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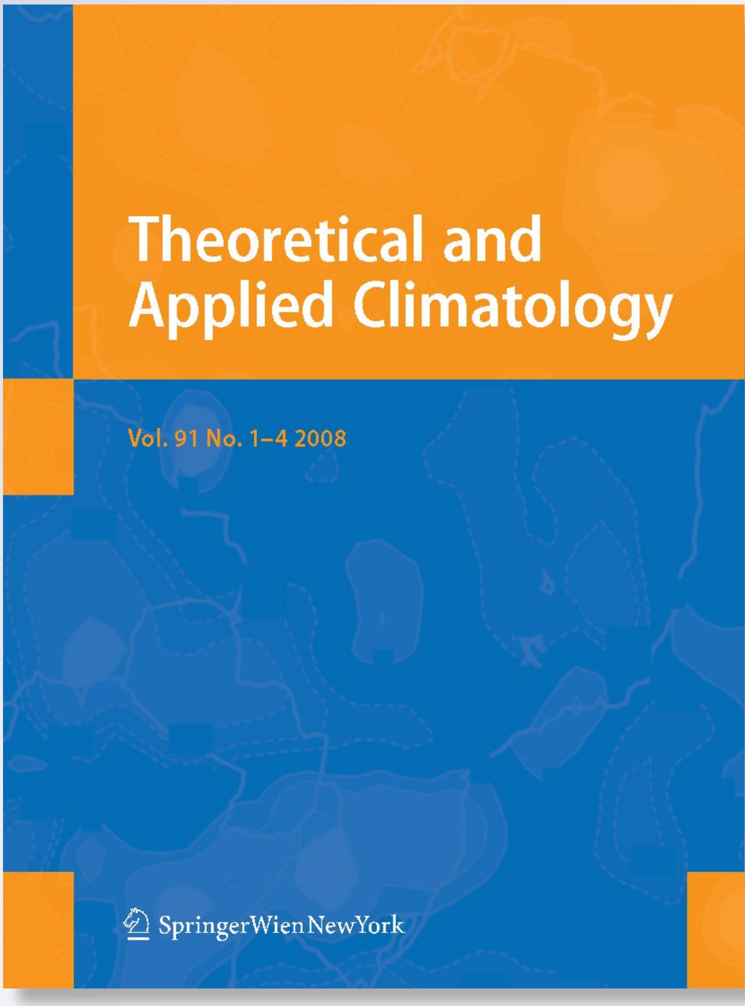

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ORIGINAL PAPER

# Analysis of the climatic constraints to maize production in the current agricultural region of Argentina—a probabilistic approach

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**Abstract** A simple method of analysis was proposed to characterize the impact of climatic conditions of a wide region of Argentina (from 27°05′S to 35°48′S, from 61°5′W to 64°21′W) on potential maize (*Zea mays* L.) grain yield, and the occurrence of various climatic constraints (low temperatures and low soil water content, frost, drought stress and heat stress) along the cycle. The analysis was based on previous studies of the eco-physiology of maize crops and the use of climatic records of six locations in the region under study. Results were analyzed using a probabilistic method, later organized as a checklist to consider when deciding on sowing date in a location of the region. Thus, for each production scenario (combination of location and sowing date), farmers would have a tool enabling them to pay particular attention to the restrictions more likely to occur, to include some cultural practices to avoid or mitigate the most severe climatic constraint to maize production.

## 1 Introduction

For several decades, maize production in Argentine was concentrated within the most productive sub-region of the Pampas, i.e., the Rolling Pampas (32°S to 36°S and 58°W to 63°W) (Hall et al. 1992). This humid (approximately 950 mm year$^{-1}$) temperate (mean annual temperature of 16°C, frost-free period of 240 days) area has the least number of climatic constraints to agriculture in Argentina and the most fertile soils (i.e., Typic Argiudolls; Soil Survey Staff 2010). Favourable international prices of agricultural commodities (from FAO website; http://www.fao.org/es/esc/prices) together with changes in climate trends, e.g., increases in precipitation up to 50% in some areas of the Pampas (Barros 2008), have promoted the expansion of agriculture into previously semiarid areas (less than 700 mm year$^{-1}$, mean annual temperature of 16°C and a frost-free period of 220 days), e.g., to the west and southwest of the Rolling Pampa, the Inland Pampa (Soriano 1991), where grazing pasture was the dominant land use. Similarly, the agricultural frontier has shifted to the north of the Rolling Pampas after deforestation of native forests (Dirección de Bosques 2007). Hence, today maize cultivation has expanded out of the traditional temperate production area (Fig. 1a), sustaining the Argentinean annual land area (ca. 3 million ha) occupied with this summer cereal, but without a profound analysis of the impact of climatic constraints on maize productivity.

Maize crops in Argentina are mostly cultivated under rainfed conditions; therefore the main climatic constraint is the water supply around flowering (Hall et al. 1982), i.e., the most critical period for kernel set (Tollenaar et al. 1992; Andrade et al. 1999). In several agricultural regions of the country, total annual rainfall (>700 mm) generally exceeds maize demand ~500–600 mm (Li et al. 2003; Suyker and Verma 2009; Zhao et al. 2010). Rainfall distribution along the year, however, exhibits low precipitations during winter (from late June to late September) and early summer (i.e., January). The low rainfall of January together with the high atmospheric demand determine a seasonal summer drought (i.e., daily evapotranspiration exceeds daily rainfalls). So, in the temperate areas of the Pampas, maize crops are sown in

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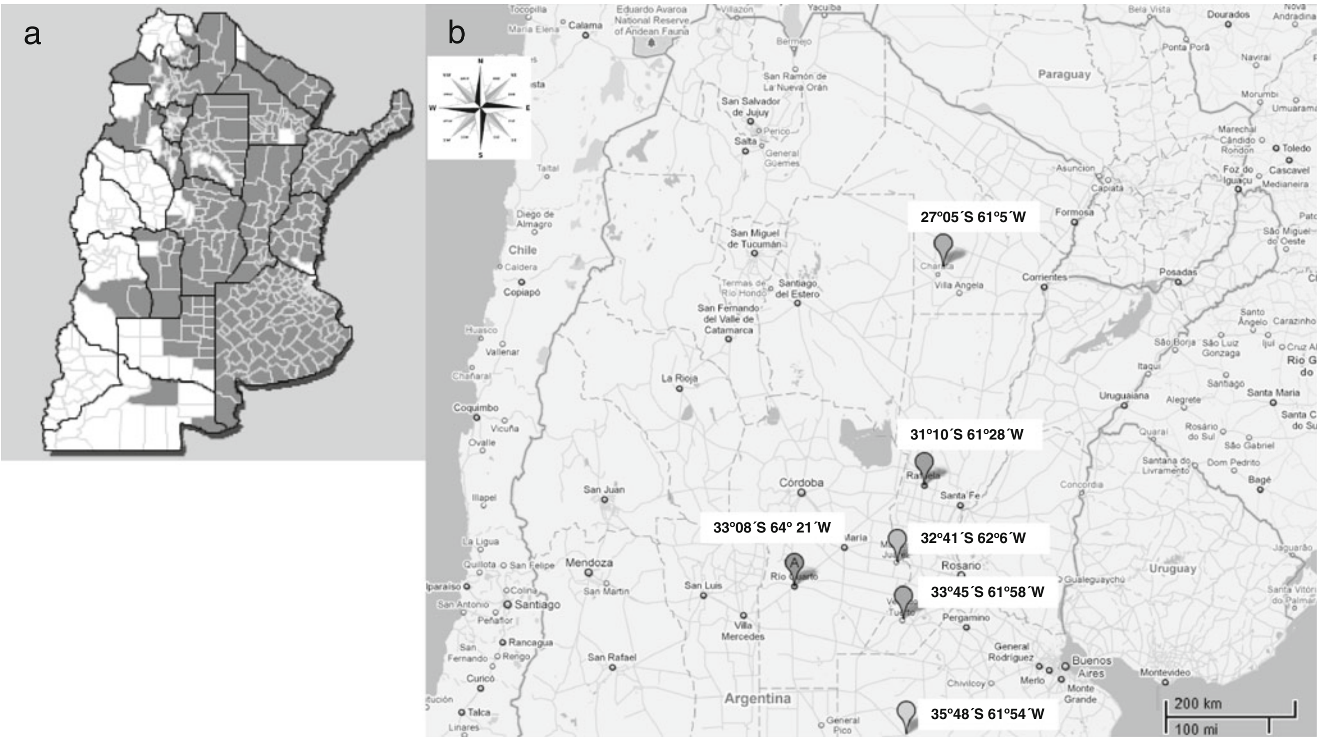


**Fig. 1** **a** Actual maize cultivation area in Argentina (source: http://www.minagri.gob.ar/SAGPyA/agricultura/cultivos_en_la_argentina/01-mapa_principales_cultivos/). **b** The location of the six locations analyzed in this work (source: http://maps.google.com/)

early spring, and flowering occurs at the end of this season, before the seasonal summer drought, with warm temperatures and high levels of solar radiation. These climatic conditions determine a long maize growing season (ca. 90 days from sowing to female flowering, 140 days total cycle) with both high light interception and light conversion to biomass. Hence, maize rainfed crops at early sowing dates (late September) attain maximum productivities (Otegui et al. 1995a). The advantage of early sowing dates could be reduced by the risk of crop damage by spring frosts during the pre-flowering period. Additionally, both low soil temperatures (Padilla et al. 2004) and less frequent rainfalls at early spring may cause uneven seedling emergence (Silberfaden 2010) with the consequent reduction of maize grain yield (Liu et al. 2004).

Another possibility to avoid the coincidence of maize flowering with the seasonal summer drought in temperate regions of Argentina is to sow maize crops at the end of the spring season (i.e., November–December). Maize crops at late sowing dates generally exhibit a short cycle due to the high air temperatures during the pre-flowering period (Otegui et al. 1995a). For these sowing dates, female flowering occurs at mid-summer (ca. at February), and the grain filling period is displaced to the end of the summer and the beginning of the autumn, with a decline of both solar radiation and air temperature (Otegui et al. 1995a). Hence, maize productivity at late sowing dates tends to be lower than those at early sowings. Moreover, maize crops at late sowing dates are mostly affected by biotic stress such as stem borer (*Diatraea saccharalis*) and fall armyworm (*Spodoptera frugiperda*) (Wiatrak et al. 2004). After the appearance of transgenic maize hybrids resistant to *Lepidoptera* (Williams et al. 1997) the late sowed maize crops have spread in the temperate regions of Argentina with very good results. Thus, the sowing date of late crops may vary from early December to mid-January, as the latitude decreases from 36°S to 31°S (Mercau and Otegui 2002). Climatic constraints to maize production at these late sowings dates may be linked to heat stress (Wilhelm et al. 1999) at mid-summer and frost injuries at early autumn, both factors mainly affecting the grain-filling period.

Despite the climatic diversity among latitudes of the Argentinean agricultural regions, and those among the different sowing dates of a location, no information exists about the risk of several climatic constraints to maize production with a probabilistic approach. Eco-physiological studies of maize crops have quoted several simple relationships which describe maize responses to environmental factors. Based on some of these relationships, Maton et al. (2007) developed a model to simulate the number of days suitable for sowing maize in a cool place in the SW of France, taking into account the risk of frost, low temperatures and the humidity of soil at sowing. Otegui et al. (1996) developed a correlative model from experimental data to explore the effects of sowing date on maize potential grain yield (i.e., without biotic and abiotic stresses) in the Rolling Pampas of Argentina. However, no information exists of the effect of sowing dates on maize grain yield in conjunction with the risk of several climatic constraints along the crop cycle for the current maize production region of Argentina. In this work, simple relationships among climate variables (i.e., maximum and minimum air temperature, solar radiation, rainfalls) and both maize phenology and crop growth, coupled with long term series (ca. 30 years) of daily climatic records, were used to predict inter-annual variability of maize developmental stages, cumulative frequencies of potential grain yields, and the risk of several climatic constraints (low temperatures and low soil water content at seedling emergence, frost damage at early and late maize stages, water deficit around flowering, and heat stress around flowering and during the effective grain-filling period) at different scenarios (combination of location and sowing date) within the current Argentine maize production area.

## 2 Material and methods

### 2.1 Locations and sowing dates

Six locations were selected in an area comprised between 27°S and 35°S and 61°W and 64°W (Fig. 1b), where altitude varies from 85 to 426 m above the sea and soil types include Entic Durustalfs, Typic Argiudolls, Entic Haplustolls and Typic Haplustolls (Table 1). Climatic series are available for these locations with the last 28–33 years of daily records of maximum and minimum air temperature, solar radiation and rainfalls. Climatic data were provided by the National Weather Service. The frost-free period decreases from the north (~180 days) to the south (~140 days) of the region, due to both a later date of the late frost and an earlier date of the early frost. Similarly both minimum and maximum air temperatures decrease as latitude increases, varying the mean annual air temperature from 21.5°C to 15.7°C. As latitude increases, mean daily solar radiation decreases (from 17 to 15.7 MJ $m^{-2}$ $day^{-1}$), but the mean photoperiod duration is almost not affected (~13 h) because the shortening of day length during the winter is balanced by the lengthening of the duration of summer days. In the same way, mean annual rainfall does not vary from the north to the south (~1,000 mm), but decreases (~860 mm) to the west of the region.

