarios (Stocker et al. 2013). Furthermore, the atmosphere can retain an additional 7% of water vapour (Bréon et al., 2013).

The majority of analyses of long-term climate change have focussed on mean values, with less emphasis on extremes (Alexander et al. 2006). Climatic extremes can be categorised into two groups: those simply based upon climate statistics (very low and very high daily temperatures or large quantities of daily or monthly precipitation occurring over a year) or more complex extremes that do not necessarily occur each year at a given site (for example, drought, flood, or hurricane) (Easterling et al. 2000). Changes in temperature and precipitation extremes have been reported (Nicholls 1995; Karl and Knight 1998; Barros 2015) and coincide with a world undergoing heating: diminution in cold extremes and a rise in hot extremes (Easterling et al. 2000; Alexander et al. 2006; Barros 2015).

Hence, it is necessary to study the future environments each crop could face if current climate trends persist or even worsen. We have taken wheat as a study model for the present work, given its historical importance in Argentina.

Wheat, one of the most important cereals globally, is widely used for human and animal consumption. Worldwide, more than 200 million hectares is harvested, with China and India currently being the largest producers (FAO 2019). Argentina is one of the producing countries, contributing 2.4% of world production (FAO 2019), and an exporter, since current annual production (19 million tonnes in 2017/2018) far outstrips internal market requirements of 6 to 7 million tonnes (Ministerio de Agricultura de Argentina 2018). This, added to the proximity of Brazil and Mercosur, configures the country as an important exporter of the crop.

In wheat, as in other C3 crops, mean temperature mainly affects development throughout the cycle. However, during anthesis and critical growth periods, mean temperature can directly affect the yield component and/or indirectly if it occurs immediately before (Slafer et al., 2003). Increases in mean temperature accelerate the accumulation of grain dry matter, with an important reduction in the grain filling period, resulting in reduced interception of radiation by the crop and hence reduced final grain weight (Slafer et al. 2003), even at the same photosynthetic rate. Also, water deficit lowers grain number in the boot stage due to the occurrence of pollen grain meiosis at this stage (Slafer et al. 2003) and lowers grain weight by reductions in the rate of fill (Martos Núñez 2003) and its duration.

Regarding the threshold of maximum temperature that has negative effects on wheat yield and/or quality, there is a certain consensus that temperatures above 30 °C lower yield and quality through reductions in the rate of starch deposition (Jenner 1994) and in dough strength (Randall and Moss 1990).

Numerous studies have attempted to quantify wheat yield loss due to climate change. In Europe, Moore and Lobell (2015) reported yield losses of 2.5% for wheat for trends of temperature and precipitation, with more detrimental effects in those southern regions unable to mitigate the impact with rainfall increase. An increase in global mean temperature over the whole growing season, reported by Lobell et al. (2011), resulted in yield loss of 5.5% per °C increase, in spite of the beneficial effects of CO_2 for C3 species. Zhao et al. (2017), without CO_2 fertilisation, effective adaptation, and genetic improvement, reported yield loss of $6.0 \pm 2.9\%$ for wheat for each °C increase in global mean temperature, in concurrence with Asseng et al. (2015). At lower latitudes, the climate change effect will be more negative, especially at a high level of warming with nitrogen (N) stress, where there would be little true CO_2 compensation for C3 species (Rosenzweig et al. 2014). Schleussner et al. (2016) found substantial differences in impacts between 1.5 and 2 °C warming with local yield reduction at middle and low latitudes, especially for wheat and maize. Trends are particularly severe for temperature in wheat evaluated at regional and national levels (Lobell et al. 2011), with 6 and 8% of yield losses for 1.5 °C and 2 °C, respectively, for wheat (Schleussner et al. 2016).

In Argentina, Abbate and Lázaro (2010) reported falls of 1.15 mg in potential grain weight (approximately 4% for a mean grain weight of 30 mg) for each °C increase in mean temperature during 35 days post-anthesis, while Verón et al. (2015) reported a 5.1% average yield loss in the Pampas. Under moderate emission scenarios for the near future (2015–2039), Rolla et al. (2018) projected a 12.7% yield average decrease for wheat.

Numerous studies have contributed towards quantifying the magnitude of climate change in Argentina. The long-term tendency for 1940–2007 of various agroclimatic indices showed heating, principally due to increments in the minimum temperature (Fernández Long et al. 2008), although for the most recent period (1975–2007), the tendency was weaker and in the opposite direction in some meteorological stations (Fernández Long et al. 2008). In the Pampas region, rises in minimum temperatures of 2 °C/century were reported during 1959–1998 (Rusticucci and Barrucand 2004) and 0.14 °C/decade increase for September, October, and November (García et al. 2018). Additionally, across this region at most of the sites evaluated, the frost period decreased for the period 1940–2007, by a mean of 7 days per decade (Fernández-Long et al., 2012).

Regarding precipitation, increases have been reported across the planet throughout the twentieth century (Easterling et al. 2000). The frequency of abundant precipitation has risen in South-Central USA and sectors of South America during 1950–2005, by 2 days/decade, and the number of consecutive days without rain has reduced since 1960 (Alexander et al. 2006). Marked precipitation increase has been observed in southern Brazil and northeastern Argentina from November to May (Berbery et al 2006; Re and Barros 2009). In northeastern Argentina, the annual maximum amount of 1- and 5-day precipitation events increased from the 1970s to the 2000s; the higher frequencies of precipitation variability favoured extreme events post-2000 even during moderate extreme phases of the ENSO (Lovino et al 2018). In the Pampas region of Argentina, mean precipitation rose by over 150 mm during the last 30 years of the twentieth century compared to its beginning, especially between October and March (Magrin et al 2005). Regarding the future, model projections have suggested that there could be an increase in the frequency of precipitation extremes over the La Plata Basin during future El Niño and La Niña events (Cavalcanti et al. 2015).

The majority of climate studies carried out in the wheat region of our country have considered mean temperatures (Fernández Long et al. 2008, 2012; Magrin et al. 2005, 2009), maximum and minimum temperatures (Rusticucci and Barrucand 2004; García et al. 2018), and extreme temperatures in relation to frost (Fernández-Long et al., 2012). Although these studies provide a basis for the current investigation, more exhaustive studies are necessary that also analyse changes in extreme rainfall variables, as proposed by Easterling et al. (2000), and temperature in relation to the threshold that prejudices wheat yield and quality — which has increased its probability of occurrence throughout the post-flowering phase, from September to December (Rivelli et al. 2021) — as well as the situation over recent years and differences within the wheat region. This type of study could serve as a model for the elaboration of perspectives for each cultivar and zone in particular.

The aim of the current work was to characterise the trend in the change in temperature and rainfall variables in two contrasting sites within the wheat-growing region of Argentina. We focused on two sites of the Pampas, one towards the north of the region and the other towards the south, in order to discern whether there were differential effects of latitude, as has been suggested by modelling studies (Barros et al 1996).

2 Materials and methods

2.1 Sites studied

Climatic data were analysed from the meteorological stations of Azul in the Province of Buenos Aires and Marcos Juárez (abbreviated as MJ) in the Province of Córdoba, located approximately 500 km apart (Fig. 1). Azul and MJ are found in different wheat-growing regions, namely IV and II subregion north, respectively.

The climatic conditions in wheat-growing region IV are adequate for crop development, with a cool temperate climate of long winters and annual rainfall of around 800–900 mm, resulting in yields generally above the national average. Within this region, Azul itself has a temperate climate associated with the Pampas, with a mean annual temperature of 15 °C and annual rainfall exceeding 900 mm. The average yield in Azul over the last 10 years (2011–2021) was 4230.91 kg/Ha (+/− 621.07 kg/Ha), compared with a national mean of 3010.90 kg/Ha (+/− 286.87 kg/Ha). The sowing period is broad because of the use of cultivars varying in cycle length: long-cycled from 25/05 to 20/06, mid-cycled from 20/06 to 20/07, and short-cycled from 20/07 to 20/08, or until 31/08 as the limit. Anthesis occurs during the first days of November and harvesting runs from 20/12 to 02/01 (pers. com. CREA (Consorcios Regionales de Experimentación Agrícola) producers).

Region II subregion north gives yields similar to or slightly above the national average, where MJ itself has a humid temperate climate with maximum mean annual temperatures of 24 °C and minimum mean annual temperatures of 11 °C, although minimum temperatures can fall below − 10 °C and maximum temperatures above 41 °C. Annual rainfall is around 800 mm. The average yield in MJ over the last 10 years (2011–2021) was 3707.25 kg/Ha (+/− 1024.57) against the aforementioned national mean of 3010.90 kg/Ha (+/− 286.87 kg/Ha). Sowing takes place from 15/05 to 30/06, anthesis in October, and harvest from 20/11 to 15/12 (pers. com. CREA producers).

Figure 2 shows the current monthly temperatures and rainfall for each locality, as well as phenology information.

2.2 Datasets and variables evaluated

Daily data of maximum (Tmax), minimum (Tmin), and mean (Tmean) temperatures and rainfall were provided

