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Long-term and recent changes in temperature-based agroclimatic indices in Argentina

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ABSTRACT: Changes in several temperature-based agroclimatic indices in the central-eastern of Argentina, most of them located within the Pampas region were analysed for 39 meteorological stations. Trends of first (FFD), last (LFD) and number (NFD) of frost days, frost period (FP), start (SGS), end (EGS) and length (LGS) of the growing season, growing degree days (GDD), diurnal temperature range (DTR), chilling hours and lowest annual minimum temperature were computed for two periods, 1940–2007 and 1975–2007. The largest changes were observed for the whole period 1940–2007 and were mostly indicative of a long-term minimum temperature warming throughout the region. During this period, generalized decreases in the NFD and in the FP (i.e., a delayed FFD and an earlier LFD) were found. Although the trends in the growing season indices were not as large as in the frost indices, they were consistent with the overall warming: an earlier SGS and a delayed in the EGS. The trends of the GDD showed a large variability between months with a generalized increased throughout the year. The DTR showed the largest number of stations with statistically significant negative trends from austral late spring (November) to austral early fall (April). For the period 1975–2007, the behaviour changes in all analysed indices: the short-term trends weakened and in some cases reversed sign. The LFD tended to occurred later in the year, particularly for the southern Pampas. The EGS shifted from mostly positive to negative trends, resulting in a shorter LGS. These trend changes were not spatially homogeneous. Although those short-term trends were predominantly non-statistically significant, they could potential affect management decisions and crop yields. In particular, frost is still an important hazard in agricultural activities and within the context of our results short- and long-term characterization of frost risk need to be considered at local and sub-regional scales. Copyright © 2012 Royal Meteorological Society

KEY WORDS agroclimatic indices; climate change; Pampas region; temperature

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1. Introduction

Climate change has gained significant international attention over the past decade due to concerns of deleterious long-term impacts on agriculture, water supply, human welfare and regional political stability. Climate change is expected to affect extremes, since small changes in mean conditions can lead to large changes in the frequency of extremes (Katz and Brown, 1992). The length of the frost-free season has increased in most mid- and high-latitude regions of both hemispheres. In the Northern Hemisphere, this is mostly manifest as an earlier start to spring (Trenberth *et al.*, 2007).

Agricultural production and related activities (e.g., irrigation, fertilization, site selection) can be highly affected by long-term changes in temperature and precipitation. Agrometeorological indices can be used to evaluate how weather and climate conditions affect plant status and crop production (Alexandrov *et al.*, 2008), and can also help in evaluating management decisions and farm technologies (Eitzinger *et al.*, 2009).

Agrometeorological indices also have been used to evaluate changes in climate conditions. For example, long-term changes of temperature-based agrometeorological indices, like frost days and length of the growing season (GS), have been documented around the world. An overall decrease in the number of frost days has been found in different regions. Frich *et al.* (2002) found evidence of fewer frost days in most of mid- and high-latitudes in the Northern Hemisphere in the last 50 years. A decreasing number of frost days were found across

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northern Europe during the 20th century (Heino *et al.*, 1999), in Canada (Bonsal *et al.*, 2001) and in New Zealand (Salinger and Griffiths, 2001). In China, the last spring frost day has been occurring earlier since the 1980s (Yaodong, 2005). Nevertheless, for the southeast of United States, Easterling (2002) showed no changes in either the number of frost days or the frost-free season, in spite of a cooling trend in annual temperatures over the 20th century in that region.

Different regions around the world have shown a lengthening of the GS, related to an increase in the near-surface air temperature (Myneni *et al.*, 1997; Tucker *et al.*, 2001; Moonen *et al.*, 2002; Walther *et al.*, 2002; Root *et al.*, 2003; Shen *et al.*, 2005; Schwartz *et al.*, 2006). Walther and Linderholm (2006) showed that in the Greater Baltic Area for the 20th century the general mean trend of the length of the GS is about 20 d. During 1951–2000, the frost-free period has increased around 0.5 d per year in Germany, Austria and Switzerland and 0.34 d per year in Estonia (Menzel *et al.*, 2003). Feng and Hu (2004) showed that the thermal time significantly increased at annual rate of up to 70 degree days per 10 years across the western United Sates but decreased 20 degree days per 10 years from the US Great Plains to the east coast.