**Table 1** Characteristics of locations and climatic records (means of the last 28–33 years) at each location

| Location | Soil type | Altitude (m) | Latitude | Longitude | Frost-free period[a] (days) | Mean air temperature (°C) | | | Mean Solar radiation (MJ $m^{-2}$ $day^{-1}$) | Annual rainfalls (mm) | Mean Photoperiod (minimum; maximum) (h) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Minimum[b] | Maximum[b] | Annual | | | |
| Las Breñas | Entic Durustalfs | 103 | 27°05'S | 61°5'W | 16 Oct–12 Apr (178 days) | 15.3 | 27.8 | 21.5 | 17.0 | 1006 | 12.95 (11.3; 14.7) |
| Rafaela | Typic Argiudoll | 91 | 31°10'S | 61°28'W | 19 Oct–16 Apr (170 days) | 10.3 | 24.5 | 18.3 | 16.2 | 1032 | 12.99 (11.01;15.1) |
| Marcos Juárez | Typic Argiudoll | 105 | 32°41'S | 62°6'W | 26 Oct–22 March (147 days) | 11.6 | 23.7 | 17.6 | 15.9 | 909 | 13.01 (10.9;15.2) |
| Río Cuarto | Entic/Typic Hapludoll | 426 | 33°08'S | 64°21'W | 16 Oct–13 Apr (178 days) | 11.2 | 22.6 | 16.9 | 14.8 | 863 | 13.02 (10.8;15.4) |
| Venado Tuerto | Typic Hapludoll | 112 | 33°45'S | 61°58'W | 22 Oct–22 March (150 days) | 9.9 | 23.02 | 16.4 | 15.9 | 938 | 13.02 (10.8;15.3) |
| Pehuajó | Entic Hapludolls | 85 | 35°48'S | 61°54'W | 11 Nov–26 March (136 days) | 9.7 | 21.8 | 15.7 | 15.7 | 955 | 13.05 (10.7;15.6) |

[a] The mean frost-free period was estimated considering the mean dates of the last and the first frost ±2 SD

[b] Minimum and maximum values were calculated from daily values of each record during the year

At each location five sowing dates were analyzed, 1st August, 1st September, 1st October, 1st November and 1st December. Despite the earliest sowing date not being a current practice at the south of the region; it was also analyzed to compare among locations the risk of different climatic constraints of each sowing date. For the same reason, earlier and later sowing dates used at the north of the region, were not included in the analysis.

### 2.2 Maize phenology

The inter-annual variability of maize phenology at each scenario (location×sowing date) was simulated with a thermal time model. The accuracy of thermal time model to simulate phenology of crops has been validated in several species (e.g., *Zea mays* [Hodges and Evans 1990]; *Triticum aestivum* [Jamieson et al. 1998]; *Brassica oleracea* [Tan et al. 2000]; *Olea europaea* [DeMelo-Abreu et al. 2004]; *Helianthus annuus* [Aiken 2005]). The thermal time model describes the duration of the different crop stages in thermal units (degree days, °Cd) to include the universal effect of temperature on crop development (Ritchie and Nesmith 1991). Hence, the thermal time duration (TT) of a phase is estimated as:

$$\mathrm{TT}\ (^{\circ}\mathrm{Cd}) = \sum (T_{\mathrm{m}} - T_{\mathrm{b}}) \tag{1}$$

where $T_{\mathrm{m}}$ is the mean air temperature of a day (the average of the minimum and the maximum air temperature) and $T_{\mathrm{b}}$ is the base temperature for the phase under study.

At each scenario, maize phenology was simulated with daily $T_{\mathrm{m}}$ of each of the years of climatic series and TT and $T_{\mathrm{b}}$ values reported for temperate argentine maize hybrids (Table 2). Dates of the following phenological stages were simulated: (i) seedling emergence ($V_e$), the seven-ligulated leaf stage ($V_7$), female flowering ($R_1$), and physiological maturity ($R_6$). The durations of the periods (in days) from sowing to each phenological stage were calculated.

While maize apex is below soil surface (from seedling germination to ~$V_{6\text{–}7}$), soil temperature better describes the effect of temperature on maize development (Vinocur and Ritchie 2001). This climatic record, however, is not often available; hence, air temperature was used to compute TT at any maize stages as most phenological models do (e.g., Ceres-Maize model; Jones and Kiniry 1986). Photoperiod effect on maize phenology (i.e., the quantitative reduction of *TT* to floral induction as the duration of the day decreases) was not considered based on previous information of the performance of temperate maize hybrids in Argentina at contrasting sowing dates (Otegui et al. 1995a; Maddonni and Otegui 1996; Otegui and Melon 1997).

### 2.3 Maize growth

A simple model was used to quantify the inter-annual variability of maize growth at each scenario. This model gave good predictions of sowing date effect on potential maize grain yields in a temperate region of Argentina (Otegui et al. 1996). Briefly, the model was based upon relationships between (i) photosynthetically active radiation intercepted by the crop (IPAR) and *TT* (Eqs. 2–4), (ii) total biomass and IPAR (Eq. 5) and (iii) grain yield and total biomass (Eq. 6).

$$\mathrm{IPAR} = \mathrm{fIPAR}\ 0.45\ \text{incident solar radiation} \tag{2}$$

$$\mathrm{fIPAR} = 0.00189\ (\mathrm{TT} - 115);\ \text{for } 592 \geq \mathrm{TT} \geq 115 \tag{3}$$

$$\mathrm{fIPAR} = 0.90;\ \text{for } 1800 >= \mathrm{TT} > 592 \tag{4}$$

$$\text{Total biomass} = -253 + 3.39\ \mathrm{IPAR} \tag{5}$$

$$\text{Grain yield} = 0.46\ \text{Total biomass} \tag{6}$$

At each scenario, simulations were carried out with daily $T_{\mathrm{m}}$ and daily incident solar radiation of each of the years of climatic series. Photosynthetically active radiation was estimated as a fraction (0.45) of incident solar radiation (Monteith 1965). To simplify maize growth estimation, a constant (3.39 $\mathrm{gMJ}^{-1}$) radiation use efficiency (RUE) was used during the whole maize cycle (Otegui et al. 1996). The reported decline of RUE with $T_{\mathrm{m}}$<20°C (Andrade et al. 1993) was not considered. This effect, which leads to a reduced crop growth, was documented in maize crops cultivated at more southern latitudes (37°45′S) than those explored in the present study. A constant harvest index (0.46) was used to estimate grain yield from total biomass, because a reduced dry matter partitioning to kernels is not expected under potential conditions (Sinclair et al. 1990).

### 2.4 Climatic constraints for maize production

The negative effects of temperature included (i) low temperatures during the seedling-emergence period, (ii) crop damage by late and early frosts and (iii) heat stress during the critical period and the effective grain-filling period.

Based on $T_{\mathrm{b}}$ for the seedling-emergence period (Table 2), *TT* was not accumulated if $T_{\mathrm{m}}$ was lower than 10°C. Consequently, under lower temperatures, or temperatures close to $T_{\mathrm{b}}$, the duration (in days) of this period was extended. Duration longer than 10 days was considered a

**Table 2** Durations (in thermal time units; TT) and base temperatures ($T_b$) of different maize phases used to simulate the inter-annual variability of maize phenology at each scenario (location×sowing date)

| Maize phase | TT (°Cd) | $T_b$ (°C) | Authors |
|---|---|---|---|
| From sowing to Ve | 90 | 10 | Padilla et al. (2004) |
| From $V_e$ to $V_7$ | 280 | 8 | Otegui and Melón (1997) |
| From $V_e$ to $R_1$ | 900 | 8 | Maddonni et al. (1999), Tanaka and Maddonni (2008) |
| From $V_e$ to $R_6$ | 1800 | 8 | Maddonni et al. (1999), Tanaka and Maddonni (2008) |
| From $R_2$ to $R_6$[a] | 700 | 8 | Tanaka and Maddonni (2008) |
| Critical period[b] | 420 | 8 | Otegui and Bonhomme (1998), Tanaka and Madonni (2008) |

Phenology was described by Ritchie et al. (1993) scale

[a] The effective grain-filling period

[b] The critical period starts at 220°Cd before $R_1$ and ends 200°Cd after $R_1$

climatic constraint due to its impact on seedling emergence synchrony (Padilla et al. 2004).

The effect of frost damage at each scenario was estimated from simulations of maize phenology and minimum daily air temperatures ($T_{min}$) of each year of the climatic series. The occurrence of $T_{min}$ below 2°C from $V_7$ onward was considered detrimental for maize growth. This temperature value is higher than those used in other studies to establish an episode of frost (Wilson et al. 1995; Otegui et al. 1996; Maton et al. 2007). However, farmers commonly observe frost damage when $T_{min}$ recorded at the meteorological enclosure is less than 3–4°C (De Fina and Ravelo 1979). It is probable that $T_{min}$ in the field is lower than that recorded in the meteorological enclosure. Thus, in this paper, maize phenological model was interrupted, and no grain yield was obtained (i.e., 100% of grain yield reduction) if $T_{min}$ were less than 2°C from $V_7$ to $R_1$. Contrarily, if the frost took place during the effective grain-filling period, fIPAR was set to zero, the post-flowering period was interrupted and grain yield was calculated from a reduced total biomass (Eq. 6) due to the low IPAR (Eq. 5). Frost damage was quantified by means of the percentage of grain yield reduction in comparison with grain yield of crops without frost damage.

At each scenario, the onset of heat stress throughout the critical period and during the effective-grain filling period was estimated from maize phenology and maximum daily air temperatures ($T_{max}$) of each of the years of climatic series. The occurrence of heat stress during the two periods was described by the number of days with $T_{max}$>35°C (Berry and Bjorkman 1980; Commuri and Jones 2001).

Climatic constraints for maize production related to water availability included (i) soil water content (SWC) at the sowing depth and in the soil profile at sowing, and (ii) water balance during the critical period.

The optimum SWC to maximize the proportion of seedling germination and to reduce the duration of seedling-emergence period is close to the upper limit of water extraction (Silberfaden 2010). Maize seeds can be sown at a depth of about 2.3 times the size of the kernels (at ~5 cm soil depth). Therefore, the upper limit of water extraction at this soil depth (~8 mm of available soil water) could be achieved with effective rainfalls >10 mm. For each location and year of the climatic series, rainfalls were accumulated every 10 days for the months of August, September, October, November and December and the resulting values were compared with the threshold value of 10 mm.

The accumulated rainfalls from 1st April to the sowing dates of each location were used to estimate the probability of sowing the crop on a soil with SWC close to the upper limit of water extraction. The date of 1st April was used as the most likely date of commencement of a fallow period (i.e., close to the harvest of the previous crop). Accumulated rainfalls were computed with daily rainfalls of each of the years of the climatic series. An accumulated rainfall value >200 mm was used as a threshold value to consider the SWC close to the upper limit of water extraction (Ratliff et al. 1983).

At each scenario, the water balance during the critical period (from $R_1$-220°Cd to $R_2$) was calculated as follows:

$$\text{Water balance}_{\text{from R1}-220^\circ\text{Cd to R2}} = \text{SWC}_{\text{at R}_1-220^\circ\text{Cd}} + \text{total rainfall}_{\text{from R}_1-220^\circ\text{Cd to R}_2} - \text{ET}_{\text{c from R}_1-220^\circ\text{Cd to R}_2} \quad (7)$$

$$\text{SWC}_{\text{at R1}-220^\circ\text{Cd}} = \text{SWC}_{\text{at sowing}} + \text{total rainfall}_{\text{from sowing to R}_1-220^\circ\text{Cd}} - \text{ETc}_{\text{from sowing to R}_1-200^\circ\text{Cd}} \quad (8)$$

where ETc is the potential crop evapotranspiration.

Soil water content at sowing was estimated from the accumulated rainfall during the fallow period, for each of the years of the climatic series. Similarly, total rainfall from sowing to $R_1$-220°Cd or from $R_1$-220°Cd to $R_2$ were accumulated during the simulated phenological stages. The ETc was estimated following Priestley–Taylor methodology modified by Ritchie (1998) (Eqs. 9–12). The albedo value varies from 0.15 at sowing to 0.23, when maximum leaf area index (LAI) is attained (Eq. 13). In this paper, LAI development was estimated from simulated fIPAR values (Eq. 14) (Flénet et al. 1996).

$$\mathrm{ETc} = \text{solar radiation}\ (23.923)(0.000204 - 0.000183\ \text{albedo})(29 + T_{\max}0.6 + T_{\min}0.4)A \tag{9}$$

$$A = 0.01\mathrm{e}^{(0.18(T_{\max}\ \text{albedo}+20)}; \text{ if } T_{\max} < 5^{\circ}\mathrm{C} \tag{10}$$

$$A = 1.1; \text{ if } 5^{\circ}\mathrm{C} < T_{\max} < 35^{\circ}\mathrm{C} \tag{11}$$

$$A = (T_{\max} - 32)0.05 + 1.1; \text{ if } T_{\max} > 35^{\circ}\mathrm{C} \tag{12}$$

$$\text{Albedo} = 0.23 - (0.23 - 0.15)\mathrm{e}^{(-0.75\mathrm{LAI})} \tag{13}$$

$$\mathrm{LAI} = -\ln(1 - \mathrm{fIPAR})/0.6 \tag{14}$$

Soil water content <100 mm (ca. less than 50% of soil water availability) at $R_2$ was considered as an index of water stress (Sadras and Milroy 1996).