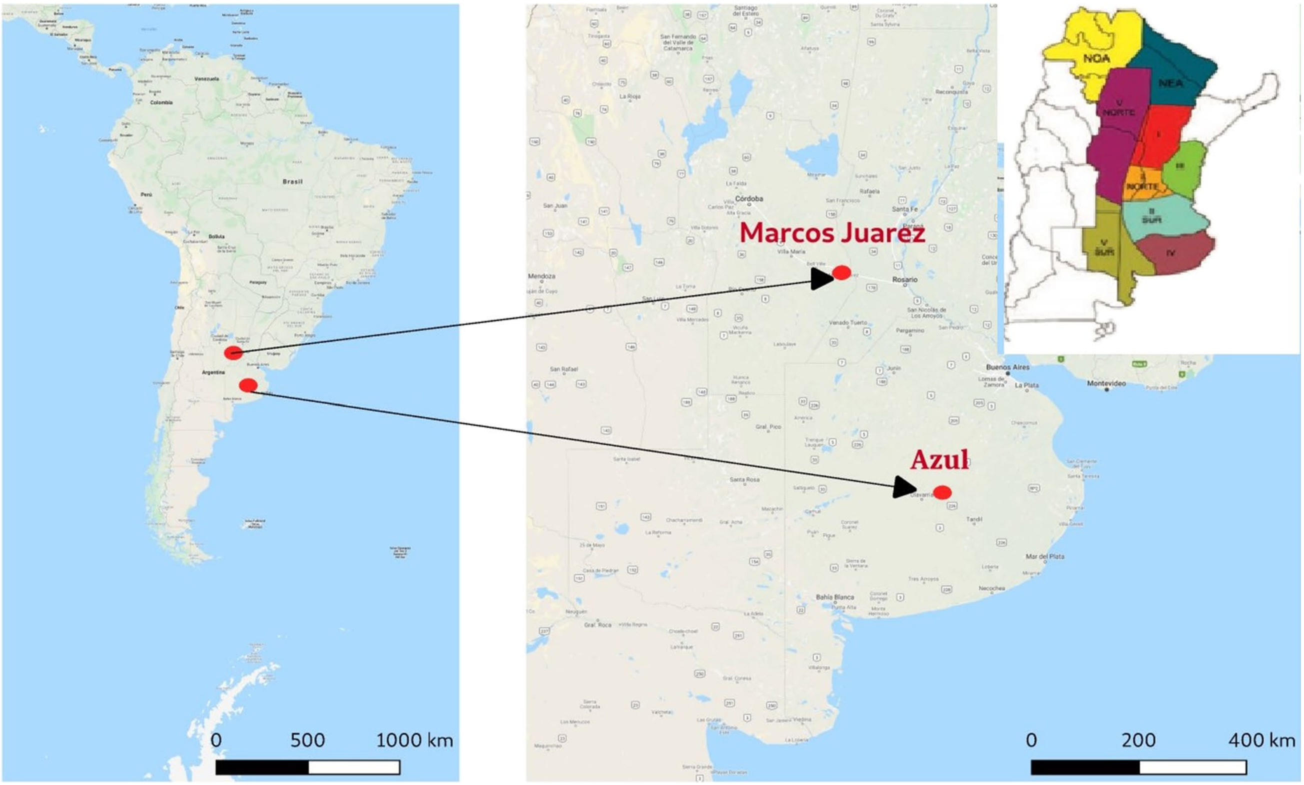

Fig. 1 Location of the sites analysed (Azul, Bs. As.; and Marcos Juárez, Córdoba) and map of the wheat-growing regions and subregions (upper right) (Molfese, 2016)

by the National Meteorological Service (Servicio Meteorológico Nacional, SMN). All measurements were made in the "Observational field", the maximum temperatures and minimum dry and wet thermometers were obtained in the meteorological shelter located at 1.5 m of height. The maximum and minimum temperatures are taken at 09:00 and 21:00 Argentine official hour (HOA) and only the highest and lowest are considered, respectively. Average temperature is calculated with the four main hours 03:00, 09:00, 15:00, and 21:00 HOA. Precipitation is measured at 09:00 on 1 day to 09:00 on the next HOA with a rain gauge within the mentioned field.

The original weather station in Azul (station A, 36°45′S 59°50′O 132 m, WMO station code 87,641) was deactivated in 1994 and a new station was immediately activated 10 km away (station B, 36° 50′S 59° 50′O 147 m, WMO station code 87,642). Station B is surrounded by farms in a rural setting and is 6.6 km from the centre of Azul.

The data from these (original station A: 1/1/1931–15/12/1994 and new station B: 16/12/1994–28/2/2015) were cross-checked with a third station (Tandil aero, 37°14′S 59°20′O), in order to verify that the 10-km distance had not significantly affected the measurements; this procedure showed that the original and new stations could be considered one and the same.

The data from MJ were provided by the station located at 32°42′S 62°10′O (WMO station code 87,467), and covered the period 1/7/1952 to 28/02/2015. This station is also rurally located amongst farms, 5.2 km from the centre of MJ.

The study of the monthly temperature series included Tmax, Tmin, Tmean, and daily thermal range (DTR). The duration of the period in each year with minimum temperatures equal to or below 0 °C (Du T ≤ 0 °C) was also determined. Extreme monthly temperature values included maximum (Vmax) and minimum (Vmin) temperatures, number of days with temperatures equal to or above 30 °C (ND T ≥ 30 °C), and accumulated degrees above 30 °C (°C T > 30 °C). The rainfall monthly variables (which included rainfall of less than 1 mm) were the number of days with precipitation (ND PP) and total precipitation (mmt PP). Extreme rainfall variables as number of days with precipitation equal to or below 5 mm (ND PP ≤ 5 mm), equal to or above 50.8 mm (ND PP ≥ 50.8 mm), and equal to or above 101.6 mm (ND PP ≥ 101.6 mm) were included according to Easterling et al. (2000) (2 and 4 in. equal to 50.8 and 101.6 mm, respectively). Accumulated precipitation from September to December each year (mm PP4 months) was also included. By their nature, variables ND T ≥ 30 °C, °C T > 30 °C, ND PP ≤ 5 mm, ND PP ≥ 50.8 mm, and ND PP ≥ 101.6 mm included many values equal to 0.

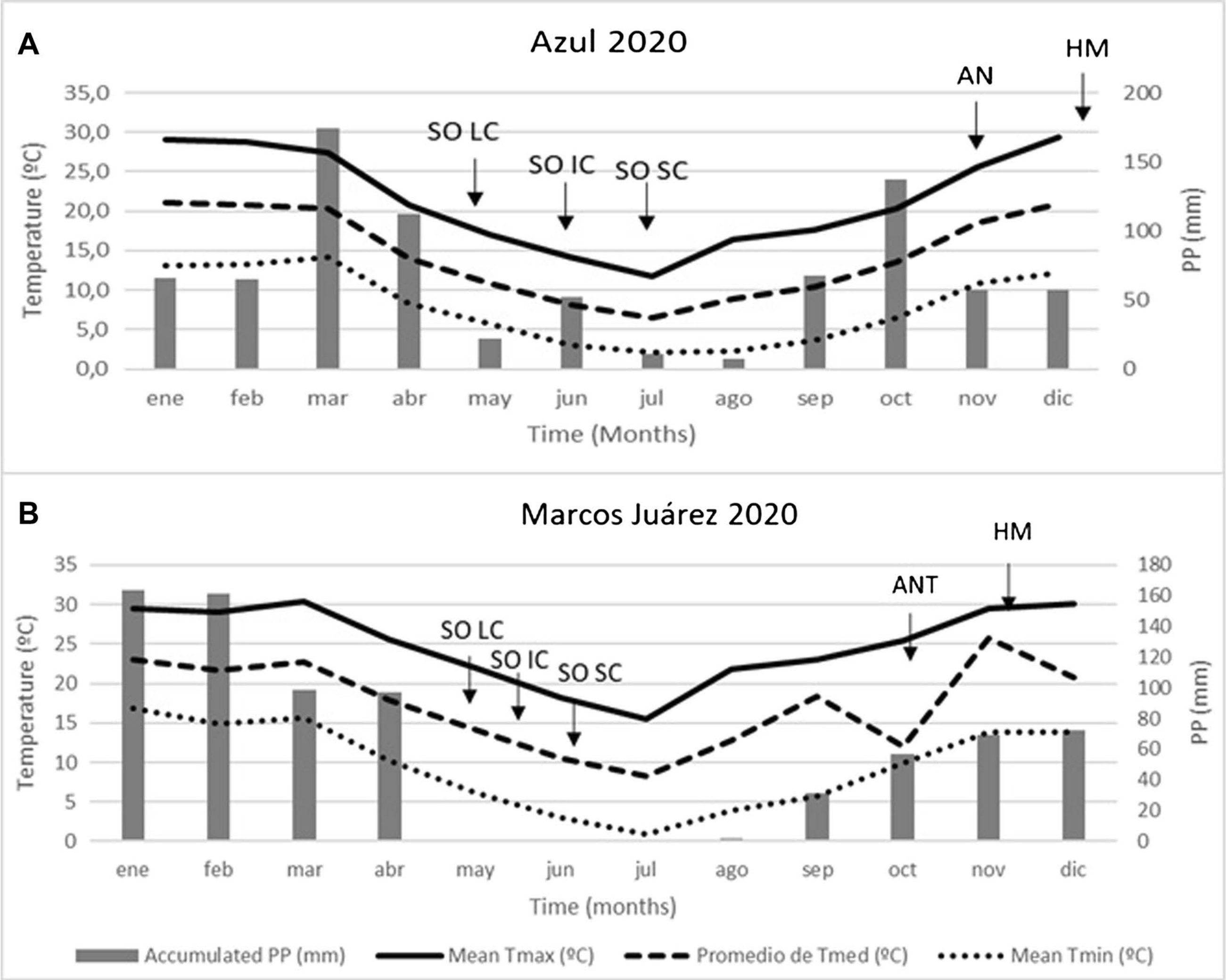

Fig. 2 Mean monthly maximum temperatures (Tmax), mean monthly mean temperatures (Tmean), mean monthly minimum temperatures, and accumulated precipitation (PP) over the last year in **A** Azul and **B** Marcos Juárez. The dates of sowing (SO) for long cycle (LC), intermediate cycle (IC), and short cycle (SC), anthesis (ANT), and harvest maturity (HM) are pointed at with arrows

Hence, 15 variables, to which prior data quality control was applied, were analysed for September, October, November, and December for the whole period of years for each site (Azul: 1931–2014; MJ:1952–2014); these months were chosen since they cover the critical period in the wheat cycle for yield and quality determination. Comparisons were made between the months at the two sites; the same month was compared at both sites due to the wide range of sowing dates and to allow extrapolation to other months and crops.

2.3 Data analysis

2.3.1 Analysis of each site

Linear regression was applied to all variables over time from both sites using the software Infostat version 2016 (Di Rienzo et al. 2016). The periods analysed (83 years for Azul, 62 years for MJ, plus the last 15 years of both series) allowed the removal of the Niño effect and volcanic activity, which are observed during periods of less than 5 years, as well as the effect of the solar cycle observed over periods below 11 years (De Saedeleer 2016). This was a deliberate decision for the current work in order to homogenise the dataset, although study of shorter periods could form the basis of future work. The regression analyses showed homogeneous distribution of residuals; nonetheless, since these are sensitive to the seasonality of the data, the analysis used to assess trends was the Mann–Kendall trend test (MK) (Mann 1945; Kendall 1975) (software RStudio 0.99.902 2009–2016), since it lacks the limitations of regression analysis and hence makes the predictions more robust, being a non-parametric test that works for all types of distribution, provided there is no serial correlation (Blain 2013). For this last analysis, the year was considered a factor and the remaining variables were considered time series. From the MK analysis, the value of the statistic *tau* (τ) (a coefficient indicative of a correlation between variables) and the two-tailed probability value (p) were obtained.

2.3.2 Differences between sites

The sites were analysed by principal components (PC) for the whole period of years in common (1952–2014) and for the first 15 years of the current century (2000–2014).