Changes in the diurnal temperature range (DTR), another agrometeorological index, have been linked to changes in crop yields. Lobell (2007) analyzed the historical yield data of rice and maize from the leading global producers and showed that an increase in DTR was associated with reduced yields. Increased DTR for a given average temperature may reduce yields because the associated increase in maximum temperature may result in a higher water stress or reductions in photosynthesis rates (Dhakhwa and Campbell, 1998). Similarly, reductions in minimum temperature associated with increased DTR may also be harmful in cases where freezing temperatures can result in crop injury or death (Rosenzweig and Tubiello, 1996; Tubiello *et al.*, 2002). For South America, Vincent *et al.* (2005) found a generalized decreased in the DTR over the continent mostly due to nighttime warming for the period 1961–2000.

This work is focused on the temperate region of South America, specifically the eastern part of Argentina (Figure 1). Most of the stations analysed in this work are located within the Pampas which represents the main agricultural region of Argentina and one of the major agricultural regions in the world (Hall *el al.*, 1992). Two additional stations outside the Pampas were added to the analysis. Those stations are situated in the north and northwestern part of Argentina, areas that experienced an exponential increase in the cultivated soya bean area and production (Grau *et al.*, 2005; Boletta *et al.*, 2006): the average soya bean production increased from 300 10^3 ton in the late 1990s to 2.5 10^6 ton in recent years (SIIA, 2010).

During the last two decades crop yields have significantly increased, greatly influenced by changes in technology and regional climate. Some of the technology improvements include: use of higher yielding and disease resistant varieties, and boost up of fertilization practices. In addition, increase in soil water availability was an essential contributor to the observed crop yield increases (Hurtado, 2008; Spescha, 2008). In the studied region, 38, 18 and 13% of the simulated yields increases for soya bean, maize and wheat between the periods 1950–1970 and 1971–1999 were associated with changes in climate (Magrin *et al.*, 2005). Within the context of future climate change, modelling results showed that increases in temperature could lead to decreases of potential yields of wheat, maize and sunflower (Magrin *et al.*, 1998) which may be offset, at least to a limited extent, by an increase in atmospheric carbon dioxide (CO_2) concentration (Magrin and Travasso, 2002).

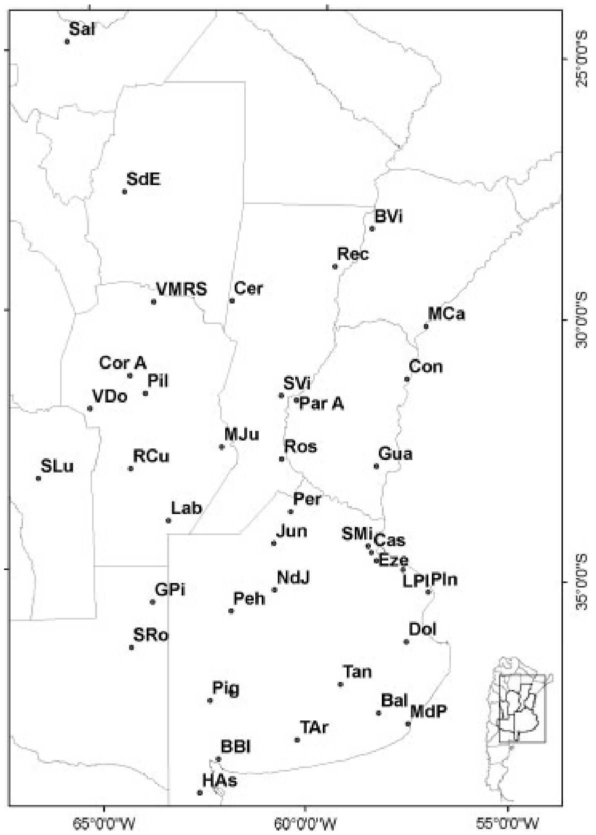

Figure 1. Studied region and meteorological stations used in this work (see Table I for station names).

Large-scale atmospheric circulation changes have occurred in this area, superimposed with a range of land-use land-cover changes that have affected temperature (Minetti and Vargas, 1983, 1992; Hoffmann *et al.*, 1997; Rusticucci and Barrucand, 2004; Fernández-Long and Müller, 2006; Nuñez *et al.*, 2008) and precipitation (Barros *et al.*, 2000; Rusticucci and Penalba, 2000; Minetti *et al.*, 2003; Haylock *et al.*, 2006; Forte Lay *et al.*, 2008). Rusticucci and Barrucand (2004) studied the changes in temperature extremes in Argentina over the period 1959–1998. They found that the largest and positive trends occurred in the summer and for the minimum temperatures. Particularly over the central-eastern Argentina, the Pampas region, Fernández-Long and Müller (2006) examined annual and monthly trends in the number of frost days from 1964 to 2003. They found a decrease, although no statistically significant, in the annual frost frequency, and a large spatial variability in the trends.