### 2.5 Data analysis

At each scenario (location×sowing date), the inter-annual variability of the different phenological stages was described by the mean date of each stage and the standard deviation (SD). At each location, the inter-annual variability of potential grain yields on the different sowing dates was presented by the cumulative frequencies of these records. For this purpose, simulated potential grain yields for each year of the climatic series were ranked in ascending order and the cumulative frequency was calculated for each value. At each location, the sowing date effect on potential grain yield was analyzed with the two-sample *t*-test (i.e., the difference between mean values=0). A test for equality of variance was previously performed to analyze the assumption of equal or different group of variances. The inter-annual variability of potential grain yield was quantified by the coefficient variation (CV) of the mean. At each scenario the cumulative frequencies of the following climatic constraints were also estimated: (i) the duration of the period from sowing to seedling emergence, (ii), total rainfall <10 mm during the different 10-day periods of the 5 months of sowing, (iii) frost damage, (iv) total rainfall <200 mm from 1 April to the five sowing dates, (v) water balance at the end of the critical period, and (vii) days with maximum air temperatures >35°C during the critical period and the effective grain filling period.

## 3 Results

### 3.1 Maize phenology

In the region under study, the simulated duration of the maize cycle (Table 3) ranged from ca. 101 days (on the latest sowing date at the most northern location; Las Breñas) to ca. 203 days (on the earliest sowing date at the south of the region; Pehuajó). Similarly, the shortest (ca. 52 days) and the longest (ca. 140 days) pre-flowering periods (from sowing to $R_1$) were simulated for the same scenarios mentioned above. At all locations, the duration of the pre-flowering period was reduced when the date of sowing was delayed from 1st August to 1st December. This trend was also recorded on the simulated duration of total maize cycle at Las Breñas and Rafaela, but was reversed on the last date of sowing at the other locations because of the longer duration of the post-flowering period. The differences between locations and sowing dates on the durations of the pre- and post-flowering periods were related to the different evolution of $T_{\mathrm{m}}$ along the year (Fig. 2). At all locations, when sowing date was delayed the pre-flowering period was simulated with higher values of $T_{\mathrm{m}}$. Similarly, the simulated grain-filling period on the last sowing date at Las Breñas and Rafaela occurred with high $T_{\mathrm{m}}$, while in the other locations, this period was simulated with falling $T_{\mathrm{m}}$.

At each scenario, the inter-annual variability of $T_{\mathrm{m}}$ on maize phenology was reflected in the *SD* of the simulated date of each phenological stage (Table 3). Both the latitude and the sowing date had an impact on the SD of the date of some ontogenic stages. For example, the SD of the date of $V_e$ increased with the latitude for all simulated sowing dates. At a given location, the SD of the date of $V_e$ decreased as sowing was delayed from 1st August to 1st December. Latitude effect on the inter-annual variability of the simulated date of $R_6$ was higher for November and December sowings than for the other sowing dates. The inter-annual variability of other ontogenetic stages did not exhibit clear response patterns to latitude or sowing date.

### 3.2 Maize growth and potential grain yield

The responses of simulated maize growth and grain yield to changes of the date of sowing differed among locations. As grain yield was estimated as a proportion of the total biomass, only results of the former variable were presented (Fig. 3). At Las Breñas, the simulated potential grain yields increased ($P$<0.001) as sowing date was delayed from 1st August (ca. 730 gm$^{-2}$) to 1st November (ca. 1,450 gm$^{-2}$)

**Table 3** Simulations of the dates (mean value and standard deviation; SD) and days after sowing (mean value) of four ontogenic stages ($V_e$, $V_7$, $R_1$, and $R_6$) of a temperate maize hybrid cultivated at six locations on five sowing dates

| Sowing date | Stage | Locations | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Las Breñas | | Rafaela | | Marcos Juárez | | Río Cuarto | | Venado Tuerto | | Pehuajó | |
| | | Date (SD) | Days | Date (SD) | Days | Date (SD) | Days | Date (SD) | Days | Date (SD) | Days | Date (SD) | Days |
| 1st Aug | $V_e$ | 13 Aug (7.3) | 13 | 23 Aug (6.9) | 23 | 29 Aug (8.7) | 28 | 1 Sep (9.8) | 31 | 6 Sep (11.3) | 37 | 10 Sep (9.8) | 41 |
| | $V_7$ | 12 Sep (16.9) | 43 | 30 Sep (7.0) | 61 | 6 Oct (10.0) | 66 | 10 Oct (5.9) | 70 | 17 Oct (7.3) | 77 | 24 Oct (6.3) | 85 |
| | $R_1$ | 25 Oct (6.9) | 86 | 23 Nov (5.8) | 115 | 29 Nov (7.3) | 120 | 3 Dec (5.9) | 125 | 9 Dec (7.7) | 131 | 18 Dec (5.5) | 140 |
| | $R_6$ | 18 Dec (7.2) | 140 | 19 Jan (5.8) | 171 | 25 Jan (7.2) | 178 | 2 Feb (7.0) | 186 | 8 Feb (11.2) | 192 | 19 Feb (7.0) | 203 |
| 1st Sep | $V_e$ | 9 Sep (2.6) | 9 | 16 Sep (5.0) | 16 | 18 Sep (5.5) | 17 | 19 Sep (4.6) | 18 | 23 Sep (6.4) | 22 | 25 Sep (5.7) | 25 |
| | $V_7$ | 2 Oct (4.7) | 32 | 17 Oct (4.3) | 46 | 20 Oct (4.6) | 49 | 21 Oct (4.0) | 51 | 27 Oct (7.1) | 57 | 2 Nov (5.2) | 63 |
| | $R_1$ | 13 Nov (5.2) | 73 | 5 Dec (4.7) | 95 | 8 Dec (5.7) | 99 | 11 Dec (5.5) | 102 | 16 Dec (7.9) | 107 | 25 Dec (6.2) | 115 |
| | $R_6$ | 2 Jan (5.3) | 124 | 28 Jan (6.8) | 150 | 3 Feb (6.2) | 155 | 11 Feb (6.8) | 163 | 15 Feb (11.3) | 168 | 27 Feb (10.6) | 180 |
| 1st Oct | $V_e$ | 7 Oct (2.1) | 6 | 10 Oct (2.7) | 10 | 11 Oct (2.7) | 11 | 12 Oct (2.7) | 11 | 13 Oct (3.3) | 13 | 16 Oct (3.4) | 15 |
| | $V_7$ | 27 Oct (6.1) | 26 | 5 Nov (6.3) | 35 | 6 Nov (4.1) | 36 | 7 Nov (3.4) | 38 | 10 Nov (4.3) | 41 | 15 Nov (5.9) | 45 |
| | $R_1$ | 3 Dec (3.4) | 64 | 18 Dec (4.7) | 78 | 20 Dec (4.6) | 81 | 23 Dec (4.9) | 84 | 29 Dec (11.4) | 89 | 2 Jan (4.1) | 93 |
| | $R_6$ | 20 Jan (4.3) | 111 | 12 Feb (4.5) | 134 | 15 Feb (5.7) | 138 | 23 Feb (6.1) | 146 | 26 Feb (11.0) | 149 | 7 Mar (6.6) | 158 |
| 1st Nov | $V_e$ | 6 Nov (0.8) | 5 | 8 Nov (1.3) | 7 | 8 Nov (1.9) | 7 | 9 Nov (2.0) | 8 | 9 Nov (2.0) | 9 | 11 Nov (2.2) | 10 |
| | $V_7$ | 25 Nov (2.3) | 25 | 30 Nov (5.2) | 29 | 20 Nov (3.2) | 19 | 1 Dec (2.9) | 30 | 2 Dec (3.4) | 32 | 5 Dec (3.0) | 35 |
| | $R_1$ | 2 Jan (3.9) | 63 | 7 Jan (3.5) | 68 | 8 Jan (4.3) | 68 | 13 Jan (4.9) | 73 | 14 Jan (5.6) | 74 | 18 Jan (3.9) | 78 |
| | $R_6$ | 24 Feb (5.2) | 116 | 5 Mar (4.6) | 124 | 8 Mar (8.5) | 127 | 16 Mar (7.3) | 136 | 19 Mar (13.1) | 139 | 28 Mar (8.5) | 147 |
| 1st Dec | $V_e$ | 5 Dec (0.9) | 4 | 6 Dec (0.9) | 6 | 6 Dec (1.1) | 5 | 6 Dec (1.1) | 6 | 7 Dec (1.4) | 6 | 7 Dec (1.4) | 6 |
| | $V_7$ | 20 Dec (1.3) | 20 | 24 Dec (2.0) | 24 | 24 Dec (2.3) | 24 | 26 Dec (2.6) | 25 | 26 Dec (3.0) | 25 | 27 Dec (2.4) | 27 |
| | $R_1$ | 21 Jan (2.2) | 52 | 30 Jan (3.2) | 61 | 1 Feb (3.5) | 62 | 6 Feb (3.8) | 67 | 5 Feb (5.8) | 67 | 9 Feb (4.5) | 70 |
| | $R_6$ | 12 Mar (3.3) | 101 | 2 Apr (6.4) | 122 | 7 Apr (6.9) | 128 | 21 Apr (9.7) | 142 | 24 Apr (17.8) | 144 | 7 May (16.4) | 158 |

Values were simulated with climatic records of each location and the information of Table 2

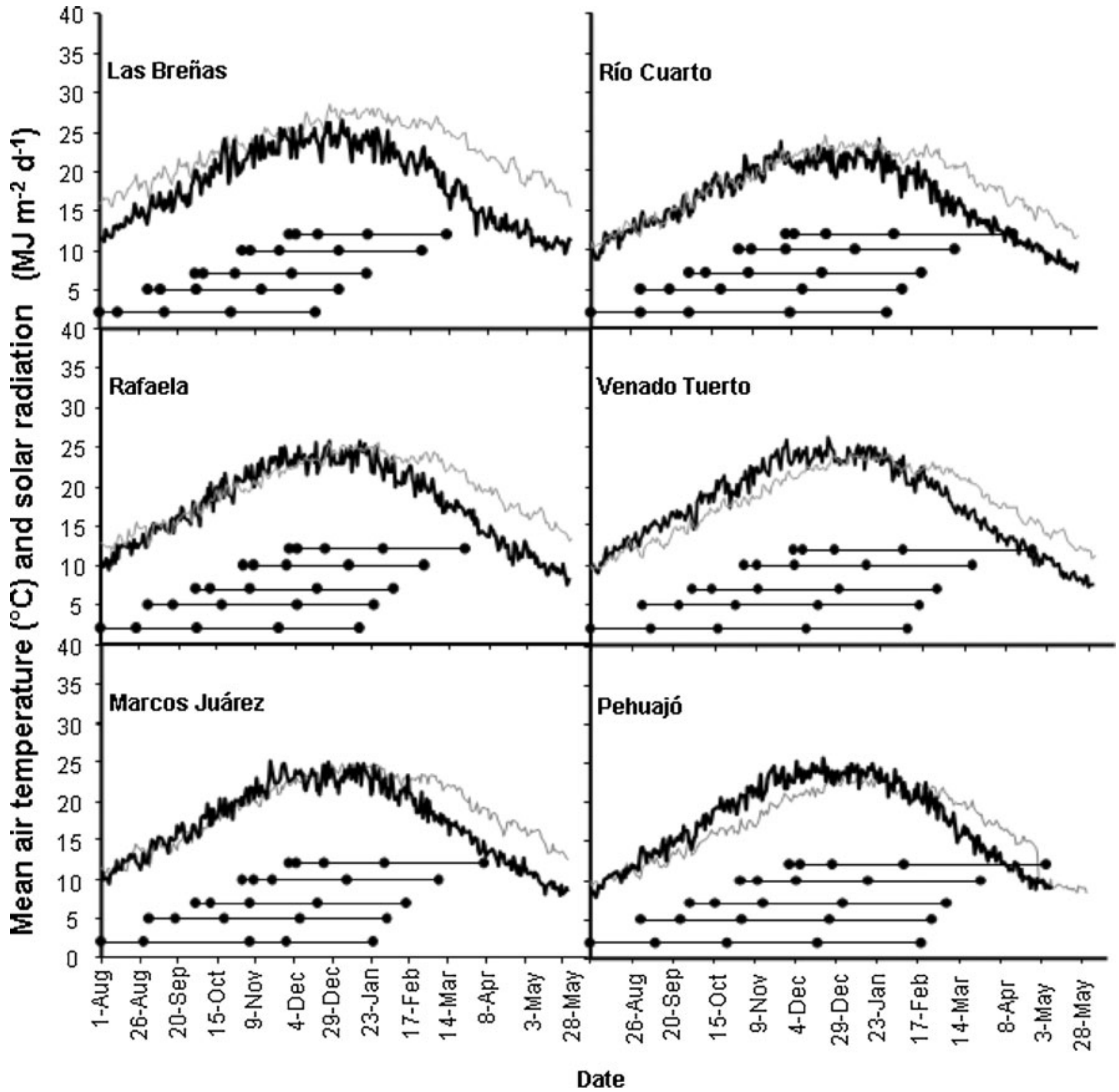


**Fig. 2** Evolution of mean air temperature (*fine lines*) and daily incident solar radiation (*thick lines*) at six locations. Values are the mean of daily records of the last 28–33 years. Simulated phenology of maize crops cultivated in five dates is included. Each circle represents the mean date of the following stages: sowing, seedling emergence ($V_e$), the seven-liguated leaf stage ($V_7$), female flowering ($R_1$) and physiological maturity ($R_6$). The date of each phenological stage was simulated with the thermal time model, records of mean air temperature and information of maize phenology (Table 2)