Additionally, the linear regression slopes from the whole period for each site for those cases where the value of *tau* from MK was significant were compared by t-test (see Eq. 1).

$$\frac{X1 - X2}{\sqrt{(error1)^2} - \sqrt{(error2)^2}} \tag{1}$$

where $X1$ and $X2$ are the slopes from the regression equation of sites "1" and "2", respectively, and "errors" 1 and 2 are the associated errors from their mean squares. The working significance level of the regressions was 5%.

2.3.3 Impact of the last years on the general tendency for the constructed variables

The extreme variables ND T $\geq$ 30 °C, °C $\geq$ 30 °C, ND PP $\leq$ 5 mm, ND PP $\geq$ 50.8 mm, and ND PP $\geq$ 101.6 mm were analysed as proportions, evaluating the significance of the proportion that represented the period 2000–2014 against the period 1952–2014 using the software STATISTICA (StatSoft Inc. 2004), which computes the level of significance for the difference between two proportions according to Eq. 2.

$$|t| = \frac{\sqrt{\left[(N1 * N2)/(N1 + N2)\right] * |p1 - p2|}}{\sqrt{(p * q)}} \tag{2}$$

where $p1$ is the proportion of the first sample (Azul); $p2$ is the proportion of the second sample (MJ); $N1$ is the size of the first sample (Azul); $N2$ is the size of the second sample (MJ); $p = (p1*\mathrm{N1} + p2*\mathrm{N2})/(\mathrm{N1} + \mathrm{N2})$; $q = 1 - p$ and the degrees of freedom are calculated as $(\mathrm{N1} + \mathrm{N2}) - 2$.

2.3.4 10-, 50-, and 100-year future projections for both sites

Using the regression equations for the complete period of each site, estimations were made of future projections for the next 10, 50, and 100 years for the variables with significant trends. Projections were also made of future wheat yield losses due to global heating, based upon an estimated 5.1% loss in yield per °C increase in mean (Verón et al. 2015) and 4% per °C increase in min temperature (García et al. 2016).

3 Results

3.1 Analysis of temperature

The monthly mean temperature variables increased significantly over the years in certain months at both sites (Table 1): in Azul, the maximum daily temperatures monthly mean in September and October (Fig. 3A), the minimum daily temperatures monthly mean in November and December, and the mean daily temperatures monthly mean in all 4 months (October Fig. 3C); and in Marcos Juárez (MJ), Tmax in September, October (Fig. 3B), and November, Tmin in October and November, and Tmean in September, October (Fig. 3D), and November. With the exception of Tmax and Tmean in December, the regression coefficients in MJ were consistently higher than those in Azul. For example, the regression coefficients for Tmax, Tmin, and Tmean for October in MJ were approximately threefold higher than those in Azul (Tmin non-significant in Azul). These observations imply that, in general for the temperature variables, the rate of climate change in MJ was higher than that in Azul.

In contrast, the DTR and Du T $\leq$ 0 °C showed no significant changes at either site (Table 1).

From these results, it appears that the variables in general are by no means showing similar changes over the study period; further evidence for this is provided by the analysis of variables focused upon more extreme temperature phenomena: Tmax, Tmin, ND T $\geq$ 30 °C, and °C $\geq$ 30 °C (Table 1). While no significant regressions were observed for Vmax, Vmin did show such regressions, although in Azul only in October (albeit with a regression coefficient higher than those observed for the temperature variables mentioned above); in contrast, in MJ, the regressions were significant in October, November, and December, with slopes higher than those observed in Azul. Just as in the case of the variables Tmax, Tmin, and Tmean mentioned above, this again implies that the rate of climate change in MJ was generally more pronounced than that in Azul.

Further evidence for differences between sites was provided by the monthly number of days with temperatures equal to or above 30 °C and accumulated degrees above 30 °C, for which significant regressions were only observed in MJ, in October and November for the former variable, and in October for the latter, with regression coefficients amongst the highest observed for all the variables analysed. Hence, there seems to be no appreciable climate change for

Table 1 Regression coefficients (*b*) and Mann Kendall slope (*tau*) for the complete period of years in Azul and Marcos Juárez for the mean and extreme temperature and rainfall variables, and comparison between regression coefficients where these were significant at both sites. Significant differences at 0.05 (*) and 0.01 (**) are indicated. *N*, no days observed with daily rainfall $\geq$ 101.6 mm for these months (September in Azul and November in Marcos Juárez)

Variable	Months	Azul 1931–2014					Marcos Juárez 1952–2014					Comparison of regression coefficients significant at both sites, 1952–2014	
		Regression		**Mann Kendall**			**Regression**		**Mann Kendall**				
		b	***p***	***tau***	***p***		***b***	***p***	***tau***	***p***		*t* value	
Tmax (°C)	September	0.0154	0.0047	0.2100	0.0054	**	0.0264	0.0150	0.1940	0.0324	*	−0.707	
	October	0.0141	0.0070	0.1860	0.0149	*	0.0412	0.0009	0.2890	0.0014	**	−2.121	*
	November	0.0094	0.2074	0.1100	0.1488		0.0230	0.0652	0.1900	0.0341	*		
	December	0.0099	0.1985	0.0731	0.3430		−0.0019	0.8737	−0.0091	0.9238			
Tmin (°C)	September	0.0076	0.2309	0.0516	0.4984		0.0064	0.5533	0.0427	0.6318			
	October	0.0123	0.0723	0.1210	0.1193		0.0331	0.0005	0.3020	0.0007	**		
	November	0.0160	0.0045	0.2340	0.0022	**	0.0222	0.0102	0.2440	0.0056	**	0.000	
	December	0.0175	0.0022	0.2480	0.0013	**	0.0192	0.0406	0.1720	0.0554			
Tmean (°C)	September	0.0115	0.0113	0.1790	0.0193	*	0.0198	0.0274	0.2040	0.0257	*	−0.915	
	October	0.0134	0.0053	0.1900	0.0150	*	0.0365	< 0.0001	0.3770	0.0000	**	−2.715	*
	November	0.0131	0.0139	0.1880	0.0153	*	0.0229	0.0197	0.2150	0.0179	*	−0.707	
	December	0.0130	0.0098	0.1990	0.0109	*	0.0093	0.3225	0.0808	0.3702			
DTR (°C)	September	0.0088	0.2623	0.0833	0.2763		0.0184	0.1989	0.1080	0.2364			
	October	0.0013	0.8646	0.0274	0.7282		0.0086	0.5600	0.0608	0.5087			
	November	−0.0062	0.4328	−0.0517	0.5064		0.0008	0.9398	−0.0218	0.8144			
	December	−0.0065	0.4715	−0.0770	0.3245		−0.0197	0.0838	−0.1320	0.1412			
Du T $\leq$ 0 °C (no. of days)	Annual	−0.0319	0.8138	−0.0064	0.9371		−0.2320	0.2006	−0.1030	0.2549			
Vmax (°C)	September	0.0021	0.8406	−0.0021	0.9808		0.0232	0.2406	0.0963	0.2919			
	October	0.0148	0.1140	0.1260	0.1014		0.0343	0.0546	0.1690	0.0639			
	November	−0.0076	0.4996	−0.0153	0.8447		0.0018	0.9001	−0.0136	0.8855			
	December	−0.0120	0.2950	−0.0771	0.3196		−0.0201	0.2387	−0.0944	0.2949			
Vmin (ºC)	September	0.0054	0.5536	0.0190	0.8065		0.0039	0.8205	0.0050	0.9603			
	October	0.0189	0.0102	0.1660	0.0340	*	0.0549	0.0006	0.2820	0.0016	**	−1.342	
	November	0.0071	0.3892	0.0781	0.3105		0.0457	0.0044	0.2700	0.0023	**		
	December	0.0227	0.0294	0.1250	0.1066		0.0413	0.0254	0.1960	0.0294	*		
ND T $\geq$ 30 °C (no. of days)	September	−0.0001	0.9270	−0.0092	0.9303		0.0000	0.9977	0.0175	0.8656			
	October	0.0005	0.9019	0.0444	0.6280		0.0434	0.0593	0.2020	0.0321	*		
	November	−0.0034	0.7655	−0.0014	0.9899		0.0638	0.0884	0.2040	0.0261	*		
	December	0.0333	0.1307	0.0871	0.2748		−0.0090	0.8218	0.0110	0.9084			

Table 1 (continued)

Variable	Months	Azul 1931–2014				Marcos Juárez 1952–2014				Comparison of regression coefficients significant at both sites, 1952–2014
		Regression		**Mann Kendall**		**Regression**		**Mann Kendall**		
		b	***p***	***tau***	***p***	***b***	***p***	***tau***	***p***	*t* value
°C T > 30 °C (°C)	September	0.0001	0.8138	−0.0080	0.9402	0.0321	0.2881	0.0860	0.3758	
	October	0.0015	0.6193	−0.0024	0.9843	0.1337	0.0800	0.1900	0.0363	*
	November	−0.0299	0.2543	−0.0014	0.9899	0.1830	0.1676	0.1280	0.1540	
	December	0.0434	0.6158	0.0133	0.8664	−0.1492	0.5086	−0.0509	0.5703	
ND PP (no. of days)	September	0.0009	0.9504	−0.0151	0.8488	0.0150	0.4433	0.0161	0.8624	
	October	0.0277	0.0939	0.1320	0.0877	0.0074	0.7559	0.0584	0.5209	
	November	−0.0033	0.8237	0.0066	0.9349	0.0118	0.6122	0.0603	0.5068	
	December	−0.0166	0.1807	−0.0860	0.2751	−0.0014	0.9479	−0.0294	0.7532	
mmt PP (mm)	September	0.0943	0.6027	0.0238	0.7514	0.0315	0.9224	−0.0159	0.8588	
	October	0.0150	0.9591	0.0547	0.4669	0.3776	0.3822	0.0148	0.8681	
	November	0.2920	0.2282	0.1070	0.1518	0.3126	0.3495	0.1030	0.2355	
	December	0.0103	0.9603	−0.0409	0.5873	0.7340	0.1765	0.1300	0.1402	
mm PP4months (mm)	September to December	0.4127	0.3809	0.0708	0.3452	15.233	0.1036	0.1710	0.0489	*
ND PP ≤ 5 mm (no. of days)	September	−0.0029	0.7850	−0.0110	0.8925	0.0189	0.2081	0.0807	0.3796	
	October	0.0155	0.2378	0.0912	0.2484	0.0127	0.4562	0.0618	0.5032	
	November	−0.0076	0.5162	−0.0294	0.7104	0.0104	0.4754	0.0636	0.4897	
	December	−0.0121	0.2388	−0.0687	0.3871	−0.0247	0.0959	−0.1530	0.1010	
ND PP ≥ 50.8 mm (no. of days)	September	0.0023	0.0851	0.115	0.2031	−0.0019	0.3860	−0.0914	0.3877	
	October	−0.0025	0.3475	−0,045	0.6142	0.0048	0.2291	0.143	0.1677	
	November	0.0011	0.6018	0.0481	0.5941	0.0011	0.7248	0.0372	0.7275	
	December	0.0020	0.1902	0.119	0.1909	0.0007	0.8697	0.0025	0.9874	
ND PP ≥ 101.6 mm(no. of days)	September	N	N	N	N	0.0014	0.1114	0.167	0.1171	
	October	−0.0007	0.1685	−0.125	0.1735	0.0014	0.0993	0.172	0.1047	
	November	−0.0006	0.2259	−0.11	0.2317	N	N	N	N	
	December	0.0001	0.9013	0.0114	0.9169	0.0009	0.5751	0.0603	0.5821	