Extreme temperatures can have a great impact on the crop production. In the case of summer crops, like soya bean maize or sunflower, their sowing date is conditioned upon the date of the last frost (Raper and Kramer, 1987; Otegui *et al.*, 1996; Otegui and Lopez Pereira, 2003). In the case of winter crops, like wheat, delays in the last frost can greatly affect the yields (Abbate *et al.*, 1994; Otegui and Lopez Pereira, 2003). In recent years, the occurrence of last frosts in November greatly affected the wheat production in the southern Pampas (Quiroz and Maneiro, 2007; Ross *et al.*, 2007). In addition, there was a generalized decreased in corn yields and some areas with soya bean had to be re-sown due to frost damage (Downes, 2007).

A preliminary analysis of the daily temperatures, i.e. maximum ($T_{\max}$) and minimum ($T_{\min}$) for selected stations within the studied area (Table I) shows generalized negative and positive long-term trends for the period 1940–2007 (Figure 2(a) and (b)). In addition, for the recent period 1975–2007 the $T_{\max}$ and $T_{\min}$ trends show a change in sign or a decreased in value. The number of stations with statistically significant negative $T_{\min}$ tendencies decreased from 31 for the whole period 1940–2007 to only 11 stations for the shorter 1975–2007 period. Moreover, for the latter period, four stations showed statistically significant positive trends. A large spatial heterogeneity of this behaviour is found within the region. For example, for a station located south of the area (Figure 2(c) and (d)) $T_{\max}$ trend change in sign, and $T_{\min}$ trend change in absolute value becoming statistically significant. However, for a western station the short-term trends remained unchanged or changed slightly (Figure 2(e) and (f)).

Several questions arise given the potential effects of changes in daily extreme temperatures in the agricultural production:

1. What are the long-term changes of the main temperature-based agrometeorological indices in this region?
2. How those agrometeorological indices have changed in the recent years?
3. What is the spatial variability of those changes?
4. Are the changes related to global climate change?

The objective of this work is to evaluate the temporal and spatial changes of the main temperature-based agrometeorological indices in the eastern region of Argentina. We analysed the trends in the indices for two periods: 1940–2007 and 1975–2007. The latter was chosen considering our preliminary analysis of the $T_{\max}$ and $T_{\min}$ trends and the observed changes in atmospheric circulation from mid-1970s in different regions of the world (Trenberth and Hurrell, 1994; Nakamura *et al.*, 1997; Wang *et al.*, 2007, 2010) and in Argentina (Rusticucci and Penalba, 2000). In this paper Section 2 describes the data, indices and methodology; the trend analysis is presented in Section 3, and discussion and conclusions follow in Section 4.

2. Observational data and methodology

2.1. Climatic data

Daily minimum ($T_{\min}$) and maximum ($T_{\max}$) temperature from 39 stations in Argentina (Table I, Figure 1) with the longest and complete records were used. In addition these stations have little urban heat island effect and they were not relocated.

Two selected periods of data were used. The first one includes almost the total period of data of all considered meteorological stations. Only three stations allowed for the trend analysis for more than 80 years (Table I). Therefore, in order to include as many stations as possible, the period 1940–2007 was analysed. A second period, 1975–2007, was also considered based on the observed changes in atmospheric circulation around mid-1970s.

2.2. Agrometeorological indices

Table II lists the definitions of the agrometeorological indices analyzed in this study. In the case of frost-based indices, the first (FFD) and last (LFD) frost day, the frost period (FP) and the number of frost (NFD) days, we used the 0 and 3 °C thresholds. The FFD is defined as the first date on or before 15 July on which $T_{\min}$ is less or equal than the temperature threshold. The LFD is the last date on or after 16 July on which $T_{\min}$ is less or equal than the temperature threshold. The FP is the number of days between the FFD and LFD and NFD is the number of days with frost.