and grain yields on 1st December (ca. 1,366 $gm^{-2}$) were lower than those on 1st November, but higher than those on the other sowing dates. A low inter-annual variability of simulated potential grain yields (CV<7%) was observed at all sowing dates. Only maize crops sown on 1st November and 1st December could attain similar potential grain yields but with different frequencies (e.g., grain yields >1,430 $gm^{-2}$ could be obtained with a frequency of 0.68 and 0.14 on 1st November and 1st December, respectively). At Rafaela, simulations of maize crops sown from 1st August to 1st October produced similar potential grain yields (ca.1,360 g $m^{-2}$; CV=5%). Contrarily, on 1st November (1,216 $gm^{-2}$; CV=6%) and 1st December (1,147 $gm^{-2}$; CV=7%), simulated grain yields were lower ($P$<0.001) than those on the other sowing dates. At Marcos Juarez, maize crops sown on 1st August (1,365 $gm^{-2}$; CV=11%) and 1st September (ca. 1,327 $gm^{-2}$; CV=11%) had the highest ($P$<0.001) simulated potential grain yields. When the sowing date was delayed beyond 1st October (ca. 1,295 $gm^{-2}$; CV=11%), simulated potential grain yields decreased (ca. 1,230 $gm^{-2}$; CV=10% and 1,160 $gm^{-2}$; CV=9%, for 1st November and 1st December, respectively). At Río Cuarto, simulated potential grain yield did not vary when sowing date was delayed from 1st August (ca. 1,324 $gm^{-2}$; CV=8%) to 1st September (ca. 1,302 $gm^{-2}$; CV=8%), but was reduced ($P$< 0.001) on 1st October (ca. 1,254 $gm^{-2}$; CV=8%). At this

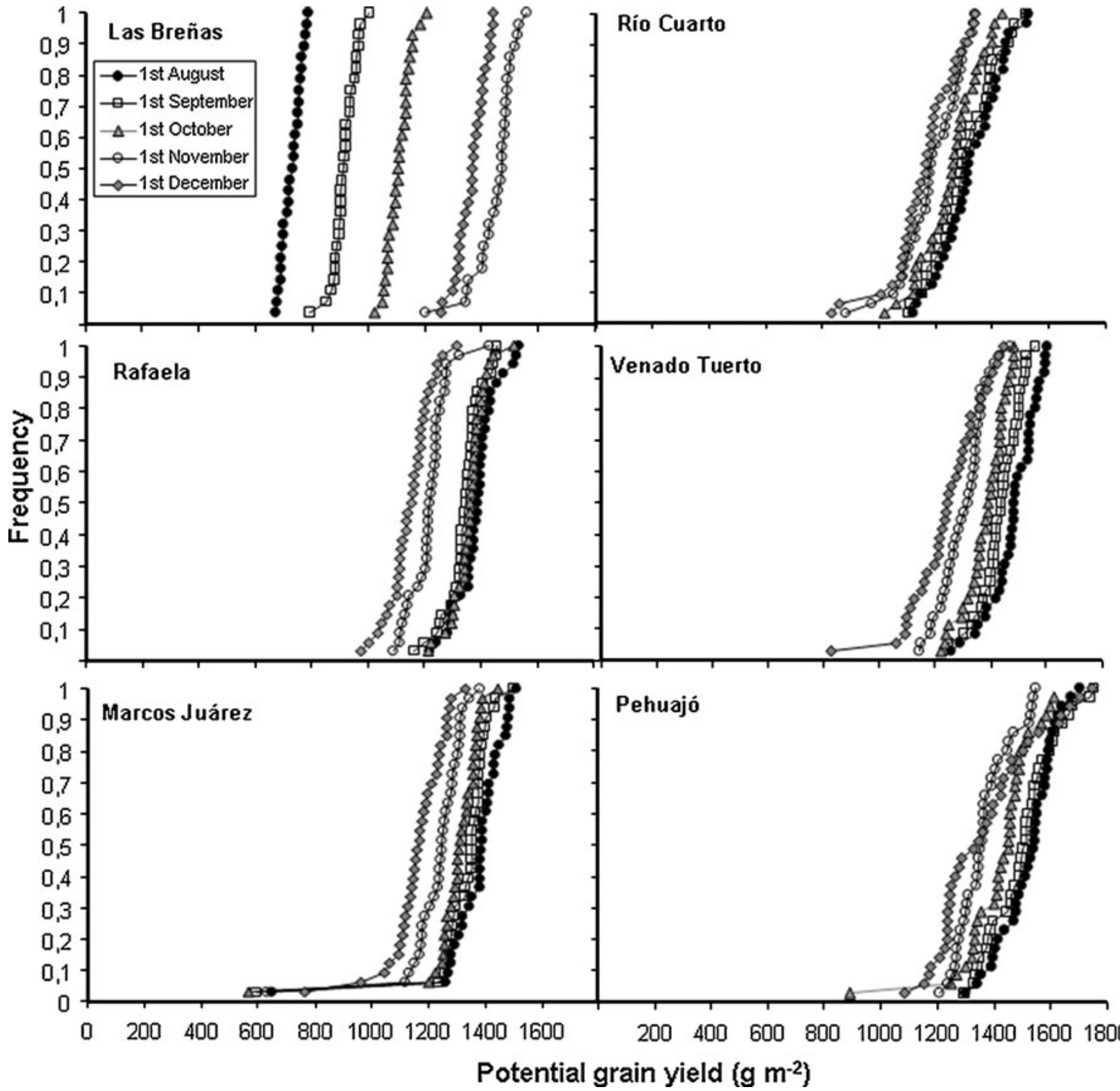


**Fig. 3** Cumulative frequencies of simulated potential grain yields of maize crops sown in five dates at six locations. Simulations were performed with a correlative model (Eqs. 2–6), considering inter-annual variability of mean air temperature and daily solar radiation and information of maize phenology (Table 2)

location, the lower potential grain yields corresponded to simulations on 1st November (ca. 1,186 gm$^{-2}$; CV=9%) and 1st December (ca. 1,158 gm$^{-2}$; CV=10%). At Venado Tuerto, the simulated potential grain yield decreased ($P<0.001$) as sowing date was delayed from 1st August (ca. 1,507 gm$^{-2}$; CV=6%) to 1st December (ca. 1,246 gm$^{-2}$; CV=10%). The higher simulated potential grain yields (>1,365 gm$^{-2}$) of the November sowing (frequency <0.14) were similar to those of December (frequency <0.17). At Pehuajó, the highest ($P<0.001$) potential grain yields were simulated for the August (ca. 1,521 gm$^{-2}$; CV=6%) and September (ca. 1,504 gm$^{-2}$; CV=7%) sowings. Intermediate grain yields were simulated for 1st October (ca. 1,424 gm$^{-2}$; CV=9%), and the lowest grain yields for 1st November (ca. 1,365 gm$^{-2}$; CV=7%) and 1st December (ca. 1,368 gm$^{-2}$; CV=12%). The comparison between November and December sowings showed that mean potential grain yields (frequency=0.5) were similar (ca. 1,360 gm$^{-2}$), but the lower yields of the November sowing (frequency≤0.45) were higher than those of December, and the reverse was observed for the higher simulated yields (frequency≤0.40) of both sowing dates.

## 3.3 Climatic constraints to maize production

### *3.3.1 Low temperatures*

During the simulated maize cycles, the frequency of $T_{min}<2°C$ increased from 0.05 at Las Breñas to 0.40 at Pehuajó (Fig. 4), especially at early stages of maize (i.e., late frosts)

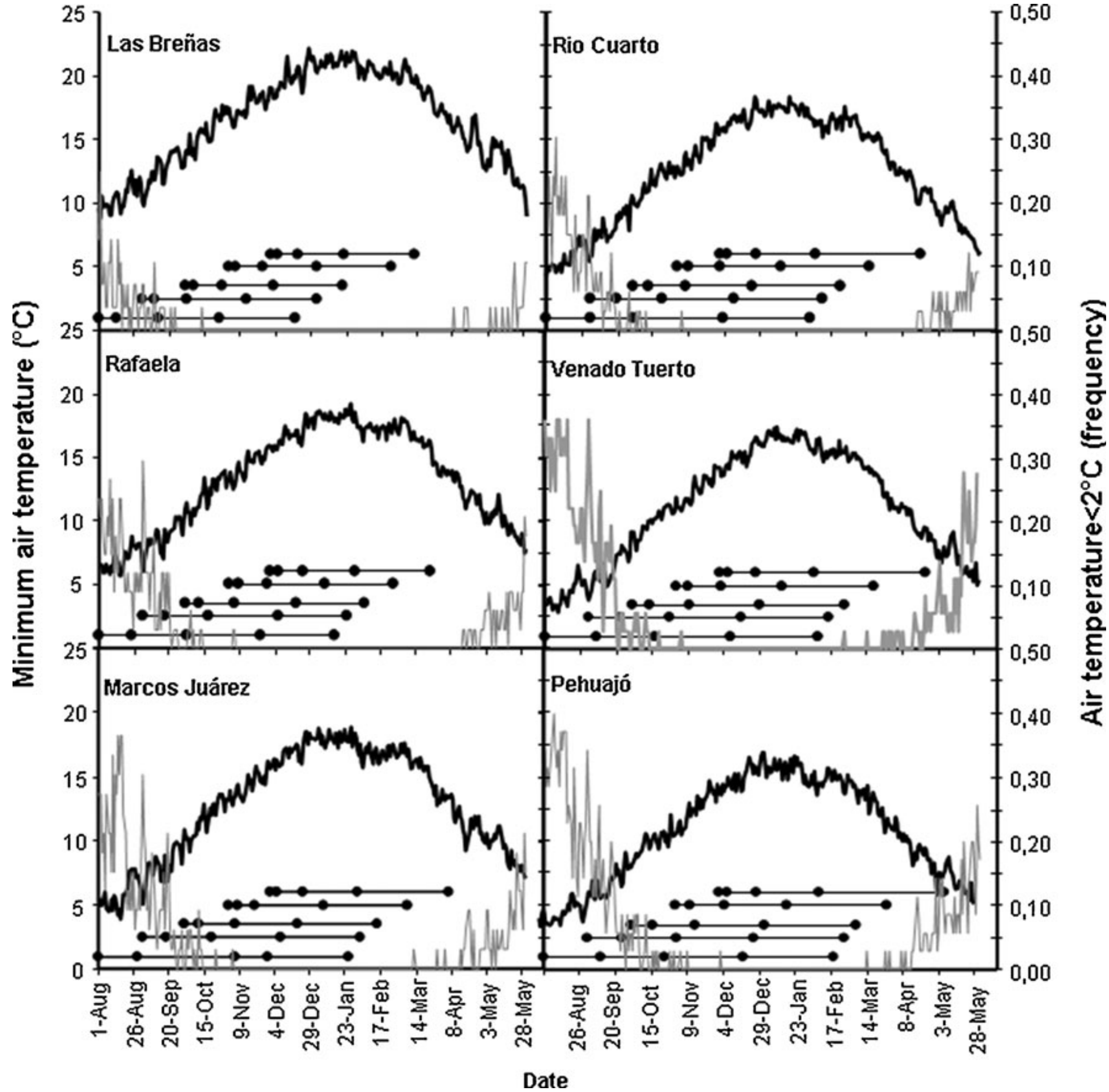


**Fig. 4** Evolution of minimum air temperature (*thick lines*) and frequencies of air temperatures <2°C (*fine lines*) at six locations. The analysis was performed with daily records of minimum air temperature of the last 28–33 years. Symbols and details as in Fig. 2

sown from 1st August to 1st September. At all locations, the frequencies of $T_{min}$<2°C during the grain-filling period (i.e., early frosts), were lower than those at early stages, and varied from 0 at Las Breñas to 0.25 at Pehuajó. Consequently, late frost damage could mainly occur in maize crops sown from 1st August to 1st September at all locations and could be extended to October sowing at Venado Tuerto and Pehuajó (Table 4). These late frosts would drastically affect maize crops (i.e., 100% of grain yield reduction). By contrast, the occurrence of early frost damage would never take place at Las Breñas and Rafaela. At the other locations, interruption of the grain-filling period by early frosts would depress potential grain yield (from 3 to 21%), mainly on December sowing, with the higher frequency at Venado Tuerto and Pehuajó.