Abbreviations: *Tmax* mean monthly maximum temperatures, *Tmin* mean monthly minimum temperatures, *Tmean* mean monthly mean temperatures, *DTR* mean monthly thermal range, *Du T ≤ 0 °C* the duration of period in each year with minimum temperatures equal to or below 0 °C, *Vmax* monthly maximum temperatures, *Vmin* monthly minimum temperatures, *ND T ≥ 30 °C* monthly number of days with temperatures equal to or above 30 °C, *°C T > 30 °C* accumulated degrees above 30 °C, *ND PP* monthly number of days with precipitation, *mmt PP* monthly total precipitation, *ND PP ≤ 5 mm* monthly number of days with precipitation equal to or below 5 mm, *ND PP ≥ 50.8 mm* monthly number of days with precipitation equal to or above 50.8 mm, *ND PP ≥ 101.6 mm* monthly number of days with precipitation equal to or above 101.6 mm, *mm PP4 months* accumulated precipitation from September to December each year

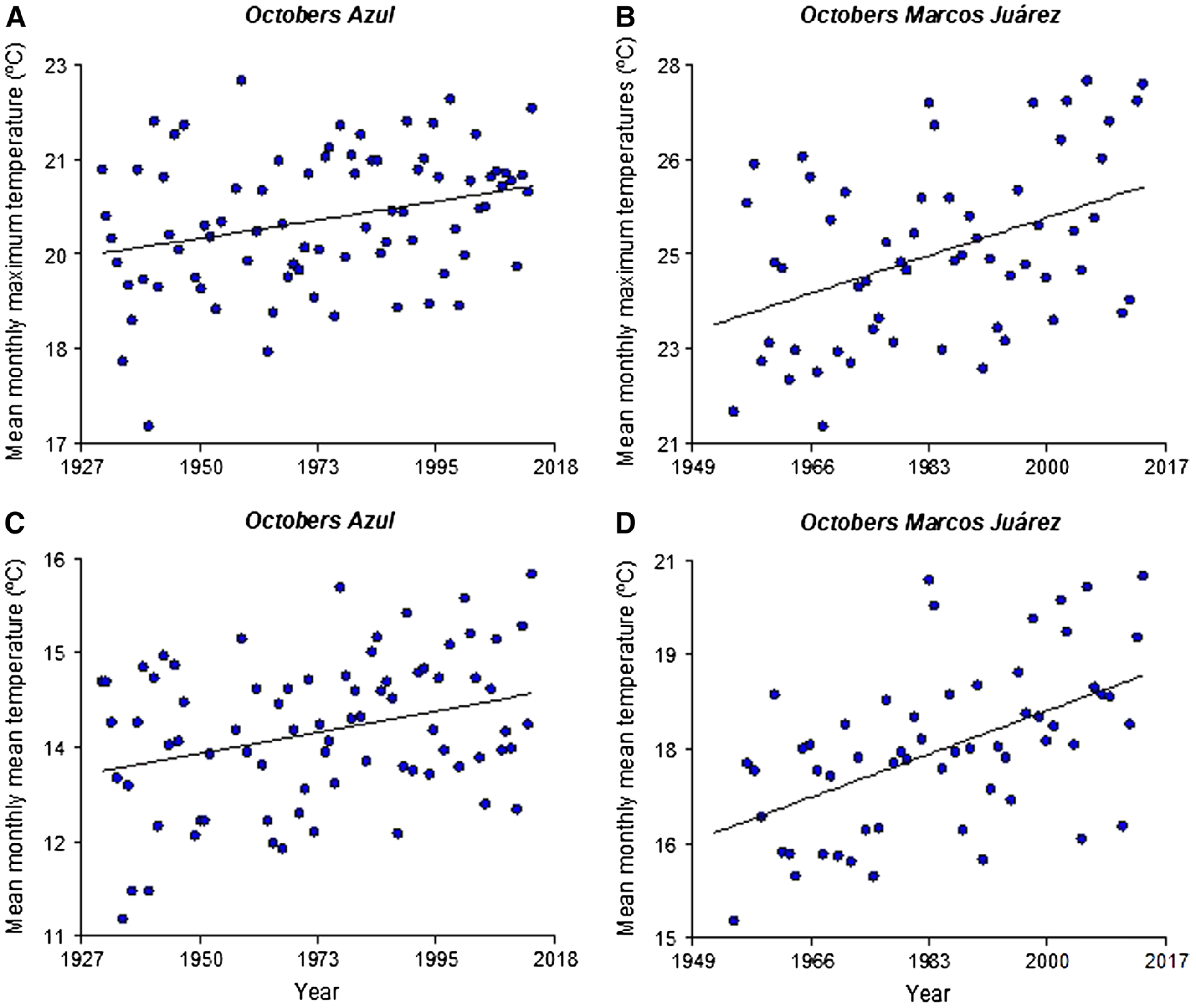

Fig. 3 Mean monthly maximum temperatures (Tmax) over years in **A** Azul and **B** Marcos Juárez and mean monthly mean temperatures (Tmean) over years in **C** Azul and **D** Marcos Juárez

these characters in Azul, in contrast to MJ, where the rate of change was considerable.

In conclusion, of all the thirty-three combinations of comparisons carried out (eight variables for which 4 months were analysed per variable, plus one variable (the duration of period in each year with minimum temperatures equal to or below 0 °C) analysed over the 4 months as a whole (Table 1)), there were (i) seven combinations (Tmax Septembers, Tmax Octobers, Tmin Novembers, Tmean Septembers, Tmean Octobers, Tmean Novembers, and Vmin Octobers) that gave significant, positive, regression coefficients in both Azul and MJ, where the magnitude of the coefficient in MJ was always numerically greater than that in Azul, including significantly so for two of them (Tmax Octobers and Tmean Octobers), according to application of Eq. 1 (Table 1); (ii) seven combinations (Tmax Novembers, Tmin Novembers, Vmin Novembers, Vmin Decembers, ND T ≥ 30 °C Octobers, ND T ≥ 30 °C Novembers, and °C T > 30 °C Octobers) that gave significant, positive, regression coefficients in MJ, but non-significant regressions in Azul, where the magnitude of the coefficient in MJ was, as would be expected, always numerically higher than that in Azul; and (iii) only two combinations (Tmin Decembers and Tmean Decembers) that opposed these trends, since they gave significant, positive, regression coefficients in Azul, but non-significant regressions in MJ. These results imply that, for those combinations showing significant climate change, the rate of change was, with notably few exceptions, considerably higher in MJ than that in Azul.

3.2 Analysis of rainfall

Of all the rainfall variables analysed (Table 1), only the regression of the accumulated precipitation from September to December each year in MJ was significant (*p*, MK), showing that, firstly, there was generally relatively little climate change over the years for rainfall, and, secondly, where there was change, this was only observed in MJ.

Regarding variables associated with extreme rainfall phenomena, i.e. the number of days with precipitation equal to or below 5 mm per month, the number of days with precipitation equal to or above 50.8 mm per month, and the number of days with precipitation equal to or above 101.6 mm (for the latter two variables, the distribution of the residual errors was non-random), no significant differences were found over the months analysed for either site, again supporting the idea that there was relatively little climate change observed for rainfall (Table 1).

3.3 Multivariate comparison between sites

Having provided evidence that for individual variables the sites showed notable differences in their rates of climate change, we applied principal component (PC) analysis to see to what extent the sites differed when all variables were considered as a whole across the whole period (1952–2014) (Fig. 4).

The sites clearly differed for PC 1, since all MJ data points had higher values for PC 1 than those in Azul, component positively correlated with the temperature variables Tmin, Tmean, and Tmax, together covering the 4 months under study, and negatively correlated with the duration of the period with temperatures equal to or below 0 °C, albeit that the correlations were low in magnitude (Table 2).

For the period 2000–2014, PC 1 was related to temperature variables and Du T ≤ 0 °C in a similar way to that observed for the whole period, as well as to variables associated with extreme events (Vmax and ND T > 30 °C), and there was also a slight tendency to be related to rainfall variables (Table 2).

In general, the sites were not discriminated by PC 2 (Fig. 4) or any other PC (results not shown).

Taken as a whole, together with the results for individual variables described earlier, the data confirm that MJ is clearly the warmer of the two sites (for the variables more correlated with PC 1, such as the temperature variables).

Additionally, the points for the years 2000–2014 (light symbols) for MJ (triangles) are slightly displaced towards higher values of PC 1 than the remaining years at this site, whereas this is not so for Azul, implying that the more recent years at MJ are warmer than previous years and indicating a possible acceleration in climate change at this site for the variables correlated with PC 1.

3.4 Impact of the period 2000–2014

Following this lead, analysis of the frequency of extreme temperature and rainfall events for the period 2000–2014 compared with that for 1952–2014 (Table 3) showed that in the more recent period, it was found that, at both sites, there were increases in variables associated with the 30 °C limit (ND T ≥ 30 °C and °C T > 30 °C) in October.