The length of the growing season (LGS) is another widely used index. In most mid-latitude regions, temperature is often the sole parameter to determine LGS, and in general, the 5 °C mean temperature (T_{mean}) threshold is widely accepted for determining the thermal growing season, in particular for mid- and high-latitudes (Jones and Briffa, 1995; Carter 1998; Frich *et al.*, 2002; Jones *et al.*, 2002, Menzel *et al.*, 2003). There are different LGS definitions, based on the length of the spells this threshold has to be exceeded or fall below. In our study, LGS is defined as the period from the start (SGS) to the end (EGS) of the growing season. The SGS is specified to be the first appearance of seven consecutive days with the T_{mean} higher than 5, 10 or 15 °C after the last winter/spring frost (Jones *et al.*, 2002). The EGS is defined to be the last appearance of seven consecutive days with T_{mean} higher than 5, 10 or 15 °C before the first autumn/winter frost. As elaborated in Peterson and Folland (2000), this definition of LGS is particularly relevant for measuring change of agricultural environment. The indices using the 5 °C base temperature coincided mostly with the frost-free period and therefore were not analysed.

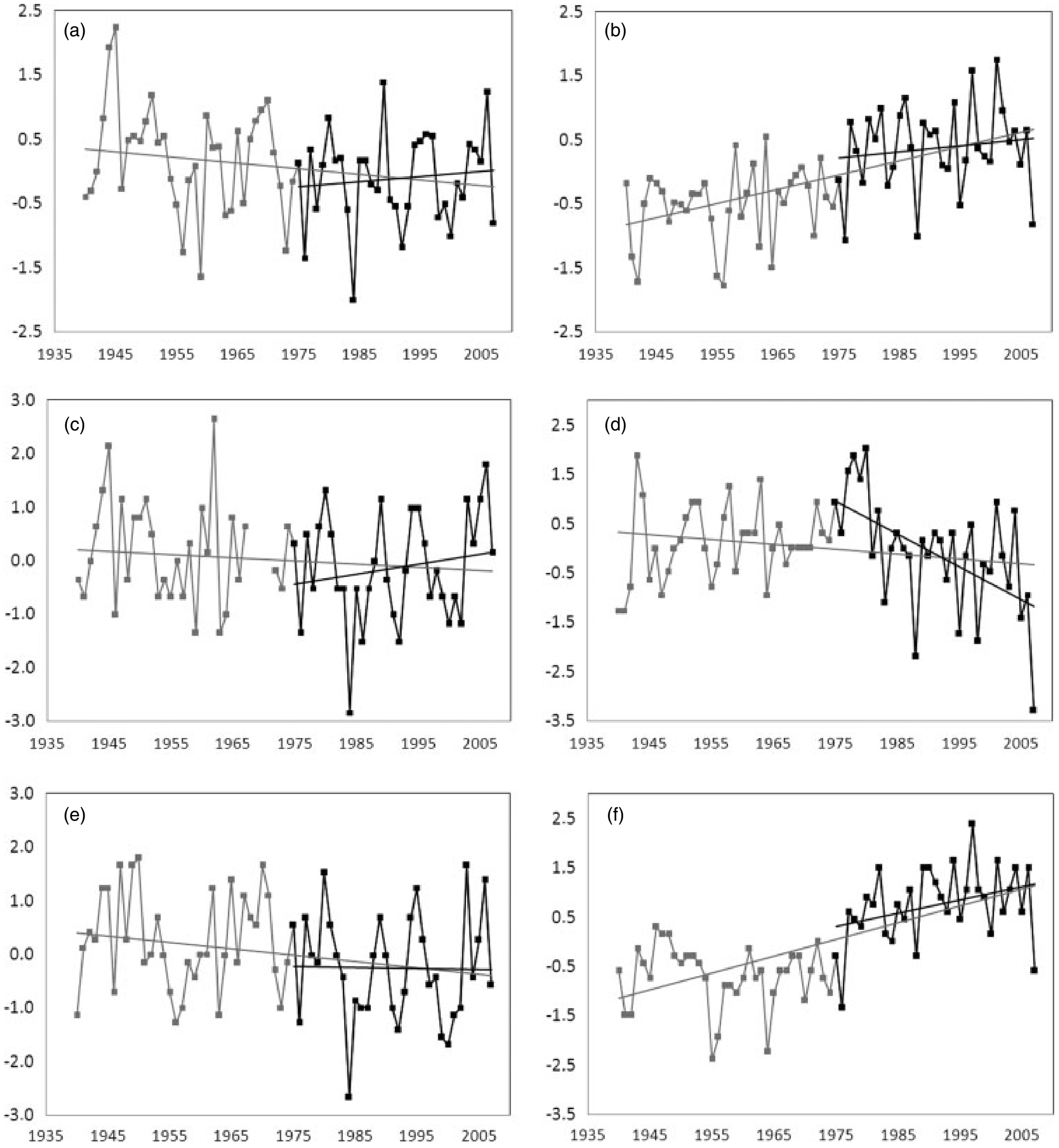

Figure 2. Annual average (standardized) of daily maximum (left panels) and minimum temperature (right panels) and their trends for the periods 1940–2007 and 1975–2007: (a) and (b) for all the stations; (c) and (d) for Coronel Suarez (CSu) and (e) and (f) for Santa Rosa (SRo).