At each location, simulations of the duration of the sowing-$V_e$ period revealed that the frequency of a duration >10 days decreased as sowing date was delayed from 1st August to 1st December (Table 4). For each sowing date, the frequency increased with latitude. Thus, in the region under study, maize crops sown on 1st August would exhibit sowing-$V_e$ periods longer than 10 days (frequencies=0.72–1). By contrast, maize crops sown on 1st December would emerge in less than 10 days (frequencies >0.92).

### 3.3.2 Water availability

The restriction of sowing based on SWC at the sowing depth was quantified by the accumulated rainfalls every 10 days and a threshold value of 10 mm (Table 5). At Las

**Table 4** Frequencies of (i) $T_{min}$<2°C (frosts) from $V_7$ onward and (ii) a sowing to $V_e$ period longer than 10 days

| Climatic constraint | Location | Sowing date | | | | |
|---|---|---|---|---|---|---|
| | | 1st August | 1st September | 1st October | 1st November | 1st December |
| Frost damage | Las Breñas | 0.14 (100%) | 0.04 (100%) | | | |
| | Rafaela | 0.20 (100%) | 0.03 (100%) | | | |
| | Marcos Juarez | 0.18 (100%) | 0.09 (100%) | | 0.03 (3%) | 0.06 (21.3%) |
| | Río Cuarto | 0.06 (100%) | 0.03 (100%) | | | 0.09 (3.5%) |
| | Venado Tuerto | 0.06 (100%) | 0.03 (100%) | 0.03 (100%) | 0.08 (3.1%) | 0.25 (13.2%) |
| | Pehuajó | 0.14 (100%) | 0.03 (100%) | 0.03 (100%) | | 0.37 (17.5%) |
| Sowing to $V_e$>10 days | Las Breñas | 0.72 | 0.50 | 0.22 | | |
| | Rafaela | 1 | 0.85 | 0.53 | 0.09 | |
| | Marcos Juárez | 1 | 0.85 | 0.67 | 0.22 | |
| | Río Cuarto | 1 | 0.94 | 0.73 | 0.22 | |
| | Venado Tuerto | 1 | 1 | 0.97 | 0.58 | 0.08 |
| | Pehuajó | 1 | 1 | 0.97 | 0.83 | 0.03 |

For 1st August, 1st September and 1st October sowings, the occurrence of $T_{min}$<2°C from $V_7$ to $R_1$ would drastically affect grain yield. For 1st November and 1st December sowings, $T_{min}$<2°C during the grain-filling period would interrupt kernel growth. Values in *brackets* indicate the simulated reduction of potential grain yield (percentage) due to frost damage. The absence of frequency values indicates the non-occurrence of the climatic constraint. Phenology was simulated with climatic records of each location and the information of Table 2

Breñas and Río Cuarto, the frequencies of accumulated rainfalls <10 mm were >0.50 between early August and early October. At Marcos Juarez, the restriction of SWC at sowing diminished (frequencies <0.50) from early October onwards. The similar trend was obtained at Venado Tuerto, but a frequency <0.50 was also established in late August. At Rafaela and Pehuajó, frequencies <0.50 were obtained from late September onward.

At all locations, accumulated rainfall during the fallow period increased when sowing was delayed (Fig. 5). At locations or years with low rainfall during August (Las Breñas, Rafaela, Río Cuarto and Marcos Juárez), cumula-

**Table 5** The frequency of accumulated rainfalls <10 mm over a period of 10 days for the months of August, September, October, November and December at six locations

| Month | Period | Frequency of accumulated rainfalls <10 mm | | | | | |
|---|---|---|---|---|---|---|---|
| | | Las Breñas | Rafaela | Marcos Juárez | Río Cuarto | Venado Tuerto | Pehuajó |
| August | 1 to 10 | 0.89 | 0.65 | 0.73 | 0.76 | 0.69 | 0.74 |
| | 11 to 20 | 1.00 | 0.88 | 0.97 | 0.91 | 0.92 | 0.80 |
| | 20 to 31 | 0.82 | 0.71 | 0.64 | 0.64 | **0.44** | 0.57 |
| September | 1 to 10 | 0.79 | 0.68 | 0.64 | 0.70 | 0.67 | 0.71 |
| | 11 to 20 | 0.68 | 0.74 | 0.79 | 0.64 | 0.78 | 0.63 |
| | 20 to 30 | 0.61 | **0.50** | 0.58 | 0.65 | 0.67 | **0.43** |
| October | 1 to 10 | 0.57 | **0.47** | **0.45** | 0.52 | **0.39** | **0.31** |
| | 11 to 20 | **0.36** | **0.41** | **0.36** | **0.33** | **0.36** | **0.33** |
| | 20 to 31 | **0.21** | **0.17** | **0.18** | **0.18** | **0.19** | **0.23** |
| November | 1 to 10 | **0.36** | **0.18** | **0.09** | **0.21** | **0.19** | **0.20** |
| | 11 to 20 | **0.29** | **0.24** | **0.24** | **0.18** | **0.17** | **0.25** |
| | 20 to 30 | **0.29** | **0.12** | **0.24** | **0.15** | **0.22** | **0.37** |
| December | 1 to 10 | **0.21** | **0.36** | **0.27** | **0.06** | **0.28** | **0.22** |
| | 11 to 20 | **0.32** | **0.25** | **0.18** | **0.06** | **0.33** | **0.25** |
| | 20 to 31 | **0.36** | **0.35** | **0.18** | **0.15** | **0.28** | **0.31** |

Data in bold was used to highlight frequencies ≤0.50

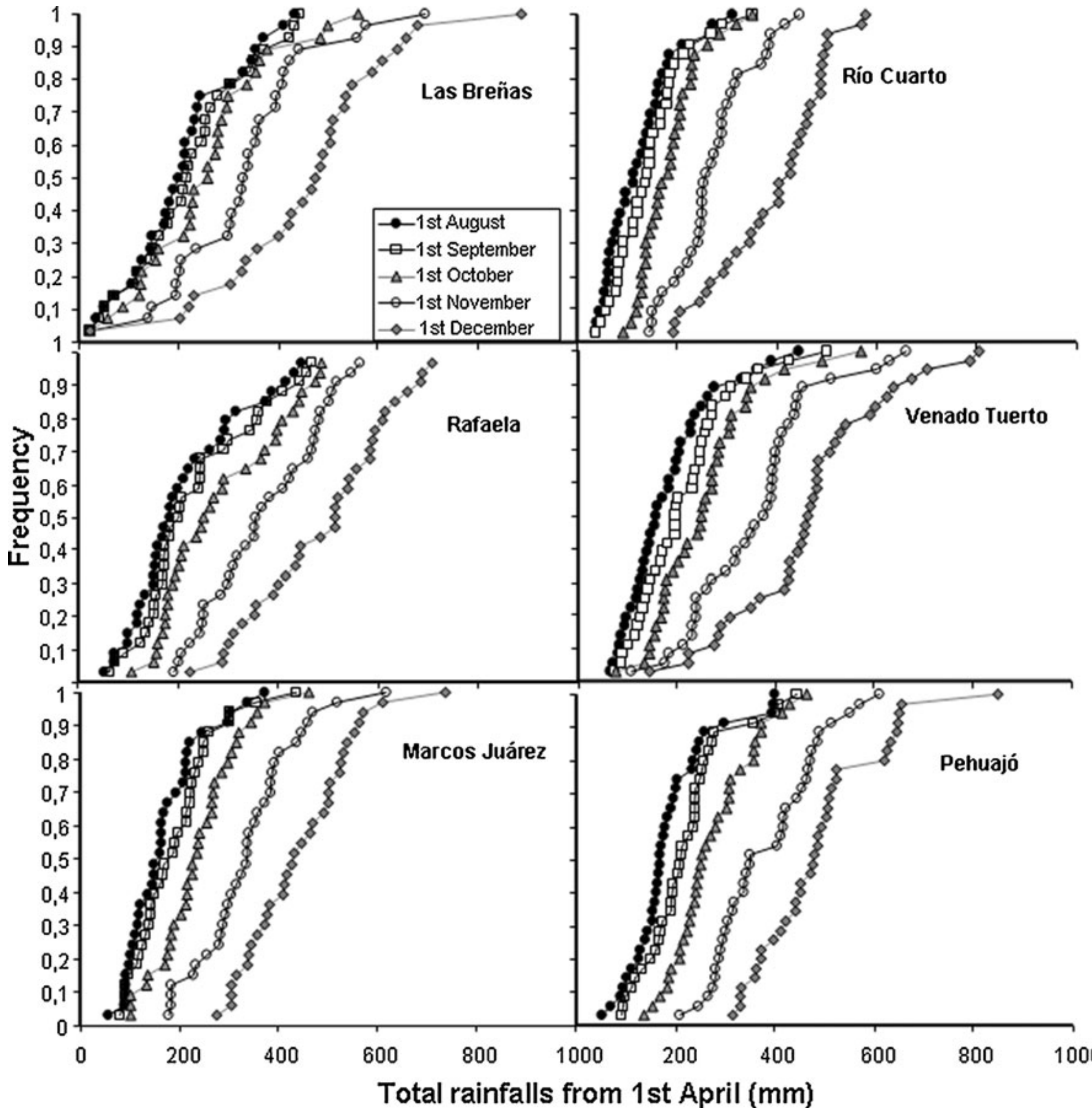


**Fig. 5** Cumulative frequencies of total rainfalls from 1st April to five sowing dates at six locations. The analysis was performed with daily rainfall records of the last 28–33 years

tive rainfall up to 1st September was close to that accumulated up to 1st August. Accumulated rainfall >200 mm with frequencies >0.50, would be reached from: (i) 1st August at Las Breñas, (ii) 1st September at Rafaela and Pehuajó, (iii) 1st October at Marcos Juárez and Venado Tuerto and (iv) 1st November at Río Cuarto. Therefore, at all locations maize crops sown on early November would have SWC close to the upper limit of water extraction.

Accumulated rainfall from sowing to the simulated beginning of the critical period ($R_1$-200°Cd), increased when sowing was delayed from 1st August to 1st November at Las Breñas, Rafaela, Marcos Juárez and Río Cuarto (Table 6). By contrast, at Venado Tuerto and Pehuajó, cumulative rainfall during this period declined steadily in response to delayed sowing date. Total ETc from sowing to $R_1$-200°Cd followed the same pattern of total rainfall at Las Breñas, Venado Tuerto and Pehuajo. Contrarily, at Río Cuarto, ETc from sowing to $R_1$-200°Cd showed the opposite pattern to that of rainfalls, while at Marcos Juarez ETc was almost not affected by the sowing date.