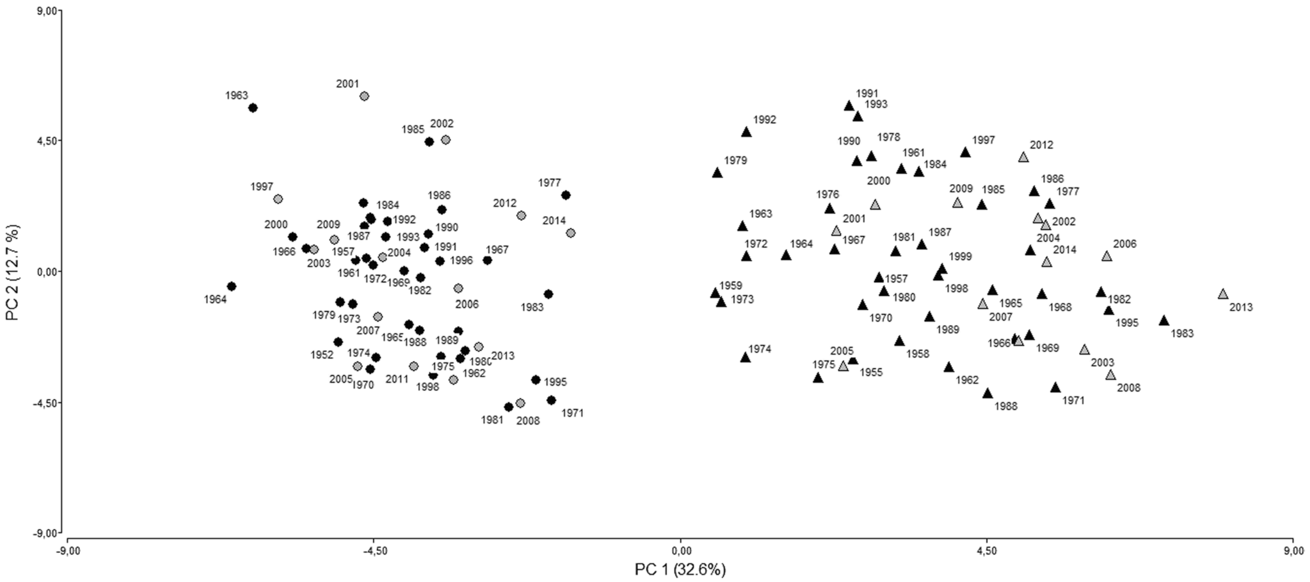

Fig. 4 Principal components (PC) 1 and 2 for both sites during the period September to December 1952–2014. Circles: Azul; triangles: Marcos Juárez; dark symbols: years 1952–1999; light symbols: 2000–2014

Table 2 Loadings of the 18 main variables that most discriminate between Azul and Marcos Juárez in the periods 1952–2014 and 2000–2014

1952–2014			2000–2014		
Variables	**e1**	**e2**	**Variables**	**e1**	**e2**
Du T ≤ 0 °C (no. of days)	−0.14	−0.18	Du T ≤ 0 °C (no. of days)	−0.16	−0.18
DTR December (°C)	−0.07	−0.28	ND PP ≤ 5 mm November (no. of days)	−0.12	−8.40E–05
ND PP ≤ 5 mm November (no. of days)	−0.06	0.07	ND PP September (no. of days)	−0.1	0.18
mmt PP September (mm)	−0.05	0.09	mmt PP September (mm)	−0.1	0.2
ND PP October (no. of days)	−0.05	0.2	ND PP October (no. of days)	−0.1	0.19
ND PP ≤ 5 mm October (no. of days)	−0.05	0.14	ND PP ≤ 5 mm October (no. of days)	−0.1	0.14
ND PP November (no. of days)	−0.05	0.16	DTR December (°C)	−0.1	−0.22
ND PP September (no. of days)	−0.04	0.13	ND PP ≥ 50.8 mm September (no. of days)	−0.07	0.13
ND PP ≥ 50.8 mm September (no. of days)	−0.02	0.02	ND PP November (no. of days)	−0.07	0.14
Tmean December (°C)	0.2	−0.04	Vmax September (°C)	0.2	0.01
Tmean September (°C)	0.21	0.05	Tmax November (°C)	0.2	−0.1
Tmax October (°C)	0.21	−0.01	Tmin November (°C)	0.2	0.04
Tmax November (°C)	0.21	−0.11	ND T > 30 °C November (nº of days)	0.2	−0.1
Tmin November (°C)	0.21	0.07	Tmin December (°C)	0.2	0.09
Tmin December (°C)	0.21	0.08	Tmax September (°C)	0.21	−0.01
Tmax September (°C)	0.22	−0.02	Tmax October (°C)	0.21	0.01
Tmean October (°C)	0.22	0.08	Tmean October (°C)	0.21	0.11

Abbreviations: *Tmax* mean monthly maximum temperatures, *Tmin* mean monthly minimum temperatures, *Tmean* mean monthly mean temperatures, *DTR* mean monthly thermal range, *Du T ≤ 0 °C* the duration of period in each year with minimum temperatures equal to or below 0 °C, *ND T ≥ 30 °C* monthly number of days with temperatures equal to or above 30 °C, *ND PP* monthly number of days with precipitation, *mmt PP* monthly total precipitation, *ND PP ≤ 5 mm* monthly number of days with precipitation equal to or below 5 mm, *ND PP ≥ 50.8 mm* monthly number of days with precipitation equal to or above 50.8 mm

Table 3 Proportions explained for the most recent 15 years for the extreme variables compared to the 1952–2014 series

Period 2000 – 2014	**Month**	**ND T ≥ 30 °C** (no. of days)	**°C T > 30 °C** (°C)	**ND PP** (no. of days)	**mmt PP** (mm)	**ND PP ≤ 5 mm** (no. of days)	**ND PP ≥ 50.8 mm** (no. of days)	**ND PP ≥ 101.6 mm** (no. of days)
Azul	9	0.00	0.00	28.57	29.52	29.39	37.50	-
	10	35.00	44.20	27.85	25.68	29.33	23.08	-
	11	23.45	24.04	24.51	25.92	25.15	35.71	-
	12	28.44	30.58	22.50	19.77	23.91	20.00	0.00
MJ	9	29.76	34.47	24.50	23.91	25.18	0.00	100.00
	10	30.43	34.65	23.39	25.92	23.45	38.46	100.00
	11	29.36	31.58	22.16	23.16	21.25	23.53	-
	12	22.96	20.24	22.40	24.31	20.13	15.00	0.00

Abbreviations: *T ≥ 30 °C* number of days with temperatures equal to or above 30 °C, *ND T ≥ 30 °C* monthly number of days with temperatures equal to or above 30 °C, *ND PP* monthly number of days with precipitation, *mmt PP* monthly total precipitation, *ND PP ≤ 5 mm* monthly number of days with precipitation equal to or below 5 mm, *ND PP ≥ 50.8 mm* monthly number of days with precipitation equal to or above 50.8 mm, *ND PP ≥ 101.6 mm* monthly number of days with precipitation equal to or above 101.6 mm

Additionally, all events of rainfall of 101.6 mm or more have been recorded in MJ in September and October during more recent years (Table 3).

The analysis of differences between proportions (Eq. 2) of the first 15 years of the century compared to the whole period showed that the temperature extremes (ND T ≥ 30 °C and °C ≥ 30 °C) had become more frequent at both sites in September, differentially so (*p* value of 0.03 and 0.02, respectively).

Regarding rainfall extremes, this was also observed for ND PP ≥ 50.8 mm for September (*p* value of 0.01).

Hence, climate change appears to have become more marked in recent years compared to previous ones, seemingly more so in MJ than in Azul.

3.5 Future projections

From the above results, twenty-four of the variables analysed were found to be changing significantly and we made projections over the next 10, 50, and 100 years based upon our regression coefficients over the whole period (Table 4). Given that the changes appear to have accelerated over the first 15 years of the century, these will likely be underestimates of the expected changes, which in any case will, of course, depend upon future greenhouse gas emission scenarios and a host of other factors.

For example, October and November maximum temperatures in MJ are expected to reach around 30 °C by 2064 and a further 2 °C in October or 0.75 °C in November by 2114 (Table 4). Furthermore, within the next 50 years, the number of days with temperatures equal to or above 30 °C could rise by 27% in October and 23% in November, accumulating 6.68 °C above the current value for October (Table 4).

Regarding Tmean, increases of between 1.15 and 1.34 °C are expected for Azul and between 1.98 and 3.65 °C for MJ, depending on the month involved; i.e. considerably higher increases are expected for MJ than for Azul. Assuming a 5.1% loss in yield per °C increase in Tmean as proposed by Verón et al. (2015), these increases translate into potential yield losses of between 5.86 and 6.83% for Azul and between 10.09 and 18.615% for MJ, again depending upon the month (Table 4). Hence, expected yield losses for MJ are considerably higher than, possibly double, those expected for Azul. If we also consider the usual anthesis dates at each site and the greater impact of high temperatures in anthesis (García et al. 2015), the damage to yield may be greater in November in Azul and in October in MJ.

Table 4 Current and future (10, 50, and 100 years) values for the variables giving significant regressions and Mann–Kendall tests, and projected % yield losses at 100 years assuming 5.1 (Verón et al. 2015) for Tmean, and 4% (García et al. 2016) for Tmin of % fall in yield per °C increase

Variable	**Value in 2014**	**Projected value at:**			Projected % yield loss at 100 years
		10 years	**50 years**	**100 years**	
Tmean Septembers Azul (°C)	13.04	13.16	13.62	14.19	5.860
Tmean Octobers Azul (°C)	16.12	16.25	16.79	17.46	6.830
Tmean Novembers Azul (°C)	17.78	17.91	18.44	19.09	6.681
Tmean Decembers Azul (°C)	20.94	21.07	21.59	22.24	6.630
Tmean Septembers MJ (°C)	15.90	16.10	16.89	17.88	10.090
Tmean Octobers MJ (°C)	20.31	20.68	22.14	23.96	18,615
Tmean Novembers MJ (°C)	20.61	20.84	21.76	22.90	13.209
Tmin Octobers MJ (°C)	12.76	13.09	14.42	16.07	13.240
Tmin Novembers Azul (°C)	11.15	11.31	11.95	12.75	6.400
Tmin Novembers MJ (°C)	12.78	13.00	13.89	15.00	8.880
Tmin Decembers Azul (°C)	13.46	13.64	14.34	15.21	7.000
Tmax Septembers Azul (°C)	18.12	18.27	18.89	19.66	
Tmax Octobers Azul (°C)	22.25	22.39	22.96	23.66	
Tmax Septembers MJ (°C)	23.35	23.61	24.67	25.99	
Tmax Octobers MJ (°C)	27.86	28.27	29.92	31.98	
Tmax Novembers MJ (°C)	28.45	28.68	29.60	30.75	
Vmin Octobers Azul (°C)	2.30	2.49	3.25	4.19	
Vmin Octobers MJ (°C)	5.00	5.55	7.75	10.49	
Vmin Novembers MJ (°C)	6.20	6.66	8.49	10.77	
Vmin Decembers MJ (°C)	6.00	6.41	8.07	10.13	
ND T ≥ 30 °C Octobers MJ (no. of days)	8.00	8.43	10.17	12.34	
ND T ≥ 30 °C Novembers MJ (no. of days)	14.00	14.64	17.19	20.38	
°C T > 30 °C Octobers MJ (°C)	37.50	38.84	44.19	50.87	
mm PP_{4meses} MJ (mm)	356.90	372.13	433.07	509.23	

Abbreviations: *Tmax* mean monthly maximum temperatures, *Tmin* mean monthly minimum temperatures, *Tmean* mean monthly mean temperatures, *Vmax* monthly maximum temperatures, *Vmin* monthly minimum temperatures, *ND T ≥ 30 °C* monthly number of days with temperatures equal to or above 30 °C, *°C T > 30 °C* accumulated degrees above 30 °C, *mm PP4 months* accumulated precipitation from September to December each year

4 Discussion

The analysis of historical climate data from Azul, Province of Buenos Aires, and Marcos Juárez, Province of Córdoba, sites in two contrasting zones representing the wheat-growing region of Argentina, allowed the characterisation of past and possible future changes in temperature and rainfall variables during the months in which wheat is grown in this country. Changes in mean and extreme temperatures and rainfall variables observed were largely consistent with those reported in the relevant literature (Alexander et al. 2006, Nakicenovic et al. 2007, IPCC 2007a, Trenberth et al. 2007, Fernández Long et al. 2008, Stocker et al. 2013, Verón et al. 2015, García et al. 2018, Rivelli et al. 2021, amongst others).

4.1 Considerations for each site

4.1.1 Mean temperature values

The maximum temperatures (Tmax) in September and October in Azul and MJ have increased significantly over the years (Table 1), more intensely so in the latter site, where besides significant increases were observed in November. At this rate, increases of 0.15 °C and 0.25 °C per decade in September in Azul and MJ, respectively, would be expected, higher than those reported by Magrin et al. (2009) for the Pampas region for this month (0.07 between 1930 and 2000, and 0.00 between 1970 and 2000). On the other hand, the expected increases for October were similar to those reported in the same study (for Azul, 0.14 °C in our study against 0.13 °C between 1930 and 2000, and, for MJ, 0.41 °C in our study against 0.43 °C between 1970 and 2000). For November, the projections for MJ (0.23 °C) were higher than those indicated in the same study for 1930–2000 and lower than those estimated for 1970–2000 (0.00 and 0.47 °C, respectively). The comparison with Magrin et al. (2009) is interesting because the trends are established at the same months in the same region, albeit that the model used in that study is outdated today.

Regarding the minimum temperatures (Tmin), these increased significantly over the years in November at both sites (Table 1), and additionally in December at Azul and in October in MJ. At this rate, increases in October in MJ of 0.03 °C per decade would be expected, similar to those from the Magrin et al. (2009) study for 1930–2000 (0.36 °C), although less than those from the same study for 1970–2000 (0.58 °C). The increases expected for November for Azul and MJ are less than those previously reported in this study (0.16 °C in Azul and 0.22 °C in MJ against 0.39 °C between 1970 and 2000, and 0.61 °C between 1970 and 2000) (Table 1). The increments in this variable in October and November in MJ (Table 1) are notably greater than those projected by Rusticucci and Barrucand (2004) of 2 °C per 100 years for the Pampas region, and, in November, the increment is also notably greater than the projection of García et al. (2018) of 0.14 °C/decade. Furthermore, increments of 0.18 °C per decade in December are projected for Azul (Table 1).

The mean temperatures (Tmean) have also risen during the months analysed at both sites over the years, except for December in MJ. These rises are consistent with those reported by Stocker et al. (2013) for the twentieth century. The rises were more marked in MJ than in Azul (Table 1). At this rate, increases in Azul of 0.12 °C per decade in September and of 0.13 °C in October, November, and December would be expected, while in MJ rises of 0.2, 0.37, and 0.23 °C per decade for September, October, and November, respectively, would be expected. It is interesting to note that in October, the differences between the sites for this variable were threefold and the expected increases for MJ almost duplicated those stipulated by the IPCC in their fourth report for the decades 2007–2017 and 2017–2027 (0.2 °C per decade for a range of emission scenarios, including for those where the concentrations of greenhouse gas and aerosols stayed at year 2000 values, IPCC 2007a). Barros (2015) found a trend of increases in the annual mean temperature of 0.5 °C for Azul and 1 °C for Marcos Juárez; our study gave less pronounced trends, although it did not include the summer months.

The increases in mean temperatures found, due to the rises in maximum temperatures in September and October, and in minimum temperatures in November and December, could reduce potential yield in wheat (Magrin and Travaso 2002, Nuñez et al. 2008) due to the shortened grain fill period not compensated for by higher rates of filling, as affirmed by Stone and Savin (1999) for temperatures above 15 °C. Elevated temperatures reduce the capture of resources, as well as affecting the partition of biomass to harvestable organs (Magrin et al. 2005). Instead, the period between spike growth and grain-setting in wheat is more sensitive to high temperature (7%/°C of increase in night temperature or 10%/°C of increase in mean temperature during this period; García et al. 2015).

The temperature rises in October, November, and December might imply possible deleterious effects on potential yield and quality at both sites, in spite of the different sowing dates between sites, due to current growing temperatures being close to optimal. Furthermore, the changes are generally more severe in MJ (i.e. 18.61% yield loss in October MJ, Table 4) than those in Azul (6.83 in Azul, Table 4), when the data is considered as a whole. This is a warning sign for food safety because yield losses are expected to occur in spite of the potential beneficial effects of increased CO_2 concentration (Lobell et al. 2011).

Further consideration of the possible consequences for yield of temperature rise at the two sites is given later in the "Discussion".

Although a better use of increased CO_2 by the crop can be achieved from added nitrogen (N) (McGrath and Lobell 2013), if yield falls, N requirements would also fall and N translocation affected, due to the grain of stressed plants having less N than control plants (Vignjevic et al. 2015). If stress due to elevated temperature acted early during post-anthesis, cultivars would have reduced the capability for synthesising UPP (unextractable polymeric protein) and hence reduce their capacity for tolerance for quality.

In contrast to that reported by Fernández Long et al. (2008) and Verón et al. (2015), the increases in Tmax, Tmin, and Tmean did not result in changes in the thermic amplitude for the period at either site.

Regarding the duration of the period with minimum temperatures equal to or less than 0 °C, no significant differences were observed (Table 1), coinciding with Alexander et al. (2006), Easterling et al. (2000) and Easterling (2002).

4.1.2 Extreme temperature

Extreme temperature values have also been subject to change. For example, (i) mean minimum monthly temperatures have risen significantly at both sites in October (0.019 °C/year in Azul against 0.055 °C in MJ) and also in MJ in November and December (0.046 °C and 0.041 °C, respectively); (ii) the number of days with temperatures equal to or above 30 °C rose significantly in MJ in October (0.43 days/decade) and November (0.64 days/decade); and (iii) the degrees accumulated above 30 °C also rose in October at MJ (Table 1). Furthermore, for the variables in (ii) and (iii), the proportion explained for the period 2000–2014 compared to that in the period 1952–2014 at both sites was significant in September (Table 3). These findings coincide with those reported by Plummer et al. (1999) for New Zealand (threshold of 30 °C), although not with those of Easterling et al. (2000) for the USA (threshold of 32.2 °C). Our findings are in agreement with Rivelli et al. (2021), who reported that the probability of occurrence of the number of days with temperatures above 30 °C increased throughout the post-flowering phase, from September to December.

In terms of yield, temperatures in excess of 30 °C lead to floret or grain abortion (Saini and Aspinall, 1982), while for industrial wheat quality, these temperatures break the positive relationship between grain protein content and dough strength, resulting in possible negative effects on quality, with an increase in the gliadin to glutenin ratio.

4.1.3 Mean and extreme rainfall values

Accumulated rainfall for September to December in MJ increased significantly (Table 1), which is consistent with Alexander et al. (2006) at the global level, Easterling et al. (2000) in the USA, and Barros et al. (1996), Magrin et al. (2009), and Barros (2015) in Argentina, while it differed from Verón et al. (2015) for this site, who reported a reduction of precipitation for wheat. Additionally, increases in extreme events have been reported by Barros (2015) for 1960–2010 and in our work this phenomenon was detected by the observation that all rainfall events equal to or greater than 101.6 mm in MJ in September and October occurred between 2000 and 2014, with none before that (Table 3). Gelmi and Seoane (2013) found a greater frequency of occurrence of extreme precipitation events over years in the zone including Azul between 1971 and 1999 compared to 1951 to 1970, implying long-term changes appear to be underway at both sites.

Regarding the consequences of these changes, the increase in abundant rainfall events could provoke N leaching and therefore changes in agronomic practices that could mean that regions of the country hitherto not apt for wheat growing could become so, and vice versa. Future changes could be even more dramatic than the projected changes given in Table 4, since these are likely to be underestimates, given the apparent acceleration of change signalled by the results from 2000 to 2014. Nonetheless, it ought to be remembered that regional precipitation changes can be projected with less certainty than temperature (Zhao et al. 2017).

4.2 Differences between sites

As seen from the results given in Table 4 for the whole period, the variables that changed significantly at both sites did so more pronouncedly in MJ than in Azul, implying more extreme future conditions at the former site. In contrast, Zhao et al. (2017) found similar impacts at site scale due to temperature increase.

Furthermore, changes in extreme temperature phenomena related to the threshold temperature were only found in MJ, not in Azul. If, besides, we consider that MJ is, according to its mean and maximum temperatures for each of the months analysed, approximately 5 °C warmer than Azul, the consequences for yield and quality in MJ could be more severe than those in Azul. Naturally, future change is related to future gas emission scenarios, as stated by the fourth report of the IPCC, but in general, the indications are that climate change will continue and accelerate unless dramatic action is taken to counter it.

The sites were strikingly different in their rates of change for maximum and median temperatures in October across the whole period (Table 1). In more recent years, the sites are beginning to differ for the number of days equal to or above 30 °C and the accumulated degrees above 30 °C in September. These changes can increase variability in yield (Hawkins et al., 2013) and quality. In general, more variables have been subject to change, and more intensely, in MJ than in Azul. Nevertheless, adaptation also significantly influenced yield, with adapted crops yielding on average 7–15% greater than non-adapted crops (Challinor et al. 2014). The different impact of climate change in these two cities should encourage differential agricultural practices and more studies of climate change impact at the local level. In addition, more extreme measures will probably need to be adopted to ameliorate these changes for yield and quality at these sites, involving, for example, earlier sowing to escape the more extreme months for certain critical stages of plant development.