The total rainfall during the critical period did not follow a similar pattern to that during the previous period, and generally exhibited a higher inter-annual variability (i.e., higher CV values) (Table 6). The lowest rainfall was accumulated during the simulated critical periods of October sowing at Pehuajó, November sowing at Las Breñas, Rafaela and Venado Tuerto, and December sowing at Río Cuarto and Marcos Juárez. Total ETc during the simulated critical period was reduced when the sowing date was delayed in almost all locations, with the exception of

**Table 6** Total rainfalls and evapo-transpiration (ETc) (mean values and CV of the mean) from sowing to the beginning of critical period, and during the critical period, and frequency of water balance <100 mm at the end of the critical period for a temperate maize hybrid cultivated at six locations on five sowing dates

| Sowing date | | | Locations | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Las Breñas | Rafaela | Marcos Juarez | Río Cuarto | Venado Tuerto | Pehuajó |
| 1st Aug | Rainfall (mm) | Sowing—critical period | 63 (CV=0.63) | 178 (CV=0.49) | 210 (CV=0.45) | 206 (CV=0.49) | 261 (CV=0.43) | 304 (CV=0.36) |
| | | Critical period | 88 (CV=0.51) | 128 (CV=0.55) | 113 (CV=0.51) | 141 (CV=0.48) | 116 (CV=0.55) | 101 (CV=0.54) |
| | ETc (mm) | Sowing—critical period | 252 (CV=0.11) | 326 (CV=0.10) | 348 (CV=0.11) | 345 (CV=0.12) | 410 (CV=0.11) | 416 (CV=0.08) |
| | | Critical period | 142 (CV=0.10) | 159 (CV=0.08) | 156 (CV=0.12) | 146 (CV=0.10) | 158 (CV=0.07) | 165 (CV=0.08) |
| | Frequency water balance <100 mm | | 0.96 | 0.76 | 0.85 | 0.81 | 0.80 | 0.86 |
| 1st Sep | Rainfall (mm) | Sowing—critical period | 101 (CV=0.53) | 210 (CV=0.44) | 227 (CV=0.35) | 231 (CV=0.34) | 260 (CV=0.42) | 294 (CV=0.35) |
| | | Critical period | 111 (CV=0.60) | 123 (CV=0.57) | 110 (CV=0.52) | 128 (CV=0.50) | 102 (CV=0.63) | 92 (CV=0.52) |
| | ETc (mm) | Sowing—critical period | 264 (CV=0.09) | 321 (CV=0.08) | 280 (CV=0.15) | 321 (CV=0.11) | 376 (CV=0.10) | 395 (CV=0.10) |
| | | Critical period | 143 (CV=0.10) | 153 (CV=0.09) | 201 (CV=0.14) | 144 (CV=0.12) | 161 (CV=0.07) | 163 (CV=0.09) |
| | Frequency water balance <100 mm | | 0.89 | 0.71 | 0.79 | 0.66 | 0.77 | 0.86 |
| 1st Oct | Rainfall (mm) | Sowing—critical period | 151 (CV=0.50) | 225(CV=0.47) | 223 (CV=0.34) | 243 (CV=0.39) | 254 (CV=0.44) | 271 (CV=0.31) |
| | | Critical period | 102 (CV=0.52) | 118 (CV=0.73) | 113 (CV=0.61) | 135 (CV=0.55) | 104 (CV=0.55) | 88 (CV=0.48) |
| | ETc (mm) | Sowing—critical period | 271 (CV=0.09) | 305 (CV=0.09) | 309 (CV=0.11) | 299 (CV=0.10) | 346 (CV=0.08) | 361 (CV=0.07) |
| | | Critical period | 146 (CV=0.08) | 150 (CV=0.09) | 148 (CV=0.13) | 140 (CV=0.11) | 157 (CV=0.08) | 160 (CV=0.07) |
| | Frequency water balance <100 mm | | 0.79 | 0.59 | 0.64 | 0.33 | 0.66 | 0.77 |
| 1st Nov | Rainfall (mm) | Sowing—critical period | 218 (CV=0.39) | 238 (CV=0.43) | 241 (CV=0.41) | 261 (CV=0.39) | 215 (CV=0.44) | 204 (CV=0.32) |
| | | Critical period | 78 (CV=0.51) | 110 (CV=0.81) | 102 (CV=0.63) | 114 (CV=0.44) | 92 (CV=0.52) | 114 (CV=0.71) |
| | ETc (mm) | Sowing—critical period | 306 (CV=0.07) | 299 (CV=0.11) | 300 (CV=0.11) | 286 (CV=0.09) | 325 (CV=0.06) | 336 (CV=0.06) |
| | | Critical period | 162 (CV=0.09) | 145 (CV=0.12) | 144 (CV=0.11) | 138 (CV=0.11) | 153 (CV=0.07) | 156 (CV=0.08) |
| | Frequency water balance <100 mm | | 0.79 | 0.67 | 0.67 | 0.33 | 0.64 | 0.80 |
| 1st Dec | Rainfall (mm) | Sowing—critical period | 153 (CV=0.48) | 192 (CV=0.56) | 195 (CV=0.47) | 236 (CV=0.38) | 188 (CV=0.44) | 179 (CV=0.33) |
| | | Critical period | 112 (CV=0.81) | 135 (CV=0.84) | 102 (CV=0.58) | 93 (CV=0.59) | 112 (CV=0.57) | 101 (CV=0.73) |
| | ETc (mm) | Sowing—critical period | 274 (CV=0.06) | 285 (CV=0.06) | 282 (CV=0.12) | 267 (CV=0.11) | 301 (CV=0.06) | 309 (CV=0.07) |
| | | Critical period | 141 (CV=0.07) | 140 (CV=0.10) | 140 (CV=0.11) | 135 (CV=0.11) | 144 (CV=0.09) | 148 (CV=0.08) |
| | Frequency water balance <100 mm | | 0.61 | 0.59 | 0.61 | 0.39 | 0.69 | 0.88 |

Maize periods were simulated with climatic records and the information of Table 2

Las Breñas, where maximum ETc values were obtained during the critical period of November sowing. Inter-annual variability of ETc values was always lower (CV<15%) than that of accumulated rainfalls (CV>30%).

As a result of water balance components, water balance values at $R_2$ varied among the different scenarios (Fig. 6). At each location, the highest frequency of water balance value <100 mm was simulated for the sowing date of 1st August at Las Breñas (frequency=0.96), Rafaela (frequency=0.76), Marcos Juárez (frequency=0.84), Río Cuarto (frequency=0.82), and Venado Tuerto (frequency=0.80) and for the December sowing at Pehuajó (frequency=0.89). By contrast, the lowest frequency of water balance value <100 mm was simulated for the sowings of 1st December at Las Breñas (frequency=0.60), 1st October and 1st December at Rafaela (frequency=0.59), 1st December at Marcos Juarez (frequency=0.60), 1st October and 1st November at Río Cuarto (frequency=0.33), and 1st November at Venado Tuerto (frequency=0.64), and Pehuajó (frequency=0.74).

### 3.3.3 Heat stress

As latitude increased, not only were the number of days with $T_{max}$ above 35°C reduced, but also the frequencies of $T_{max}$ above 35°C (Fig. 7). For example, at Las Breñas, $T_{max}$>35°C could occur from late August (frequency ~0.10) to early April (frequency ~0.05), with the maximum frequency (~0.50) around January. Contrarily, at Pehuajó $T_{max}$>35°C could be registered from mid-November (frequency<0.05) to mid-

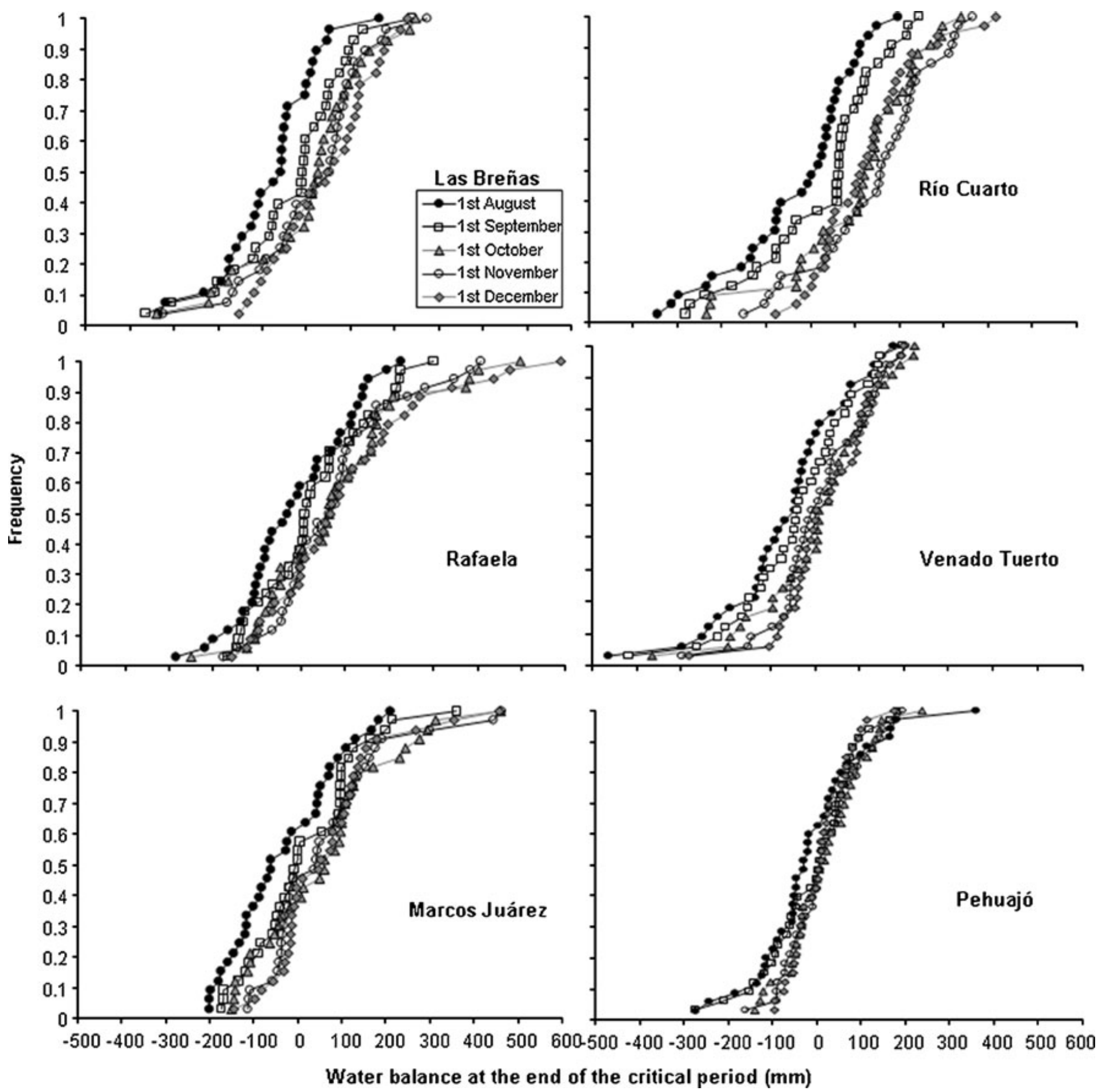


**Fig. 6** Cumulative frequencies of water balance at the end of the simulated critical periods of maize crops sown in five dates at six locations. The water balance was performed with daily rainfall records of the last 28–33 years and simulations of daily ETc (Eqs. 9–14)

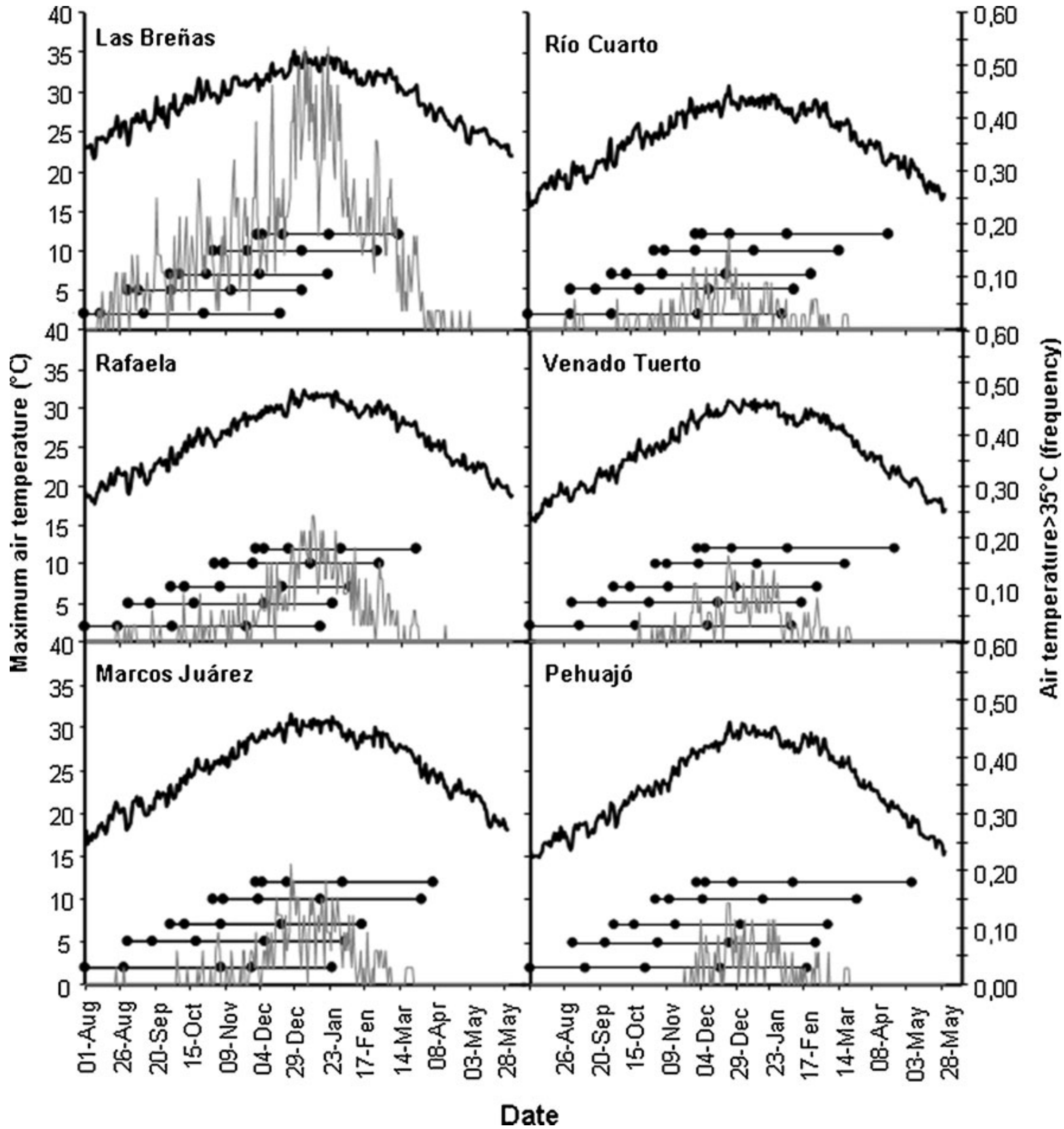


**Fig. 7** Evolution of maximum air temperature (*thick lines*) and frequencies of air temperatures >35°C (*fine lines*) at six locations. The analysis was performed with daily records of maximum air temperature of the last 28–33 years. Symbols and details as in Fig. 2

March (frequency<0.05), and the maximum frequency (~0.15) at late December. Thus, at Las Breñas, Rafaela and Marcos Juarez, simulated critical periods of maize in early sowings (1st August and 1st September) would be exposed to low frequencies of days with $T_{max}$>35°C (Fig. 8). By contrast, the higher frequencies of days with $T_{max}$>35°C would be registered during the grain-filling periods of maize sown from 1st August to 1st September at Rafaela and Marcos Juarez and on 1st October at Las Breñas (Fig. 9). At these locations, the number of days with $T_{max}$>35°C during the simulated grain-filling period was greater than that during the simulated critical period. At the other locations few days with $T_{max}$>35°C would be recorded during both mentioned simulated periods.