4.3 Consequences of these findings for wheat cultivation

Our findings suggest climate change is expected in the wheat-growing region under study, the magnitude of which will depend upon the particular site involved. A special report of the IPCC (IPCC 2018) shows the consequences for crop production in general, and wheat production in particular, of these sorts of changes. It states that limiting global warming to 1.5 °C, compared with 2 °C, is projected to result in smaller net reductions in yields than would otherwise occur in maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America, as well as in smaller reductions in the CO_2-dependent nutritional quality of rice and wheat. Temperature and precipitation trends have reduced crop production and yields, with the most negative impacts being on wheat and maize, and climate variability has been found to explain more than 60% of maize, rice, wheat, and soybean yield variation in the main global breadbasket areas, with the percentage varying according to crop type and scale. Additionally, the report provides evidence that higher atmospheric CO_2 concentration will not compensate for increased temperatures, stating that observations of trends in actual crop yields indicate that reductions as a result of climate change remain more common than crop yield increases, despite increased atmospheric CO_2 concentrations. Furthermore, production stimulation at increased atmospheric CO_2 concentrations was mostly driven by differences in climate and crop species, while yield variability due to elevated CO_2 was only about 50–70% of the variability due to the climate. A significant reduction has been projected for global wheat production of 6.0 ± 2.9% for each degree Celsius increase in global mean temperature, and it should be noted that crop production is also negatively affected by the increase in climate extremes, including changes in rainfall extremes, increases in hot nights (Welch et al. 2010; Okada et al. 2011; García et al. 2018), extremely high daytime temperatures, and water stress.

In addition to the consequences for yield, the faster growth rates induced by elevated CO_2 have been found to coincide with lower protein content in several important C3 cereal grains (Myers et al. 2014), consistent with the reduced grain protein content and hence nutritional quality observed by Taub et al. (2008) and Pleijel and Uddling (2012).

Hence, the changes we are projecting in the study have potentially serious consequences for wheat production in Argentina. Assuming the aforementioned 5.1% fall in yields per degree Celsius increase in global mean temperature (Verón et al. 2015), our mean projections suggest that yields in Azul and Marcos Juaréz could fall by as much as approximately 6.5% and 14%, respectively, over the coming 100 years; the true figures will depend upon many factors, including the coincidence of the temperature changes with the critical yield determining periods in the wheat plant cycle. Although the increase in CO_2 could to some extent counteract the negative effects of warming on yield, this would be expected to reach a *plateau* due to possible feedback mechanisms (Long et al. 2006), whereas the temperatures would be expected to continue to exert deleterious effects in an increasing manner over time.

This in turn suggests that considerable countrywide changes in wheat production practices might be needed in the future. The changes in precipitation mentioned by Lovino et al. (2011) (see "Introduction") have already led to land use changes. It may be the case, as previously mentioned, that some current wheat-growing areas will cease to be apt for this purpose, representing enormous challenges that might only be offset by the conditions in some currently non-wheat-growing areas changing to allow wheat to be grown there. This pattern would be expected to occur in wheat-growing regions across the globe, unless large-scale remedial actions are implemented.

In this shifting regional and global scenario, what seems certain is that uncertainty lies ahead.

5 Conclusions

Two contrasting sites in the current wheat-growing region of Argentina (Azul, Province of Buenos Aires; and Marcos Juárez, Province of Córdoba) showed changes, broadly consistent with previous studies on climate change (Alexander et al. 2006; Nakicenovic et al. 2007; IPCC 2007b;

Trenberth et al. 2007; Fernández Long et al. 2008; Stocker et al. 2013; García et al. 2018), in both mean and extreme temperatures and rainfall values, by analysing climate data from the period of the year in which wheat yield and quality are broadly defined. The possible future scenarios that could result from these changes show greater severity for Marcos Juárez than for Azul, implying greater problems for yield and quality, unless measures can be found that ameliorate the changes; this is in spite of the fact that the two sites are only separated by approximately 500 km. As far as we are aware, extreme temperature and rainfall variables had not been previously analysed in the context of wheat production for these sites.

The first 15 years of the current century gave greater rates of change than the complete period, implying that future conditions could be even more acute than the simple projections imply, suggesting that new and severe challenges for agronomic production will have to be faced in the future. And, as previously mentioned, detrimental effects on yield due to temperature increase will not be totally countered by CO_2 increases, since these are expected to reach a *plateau* (Long et al. 2006), while temperature increases are expected to continue to rise. Also, the percentage fall in yield due to high temperatures depends on the moment of the cycle and the temperature range, in addition to the sensitivity of the genotypes: aspects that need to be explored. This type of study could help redefine the current "core" regions of different crops in the future.

We consider that the root causes of climate change need to be tackled and where this proves inadequate, alternative remedial action needs to be taken to avert prejudicing crop production in terms of both yield and quality, which would add serious uncertainty to a world already facing enormous challenges in feeding its burgeoning population.

Author contribution S.M.L. Basile, J.A. Tognetti and W.J. Rogers designed the study. S.M.L. Basile performed the analyses. S.M.L. Basile and W.J. Rogers wrote the manuscript. L.M. Gandini supervised and suggested analyses. J.A. Tognetti supervised analyses and criticised the manuscript.

Funding The study was financed by projects CONICET PIP 11420090100291, CIC-PBA No. 673/06, and UNCPBA 03/A192 and 03/A215.

Availability of data and materials The climatic data used in this study were provided by the Argentinean National Meteorological Service. cim@smn.gov.ar Lic. Ana Teresa Gómez and Insp Met Alicia de la Puente.

Declarations

Ethics approval Not applicable.

Consent to participate All the authors agree with the content of the manuscript.

Consent to publish All the authors agree with the publication of the content of the manuscript.

Competing interests The authors declare no competing interests.

References

Abbate PE, Lázaro L (2010). Estimación del rendimiento potencial de trigo en Paraguay y sus requerimientos de agua y nutrientes. In: Kholi MM, Cubilla LE, Cabrera G (eds), Del grano al pan. Editorial CAPECO/INBIO, Asunción, Paraguay, pp. 11–29.

Agnolucci P, Rapti C, Alexander P, De Lipsis V, Holland RA, Eigenbrod F, Ekins P (2020). Impacts of rising temperatures and farm management practices on global yields of 18 crops. Nat. Food. https://doi.org/10.1038/s43016-020-00148-x

Alexander LV, Zhang X, Peterson TC et al (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res. https://doi.org/10.1029/2005JD006290

Asseng S, Ewert F, Martre P et al (2015) Rising temperatures reduce global wheat production. Nat Clim Change. https://doi.org/10.1038/NCLIMATE2470

Barros V, Castañeda ME, Doyle M (1996). Variabilidad interanual de la precipitación: Señales del ENSO y del gradiente meridional hemisférico de temperatura. In: 'Impacto de las variaciones climáticas en el desarrollo regional un análisis interdisciplinario'. VII Congreso Latinoamericano e Ibérico de Meteorología, CAMFLISMET, Argentina, pp. 321–322.

Barros V (2015). Estudio de los cambios climáticos observados en el clima presente y proyectados a futuro en la República Argentina. Aspectos regionales. Tercera Comunicación Nacional de la República Argentina a la Convención Marco de las Naciones Unidas sobre Cambio Climático. Jefatura de Gabinete de Ministros. Presidencia de la Nación, Buenos Aires, Argentina. http://3cn.cima.fcen.uba.ar/TCN_CIMA_Vbarros_2015.pdf

Blain GC (2013) The Mann-Kendall test: the need to consider the interaction between serial correlation and trend. Acta Sci Agron. https://doi.org/10.4025/actasciagron.v35i4.16006

Berbery EH, Doyle M, Barros V (2006) Regional precipitation trends. In: Barros V, Clarke R, Silva Días P (eds), Climate change in the La Plata basin. Buenos Aires, CIMA/CONICET-UBA, pp. 61–73

Bréon FM, Collins W, Fuglestvedt J et al (2013). Chapter 8: anthropogenic and natural radiative forcing. In: Climate change. The Physical Science Basis, IPCC, pp. 659–740.

Cavalcanti IFA, Carril AF, Penalba OC et al (2015) Precipitation extremes over La Plata basin-review and new results from observations and climate simulations. J Hydrol. https://doi.org/10.1016/j.jhydrol.2015.01.028

Challinor AJ, Watson J, Lobell DB et al (2014) A meta-analysis of crop yield under climate change and adaptation. Nat Clim Change. https://doi.org/10.1038/nclimate2153

Chen X, Tung KK (2014) Varying planetary heat sink led to global-warming slowdown and acceleration. Science. https://doi.org/10.1126/science.1254937

De Saedeleer B (2016) Climatic irregular staircases: generalized acceleration of global warming. Sci Rep. https://doi.org/10.1038/srep19881

Di Rienzo JA, Casanoves F, Balzarini MG et al (2016). InfoStat versión 2016. Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina. [online]. Available in: http://www.infostat.com.ar

Easterling DR (2002) Recent changes in frost days and the frost-free season in the United States. B Am Meteorol Soc. https://doi.org/10.1175/1520-0477-83.9.1327

Easterling DR, Meehl GA, Parmesan C et al (2000) Climate extremes: observations, modeling, and impacts. Science. https://doi.org/10.1126/science.289.5487.2068

FAO (Food and Agriculture Organization of the United Nations). (2019). FAOSTAT Producción agrícola [online]. http://www.fao.org/faostat/es/#data/QC Accessed January 2019.

Fernández Long ME, Barnatán I, Serio L, Murphy G (2008). Cambios en la disponibilidad térmica para los cultivos de la región pampeana argentina. Rev Fac Agron UBA. 28(2,3): 111–120. http://ri.agro.uba.ar/files/download/revista/facultadagronomia/2008FernandezLong.pdf

Fernández-Long ME, Muller GV, Beltrán-Przekurat A, Scarpati OE (2012) Long-term and recent changes in temperature-based agroclimatic indices in Argentina. Int J Climatol. https://doi.org/10.1002/joc.3541

García GA, Dreccer MF, Miralles DJ, Serrago RA (2015) High night temperatures during grain number determination reduce wheat and barley grain yield: a field study. Glob Chang Biol. https://doi.org/10.1111/gcb.13009

García GA, Miralles DJ, Serrago RA, Alzueta I, Huth N, Dreccer MF (2018) Warm nights in the Argentine Pampas: modelling its impact on wheat and barley shows yield reductions. Agric Sist. https://doi.org/10.1016/j.agsy.2017.12.009

García GA, Serrago RA, Dreccer MF, Miralles DJ (2016) Post-anthesis warm nights reduce grain weight in field-grown wheat and barley. Field Crop Res. https://doi.org/10.1016/j.fcr.2016.06.002

Gelmi M, Seoane R (2013) Variación temporal de índices de precipitaciones extremas en el centro de la Provincia de Buenos Aires. GEOACTA 38:47–60

Hall AJ, Richards RA (2013) Prognosis for genetic improvement of yield potential and water-limited yield of major grain crops. Field Crops Res. https://doi.org/10.1016/j.fcr.2012.05.014

Hawkins E, Osborne TM, Kit Ho C, Challinor AJ (2013) Calibration and Bias Correction of Climate Projections for Crop Modelling: an Idealised Case Study over Europe. Agric for Meteorol. https://doi.org/10.1016/j.agrformet.2012.04.007

IPCC (2007a) Intergovernmental panel on climate change. [online]. https://archive.ipcc.ch/publications_and_data/ar4/syr/en/mains3-2.html. Accessed Jan 2022.

IPCC (2007b) Intergovernmental panel on climate change. [online]. https://archive.ipcc.ch/publications_and_data/ar4/syr/en/spms3.html. Accessed Jan 2022.

IPCC (2018) Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Masson-Delmotte V, Zhai P, Pörtner H-O et al. (eds). In Press.

Jenner CF (1994) Starch synthesis in the kernel of wheat under high temperature conditions. Aust J Plant Physiol. https://doi.org/10.1071/PP9940791

Karl TR, Knight RW (1998) Secular trends of precipitation amount, frequency, and intensity in the United States. Bull Am Meteorol Soc. https://doi.org/10.1175/1520-0477(1998)079%3c0231:STOPAF%3e2.0.CO;2

Kendall MG (1975) Rank correlation methods. Oxford University Press, New York

Lobell DB, Schlenker W, Costa-Roberts J (2011) Climate trends and global crop production since 1980. Science. https://doi.org/10.1126/science.1204531

Long SP, Ainsworth EA, Leakey ADB et al (2006) Food for thought: lower-than-expected crop yield stimulation with rising CO_2 concentrations. Science. https://doi.org/10.1126/science.1114722

Lovino MA, Müller OV, Müller GV et al (2018) Interannual-to-multidecadal hydroclimate variability and its sectoral impacts in northeastern Argentina. Hydrol Earth Syst Sci. https://doi.org/10.5194/hess-22-3155-2018

McGrath JM, Lobell DB (2013) Regional disparities in the CO_2 fertilization effect and implications for crop yields. Environ Res Lett. https://doi.org/10.1088/1748-9326/8/1/014054

Magrin GO, Travasso MI (2002) Chapter 10. An integrated climate change assessment from Argentina. In: Doering O, Randolph JC, Southworth J, Pfeifer RA (eds) Effects of climate change and variability on agricultural production systems. Kluwer Academic Publishers, Boston, USA, pp 193–219

Magrin GO, Travasso MI, Rodriguez GR (2005) Changes in climate and crop production during the 20th century in Argentina. Clim Change. https://doi.org/10.1007/s10584-005-5374-9

Magrin GO, Travasso MI, Rodriguez GR et al (2009) Climate change and wheat production in Argentina. Int J Global Warm. https://doi.org/10.1504/IJGW.2009.027090

Mann HB (1945) Non-parametric tests against trend. Econometrica. https://doi.org/10.2307/1907187

Martos Núñez VM (2003). Influencia del régimen hídrico sobre componentes de calidad del trigo duro (*Triticum durum* Desf.) en ambiente mediterráneo. Tesis de Licenciatura en Farmacia, Universidad de Granada, Facultad de Ciencias. Granada, España.

Ministerio de Agricultura de Argentina. (2018). Secretaría de Alimentos y Bioeconomía Dirección Nacional de Alimentos y Bebidas. Dirección de Cadenas Alimentarias. CADENA de la HARINA DE TRIGO- RESUMEN. http://www.alimentosargentinos.gob.ar/HomeAlimentos/Cadenas%20de%20Valor%20de%20Alimentos%20y%20Bebidas/informes/Resumen_Cadena_2018_harina_de_trigo_julio_2018.pdf Accessed September 2019.

Myers SS, Zanobetti A, Kloog I et al (2014) Rising CO_2 threatens human nutrition. Nature. https://doi.org/10.1038/nature13179

Molfese E (2016). Caracterización de la calidad del trigo pan en el centro sur bonaerense. (1a ed). Argentina: ediciones INTA.

Moore FC, Lobell DB (2015) The fingerprint of climate trends on European crop yields. Proc Natl Acad Sci USA. https://doi.org/10.1073/pnas.1409606112

N Nakicenovic J Alcamo G Davis (2007) Special report on emissions scenariosm vol. 2000. IPCC Cambridge University Press Cambridge, 570

Nicholls N (1995) Long term climate monitoring and extreme events. Clim Change. https://doi.org/10.1007/BF01095148

Nuñez M, Solman S, Cabré S (2008). Regional climate change experiments over southern South America. II: climate change scenarios in the late twenty first century. Clim Dyn. https://doi.org/10.1007/s00382-008-0449-8

Okada M, Iizumi T, Hayashi Y, Yokozawa M (2011). Modeling the multiple effects of temperature and radiation on rice quality. Environ Res. Lett. https://doi.org/10.1088/1748-9326/6/3/034031

Pleijel H, Uddling, J (2012). Yield vs. quality trade-offs for wheat in response to carbon dioxide and ozone. Glob Change Biol. https://doi.org/10.1111/j.1365-2486.2011.2489.x

Plummer N, Salinger MJ, Nicholls N et al (1999). Changes in climate extremes over the Australian region and New Zealand during the twentieth century. In: Karl TR, Nicholls N, Ghazi A (Eds.), Weather and climate extremes. Springer, Dordrecht. Holland, pp. 183–202.

Randall PJ, Moss HJ (1990) Some effects of temperature regime during grain filling on wheat quality. Aust J Agric Res. https://doi.org/10.1071/AR9900603

Ray DK, Gerber JS, MacDonald GK, West PC (2015) Climate variation explains a third of global crop yield variability. Nat Commun. https://doi.org/10.1038/ncomms6989

Re M, Barros VR (2009) Extreme rainfalls in SE South America. Clim Change. https://doi.org/10.1007/s10584-009-9619-x

Reynolds M, Foulkes MJ, Slafer GA et al (2009) Raising yield potential in wheat. J Exp Bot. https://doi.org/10.1093/jxb/erp016

Rivelli·GM, Fernández Long ME, Abeledo LG, Calderini DF, Miralles DJ, Rondanini DP (2021) Assessment of heat stress and cloudiness probabilities in post-flowering of spring wheat and canola in the Southern Cone of South America. Theor Appl Climatol. https://doi.org/10.1007/s00704-021-03694-x

Rolla AL, Nuñez MN, Guevara ER et al (2018).Climate impacts on crop yields in Central Argentina. Adaptation strategies. Agric Syst. https://doi.org/10.1016/j.agsy.2017.08.007

Rosenzweig C, Elliott J, Deryng D et al (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc Natl Acad Sci USA. https://doi.org/10.1073/pnas.1222463110

Rusticucci M, Barrucand M (2004) Observed trends and changes in temperature extremes over Argentina. J Clim. https://doi.org/10.1175/1520-0442(2004)017%3c4099:OTACIT%3e2.0.CO;2

Saini HS, Aspinall D (1982) Abnormal sporogenesis in wheat (*Triticum aestivum* L.) induced by short periods of high temperature. Ann Bot. https://doi.org/10.1093/oxfordjournals.aob.a086310

Schleussner C-F, Lissner TK, Fischer EM et al (2016). Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 ºC and 2 ºC. Earth Syst Dyn. 10.5194/esd-7-327-2016

Slafer GA, Miralles DJ, Savin R et al (2003). Capítulo 7: Ciclo ontogénico, dinámica del desarrollo y generación del rendimiento y la calidad en trigo. In: Satorre EH, Benech Arnold RL, Slafer GA, et al (eds), Producción de Granos. Bases Funcionales para su Manejo. Facultad de Agronomía. Bs. As. Argentina, pp. 101–132.

StatSoft, Inc. (2004). STATISTICA (data analysis software system), version 7. www.statsoft.com. Accessed August 2019.

Stocker TF, Qin D, Plattner GK et al (2013). Technical summary. In: Stocker TF, Qin D, Plattner GK et al (eds). Climate Change 2013: *The physical science basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change´. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Stone PJ, Savin R (1999) Grain quality and its physiological determinants. In: Satorre EH, Slafer GA (eds) Wheat: ecology and physiology of yield determination. Food Product Press, New York, USA, pp 50–120

Taub D, Miller B, Allen H (2008) Effects of elevated CO2 on the protein concentration of food crops: a meta-analysis. Glob Change Biol. https://doi.org/10.1111/j.1365-2486.2007.01511.x

Trenberth KE, Jones PD, Ambenje P et al (2007). Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M et al (eds), Climate Change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge and New York, USA.

UNFCCC (United Nations Framework Convention on Climate Change) (2016). Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015. Decision 1/CP.21 Adoption of the Paris Agreement. https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf

Verón SR, de Abelleyra D, Lobell DB (2015) Impacts of precipitation and temperature on crop yields in the Pampas. Clim Change. https://doi.org/10.1007/s10584-015-1350-1

Vignjevic M, Wang X, Olesen JE, Wollenweber B (2015) Traits in spring wheat cultivars associated with yield loss caused by a heat stress episode after anthesis. J Agron Crop Sci. https://doi.org/10.1111/jac.12085

Welch JR, Vincent JR, Auffhammer M et al (2010): Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. Proc Natl Acad Sci U.S.A. https://doi.org/10.1073/pnas.1001222107

World Bank (2013). Turn down the heat: climate extremes, regional impacts, and the case for resilience. A report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics. Washington, DC: World Bank. License: Creative Commons Attribution—NonCommercial–NoDerivatives3.0 Unported license (CC BY-NC-ND 3.0). ISBN (electronic): 978–1–4648–0056–6

Zhao C, Liu B, Piao S et al (2017). Temperature increase reduces global yields of major crops in four independent estimates. Proc Natl Acad Sci U S A. https://doi.org/10.1073/pnas.1701762114