## 4 Discussion

The analysis of different scenarios for the production of a crop should include not only the effect of climatic factors ($CO_2$, solar radiation and $T_m$) on the potential grain yield (i.e., grain yield without restrictions) but also the impact of biotic (pest, diseases) and abiotic (water, nutrients, frost, heat stress, etc.) stresses (Van Ittersum and Rabbinge 1997). The correlative

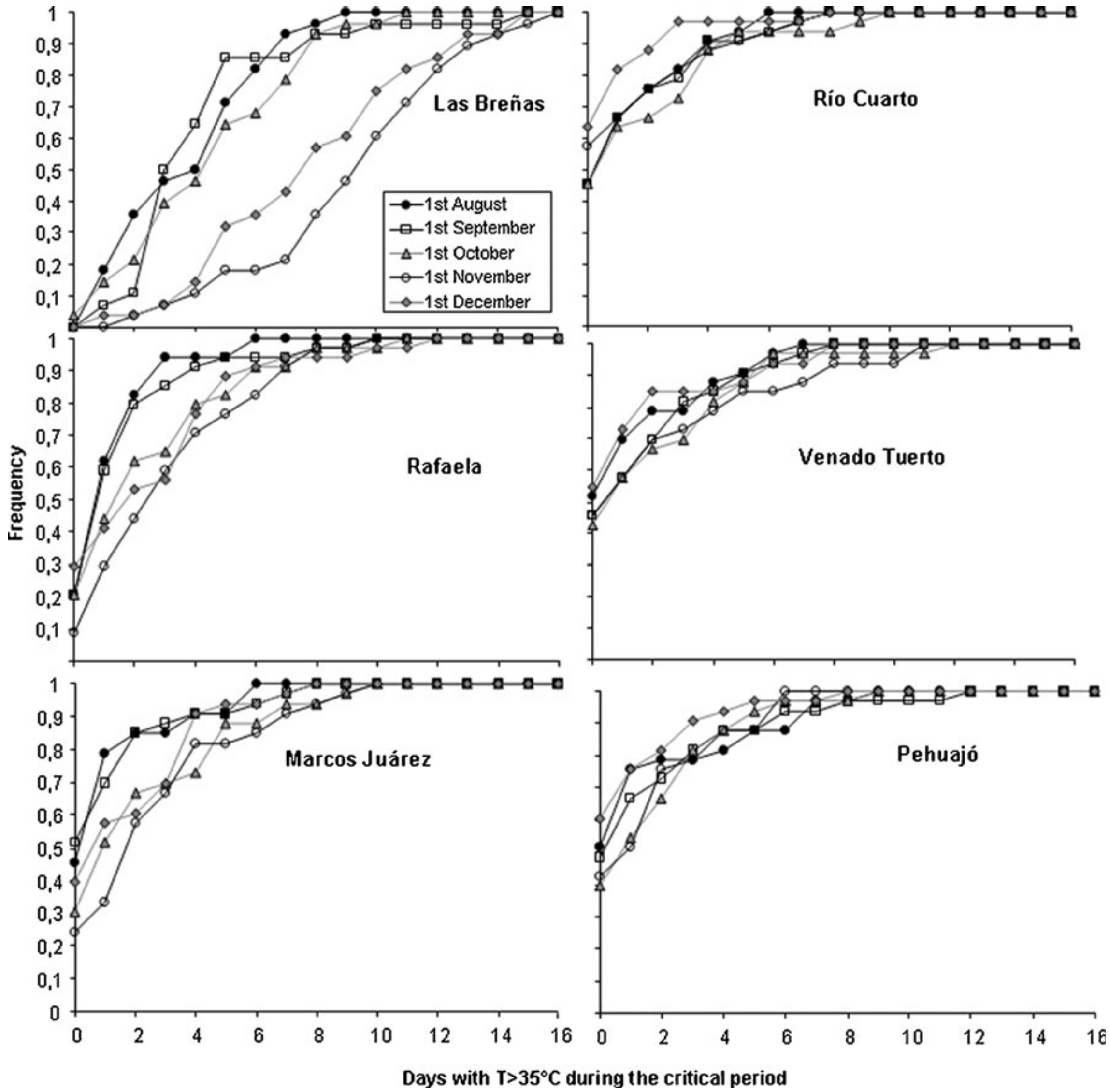


**Fig. 8** Cumulative frequencies of the number of days with maximum air temperatures >35°C during the simulated critical period of maize crops sown in five dates at six locations

model (Otegui et al. 1996) was a useful tool to simulate the effect of latitude and sowing date (both factors determinants of daily $T_m$ and solar radiation) on the potential grain yield of maize crops in a wide agricultural region (from 27°05′S to 35°48′S) of Argentina. For example, the higher potential grain yields were simulated for the earliest sowing date (i.e., 1st August) at almost all locations (from 31°S to 35°S), with the exception of Las Breñas (27°05′S, 61°5′W), where potential grain yield was maximized on 1st November. In this location, the length of the longest cycle of the early sowings failed to offset the low levels of daily solar radiation.

For the most productive sowing dates, the higher simulated potential grain yields (ca. 1,500 $gm^{-2}$; CV=5–6%) were obtained at Pehuajó (35°48′S, 61°54′W) and Venado Tuerto (33°45′S, 61°58′W), intermediate grain yields (ca. 1,450 $gm^{-2}$ CV=5%) at Las Breñas (27°05′S, 61°5′W), followed by those (ca. 1,370 $gm^{-2}$; CV=5–10%) at Marcos Juarez (32°41′S, 62°6′W) and Rafaela (31°10′S, 61°28′W), and the lower ones (ca. 1,320 $gm^{-2}$; CV=8%) at Río Cuarto (33°08′S, 64°21′W). Changes in the simulated potential grain yield among locations, sowing dates and years (i.e., the inter-annual variability expressed by the CV), were determined by the different $T_m$ and solar radiation values (Sivakumar and Virmani 1984; Gosse et al. 1986; Kiniry et al. 1989; Otegui et al. 1995a) because RUE (~3.4 gMJ $IPAR^{-1}$) and harvest index (~0.46) were kept constant. Therefore, the simulated potential grain yields could be close to those obtained under optimum growing conditions, but may be overestimating the potential yields in cooler regions (15–18°C) of Argentina (e.g.,

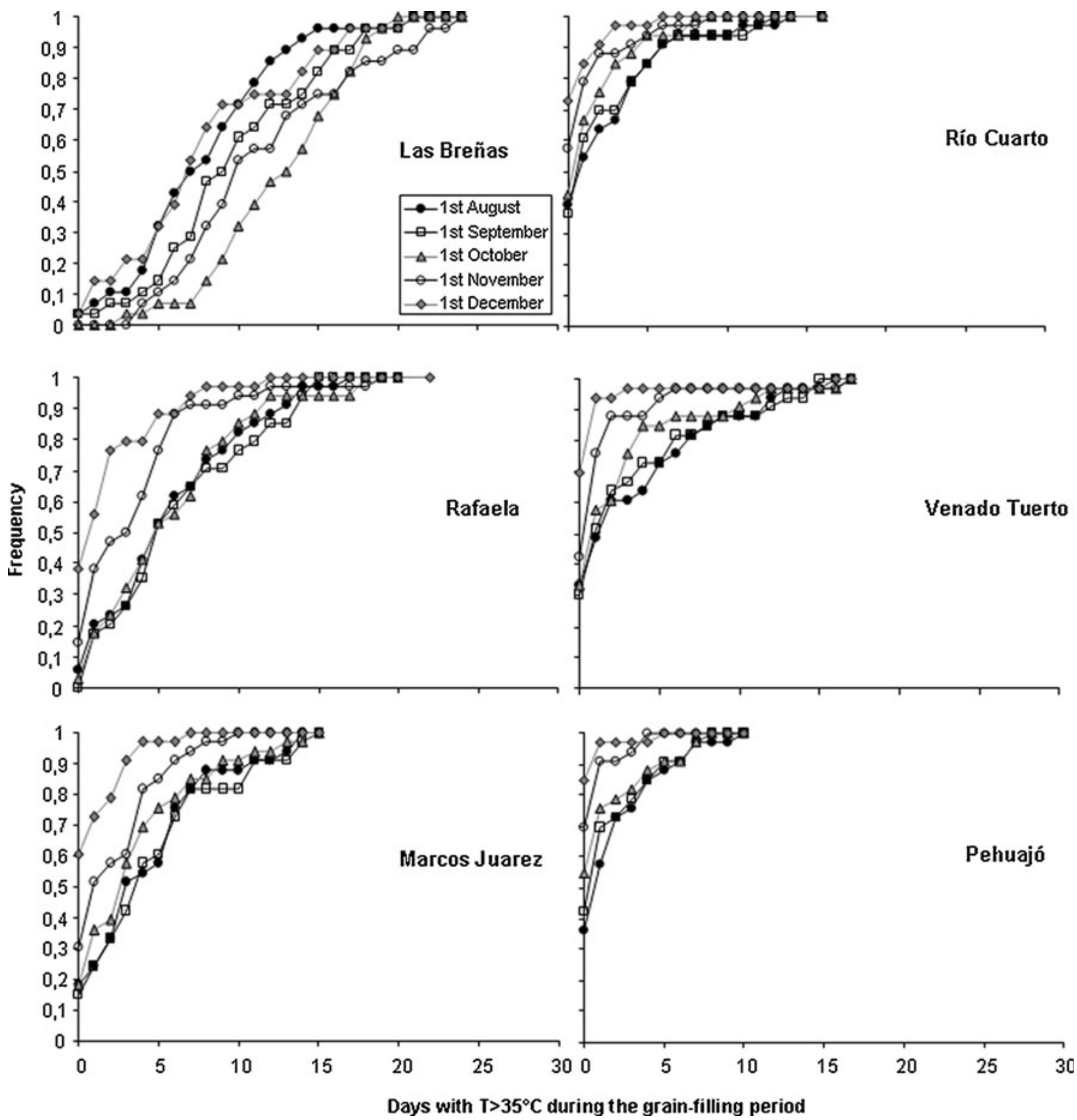


**Fig. 9** Cumulative frequencies of the number of days with maximum air temperatures >35°C during the simulated grain-filling period of maize crops sown in five dates at six locations

Balcarce, 37°45′S, 58°18′W), where lower values of RUE were recorded (~2.3 $gMJ^{-1}$ IPAR; Andrade et al. 1992, 1993). Similarly, a reduction of harvest index may also occur at the mentioned latitude on late sowings, due to the higher response to environmental conditions of vegetative compared to reproductive growth (Andrade 1995). On the other hand, the simulated values of potential grain yield obtained in this work would be lower than those of other maize hybrids with harvest indexes higher than 0.46 (Echarte and Andrade 2003). These errors of the simulated potential grain yields are very easy to solve, changing the values of RUE and harvest index.

The correlative model simulated the evolution of light capture from daily records of solar radiation and $T_m$, where $T_m$ determined *fIPAR* evolution and crop phenology (Muchow and Carberry 1989; Ritchie and Nesmith 1991). So, from 31°S to 35°S, the higher simulated potential grain yields of August sowing were due to the longer maize cycle, which overcompensated the low values of daily incident solar radiation at early stages of maize growth. By contrast, in late sowing dates (i.e., 1st November–1st December) the lower potential grain yields were due to both the short maize cycle and the decline in solar radiation values. This trend has not been observed at Las Breñas, where the higher potential grain yields were simulated with the November sowing, because simulated crop cycle coincided with the higher records of daily incident solar radiation. A different pattern of potential grain yield response to sowing date could be achieved if photoperiod effect on the duration of the cycle (Kiniry et al. 1983) and $T_m$ effect on leaf expansion rate (Ritchie and Nesmith 1991) were considered, especially in late sowing dates when vegetative growth is positively promoted by both factors (Maddonni and Otegui 1996). Other crop simulation models, such as Ceres-Maize (Jones and Kiniry 1986), can be used to explore the response of potential grain yields to sowing dates considering the mentioned photoperiod and $T_m$ effects on vegetative maize growth.

Regardless of the model used, the study of climatic constraints for the production of a crop in a location should include information on the probability of occurrence of the various abiotic restrictions during periods of increased sensitivity of the crops. The results could be arranged in a table, as a "pre-flight checklist" which could assist farmers to give particular attention to those climatic constraints with higher probabilities of occurrence (Table 7). For example, SWC at the sowing depth and the water balance during the critical period would be the most severe constraints on 1st August at Las Breñas, followed by low $T_m$ during the seedling emergence period. The low SWC at sowing together with low $T_m$ have negative effects on maize grain yield, because their impact on uneven seedling emergence (Liu et al. 2004; Andrade and Abbate 2005) and the death of seedlings (Pommel and Bonhomme 1998; Pommel et al. 2002). Similarly, a restrictive water balance during the critical period reduces kernel set and grain yield (Otegui et al. 1995b; Cárcova et al. 2000). Hence, some strategies or decisions could be considered by farmers at Las Breñas to mitigate these constraints. For example, no-tillage system has a positive impact on SWC but reduces soil temperature (Fabrizzi et al. 2005). Since no-tillage system is already widely adopted in Argentina, hybrids better adapted to low $T_m$ should be used at early sowings (e.g., hybrids with a low $T_b$ for the germination process; Giauffret et al. 1995). Unfortunately, little information exists on the behaviour of commercial hybrids sown in soils with low $T_m$, but a recent study (Padilla et al. 2004) documented genotypic differences for the *TT* of the germination process, but with a similar $T_b$ (10°C) among hybrids. Hence, until now the decision of delaying sowing date to 1st December seems to be the best option to reduce the climatic constraints at Las Breñas. Moreover, higher potential grain yields would be obtained in December sowing (Fig. 3), with a less restrictive water balance around the critical period. At this scenario caution should be taken to mitigate heat stress during the reproductive periods. One strategy could be the

**Table 7** Comparisons of climatic constraints for maize productivity on five sowing dates at six locations

| | | | *Las Breñas* | 27º05´S | 61º5´W |
|---|---|---|---|---|---|
| ***Climatic constraint*** | **1st August** | **1st September** | **1st October** | **1st November** | **1st December** |
| Frost damage | 0.01-0.25 | 0.01-0.25 | 0 | 0 | 0 |
| Seedling emergence period>10 days | 0.51-0.75 | 0.26-0.50 | 0.01-0.25 | 0 | 0 |
| Rainfalls<10mm at sowing | 0.76-1 | 0.26-0.50 | 0.26-0.50 | 0.26-0.50 | 0.26-0.50 |
| Total rainfalls < 200m during the fallow period | 0.26-0.50 | 0.26-0.50 | 0.26-0.50 | 0.01-0.25 | 0.01-0.25 |
| Water balance at the end of critical period<100mm | 0.76-1 | 0.76-1 | 0.76-1 | 0.76-1 | 0.51-0.75 |
| More than 5 d with *Tmax*>35°C during the critical period | 0.26-0.50 | 0.01-0.25 | 0.26-0.50 | 0.76-1 | 0.51-0.75 |
| More than 5 d with *Tmax*>35 during the grain-filling period | 0.51-0.75 | 0.76-1 | 0.76-1 | 0.76-1 | 0.51-0.75 |
| | | | *Rafaela* | 31º10´S | 61º28´W |
| ***Climatic constraint*** | **1st August** | **1st September** | **1st October** | **1st November** | **1st December** |
| Frost damage | 0.01-0.25 | 0.01-0.25 | 0 | 0 | 0 |
| Seedling emergence period>10 days | 0.76-1 | 0.76-1 | 0.51-0.75 | 0.01-0.25 | 0 |
| Rainfalls<10mm at sowing | 0.51-0.75 | 0.51-0.75 | 0.26-0.50 | 0.01-0.25 | 0.26-0.50 |
| Total rainfalls < 200m during the fallow period | 0.51-0.75 | 0.26-0.50 | 0.26-0.50 | 0.01-0.25 | 0 |
| Water balance at the end of critical period<100mm | 0.76-1 | 0.51-0.75 | 0.51-0.75 | 0.51-0.75 | 0.51-0.75 |
| More than 5 d with *Tmax*>35°C during the critical period | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 |
| More than 5 d with *Tmax*>35 during the grain-filling period | 0.26-0.50 | 0.26-0.50 | 0.26-0.50 | 0.01-0.25 | 0.01-0.25 |
| | | | *Marcos Juarez* | 32°41´S | 62°6´W |
| ***Climatic constraint*** | **1st August** | **1st September** | **1st October** | **1st November** | **1st December** |
| Frost damage | 0.01-0.25 | 0.01-0.25 | 0 | 0.01-0.25 | 0.01-0.25 |
| Seedling emergence period>10 days | 0.76-1 | 0.76-1 | 0.51-0.75 | 0.01-0.25 | 0 |
| Rainfalls<10mm at sowing | 0.76-1 | 0.51-0.75 | 0.26-0.50 | 0.01-0.25 | 0.01-0.25 |
| Total rainfalls < 200m during the fallow period | 0.51-0.75 | 0.51-0.75 | 0.26-0.50 | 0.01-0.25 | 0 |
| Water balance at the end of critical period<100mm | 0.76-1 | 0.76-1 | 0.51-0.75 | 0.51-0.75 | 0.51-0.75 |
| More than 5 d with *Tmax*>35°C during the critical period | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 |
| More than 5 d with *Tmax*>35 during the grain-filling period | 0.26-0.50 | 0.26-0.50 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 |

Frequencies were represented by colours

0: 0.01-0.25: 0.26-0.50: 0.51-0.75: 0.76-1:

**Table 7** (continued)

| *Climatic constraint* | 1st August | 1st September | *Río Cuarto* 1st October | 33°08´S 1st November | 64° 21´W 1st December |
|---|---|---|---|---|---|
| Frost damage | 0.01-0.25 | 0.01-0.25 | 0 | 0.01-0.25 | 0.01-0.25 |
| Seedling emergence period>10 days | 0.76-1 | 0.76-1 | 0.51-0.75 | 0.01-0.25 | 0 |
| Rainfalls<10mm at sowing | 0.51-0.75 | 0.51-0.75 | 0.26-0.50 | 0.01-0.25 | 0.01-0.25 |
| Total rainfalls < 200m during the fallow period | 0.76-1 | 0.76-1 | 0.51-0.75 | 0.01-0.25 | 0.01-0.25 |
| Water balance at the end of critical period<100mm | 0.76-1 | 0.51-0.75 | 0.26-0.50 | 0.26-0.50 | 0.26-0.50 |
| More than 5 d with *Tmax*>35°C during the critical period | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 |
| More than 5 d with *Tmax*>35°C during the grain- filling period | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 |
| *Climatic constraint* | 1st August | 1st September | *Venado Tuerto* 1st October | 33°45´S 1st November | 61°58´W 1st December |
| Frost damage | 0.01-0.25 | 0.01-0.25 | 0 | 0 | 0.01-0.25 |
| Seedling emergence period>10 days | 0.76-1 | 0.76-1 | 0.51-0.75 | 0.01-0.25 | 0 |
| Rainfalls<10mm at sowing | 0.51-0.75 | 0.51-0.75 | 0.26-0.50 | 0.01-0.25 | 0.26-0.50 |
| Total rainfalls < 200m during the fallow period | 0.51-0.75 | 0.26-0.50 | 0.26-0.50 | 0.01-0.25 | 0.01-0.25 |
| Water balance at the end of critical period<100mm | 0.76-1 | 0.76-1 | 0.51-0.75 | 0.51-0.75 | 0.51-0.75 |
| More than 5 d with *Tmax*>35°C during the critical period | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 |
| More than 5 d with *Tmax*>35 during the grain- filling period | 0.26-0.50 | 0.26-0.50 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 |
| *Climatic constraint* | 1st August | 1st September | *Pehuajó* 1st October | 35°48´S 1st November | 61°54´W 1st December |
| Frost damage | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0 | 0.26-0.50 |
| Seedling emergence period>10 days | 0.76-1 | 0.76-1 | 0.76-1 | 0.76-1 | 0.01-0.25 |
| Rainfalls<10mm at sowing | 0.51-0.75 | 0.51-0.75 | 0.26-0.50 | 0.26-0.50 | 0.26-0.50 |
| Total rainfalls < 200m during the fallow period | 0.51-0.75 | 0.26-0.50 | 0.01-0.25 | 0 | 0 |
| Water balance at the end of critical period<100mm | 0.76-1 | 0.76-1 | 0.76-1 | 0.76-1 | 0.76-1 |
| More than 5 d with *Tmax*>35°C during the critical period | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 |
| More than 5 d with *Tmax*>35°C during the grain- filling period | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 | 0.01-0.25 |

Frequencies were represented by colours

0: 0.01-0.25: 0.26-0.50: 0.51-0.75: 0.76-1:

use of tropical maize hybrids. In a recent study, irrigated tropical maize hybrids exhibited a better performance (i.e., a lower grain yield reduction) than temperate hybrids under episodes of heat stress (Rattalino Edreira et al. 2011). Crop water status during episodes of high temperatures determines the impact of heat stress (Hare et al. 1998). The reduction of SWC is accompanied by stomata closure, promoting the rise of leaf temperature to a point in which the latter is higher than the air temperature and independent of the vapour pressure deficit. Therefore, if air temperature at midday reaches records of 38°C, the foliage of the crop could be stressed to 43°C (Cárcova et al. 1998). Thus, tropical maize hybrids under drought conditions in Africa showed a higher grain yield reduction than those irrigated during episodes of heat stress (Lobell et al. 2011). These effects probably take place at Las Breñas in maize crops on November sowing because the high frequencies of $T_{max}$> 35°C around silking are coupled with the low water balance values during the reproductive periods. In the December sowing, conservative cultural practices such as weed control and stubble cover (Fernandez et al. 2008) could contribute to reduce the effects of $T_{max}$>35°C during the reproductive periods. A delayed of sowing date to early January could also be considered at Las Breñas due to the extended frost-free period and the declined values of $T_{max}$.

At the other locations, the restriction of low $T_m$ at sowing is extended to October or November (Table 7). Thus, at Rafaela the productivity of maize crops sown on 1st August would be limited by low $T_m$ and SWC at the sowing depth, low accumulated rainfalls during the fallow period, and low water balance value during the critical period. The mentioned climatic constraints for maize production would decrease from October onwards, with less limiting factors in the December sowing and the lowest potential grain yield. Hence, at this location the November sowing seems to be the best option to cultivate rainfed maize crops. At Marcos Juárez, Río Cuarto and Venado Tuerto, the November sowing had the fewest climatic frequencies of low $T_m$, low SWC and $T_{max}$, but a higher frequency of early frosts than the October sowing. The choice of a hybrid with a shorter cycle would be sufficient to reduce the risk of frost damage. Moreover, at the south of this region, mid-season hybrids exhibited a similar grain yield than those with a longer season (Capristo et al. 2007).

Hence, a lower risk of early frost damages could be coupled with a good crop performance. Finally, the checklist of Pehaujó would prove the seriousness of the low $T_m$ during the sowing of maize crops from early August to November, the risk of late frosts from August to October and of early frosts on December sowing (Table 6). The frequencies of climatic constraints tend to decrease from August to November, especially those related to SWC at sowing and frost damages. Maize crops cultivated in December would grow under less restrictive environment than those sown in November, and could attained similar potential grain yields. For the December sowing, farmers should pay attention to the impact of early frosts during the grain-filling period.

## 5 Conclusions

This paper proposes a simple method of analysis to characterize the impact of various climatic constraints to maize production in a wide region of Argentina. The analysis was based on previous studies of the eco-physiology of maize crops and climatic records of different locations in the region under study. It was useful to classify the influence of climatic conditions on different sowing dates at each location to consider the decision of the most suitable sowing date for maize crops or the inclusion of some cultural practices to mitigate the most serious constraints. The work was based on some assumptions: the use of a single long cycle (thermal units) for all scenarios, no photoperiod effect on maize cycle and threshold values to establish the severity of certain climatic restrictions (e.g., accumulated rainfall >200 mm during the fallow period to consider the SWC close to upper limit of water extraction). However, the frequency of several climatic records has been presented to determine the most appropriate threshold of a particular restriction. For example for soils with a higher sandy content, the SWC at the upper limit of water extraction would be lower that the threshold value used in this work. Other phenological models could be used (e.g., Ceres-Maize) to simulate the response of maize growth to the environmental factors at different sowing dates, but so far there is no model that renders the frequencies of climatic restrictions for critical ontogenic stages of maize crops.

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