Crops grow when the daily T_{mean} is above a given temperature threshold, varying according to the specie and its phenological state. Different indices are used to quantify that process. Thermal time or growing degree day (GDD) has been used to assist in selections of crops and hybrids to assure the selected crops will achieve maximum growth at the time they reach maturity and potential yield. Relationships between crop growth and GDD also have been used to predict crop yield (Mall *et al.*, 2000; León *et al.*, 2001). Changes in monthly GDD could affect the duration of some phenological stages, and in particular the ones that could decisively affect crop production. Therefore, we decided to analyse the monthly GDD values. GDD for each month and for three different temperature thresholds, or base temperature T_{b}, 5, 10 and 15 °C, $\mathrm{GDD}_{T_{\mathrm{b}}}$, were computed according to:

$$\mathrm{GDD}_{T_{\mathrm{b}}} = \sum_{1}^{n} (T_{\mathrm{mean}} - T_{\mathrm{b}}) \tag{1}$$

where n is the number of days in a given month, and T_{mean} is the daily average temperature computed using daily T_{min} and T_{max}. There is no accumulation if $T_{\mathrm{mean}} < T_{\mathrm{base}}$. We are not including in the analysis the GDD for base temperatures over 15 °C for the winter months (June to August).

Most plants from temperate regions, including deciduous fruit trees, require accumulating a given amount of

Table I. Meteorological stations (abbreviation and name), latitude (Lat), longitude (Lon), elevation (m) and initial year of available data.

Abbreviation	Station	Lat (S)	Lon (W)	Elevation (m)	Year
Sal	Salta	24.85	65.48	1221	1925
SdE	Santiago del Estero	27.77	64.30	199	1931
BVi	Bella Vista	28.43	58.92	70	1928
Cer	Ceres	29.88	61.95	88	1931
VMRS	Villa María del Río Seco	29.90	63.68	341	1931
MCa	Monte Caseros	30.27	57.65	54	1931
CorA	Córdoba	31.32	64.22	474	1956
Pil	Pilar	31.67	63.88	338	1925
Par A	Paraná	31.78	60.48	78	1931
VDo	Villa Dolores	31.95	65.13	569	1930
Ros	Rosario	32.92	60.78	25	1935
Gua	Gualeguaychú	33.00	58.62	21	1931
RCu	Río Cuarto	33.12	64.23	421	1931
SLu	San Luis	33.27	66.35	713	1931
Per	Pergamino	33.93	60.55	65	1931
Lab	Laboulaye	34.13	63.37	137	1939
SMi	San Miguel	34.55	58.73	26	1933
Eze	Ezeiza	34.82	58.53	20	1956
LPl	La Plata	34.97	57.90	23	1956
PIn	Punta Indio	35.37	57.28	22	1956
NdJ	Nueve de Julio	35.45	60.88	76	1931
Dol	Dolores	36.35	57.73	9	1931
SRo	Santa Rosa	36.57	64.27	191	1937
CSu	Coronel Suarez	37.43	61.88	233	1936
Pig	Pigüé	37.60	62.38	304	1935
Bal	Balcarce	37.75	58.30	130	1961
MdP	Mar del Plata	37.93	57.58	21	1950
BBl	Bahía Blanca	38.73	62.17	83	1956
Rec	Reconquista	29.18	59.70	53	1948
Tan	Tandil	37.23	59.25	175	1960
GPi	General Pico	35.70	63.75	141	1956
Cas	Castelar	34.67	58.65	22	1959
MJu	Marcos Juarez	32.70	62.15	114	1952
HAs	Hilario Ascasubi	39.38	62.62	22	1961
SVi	Sauce Viejo	31.70	60.82	18	1958
Jun	Junín	34.55	60.92	81	1958
Peh	Pehuajó	35.87	61.90	87	1951
Con	Concordia	31.30	58.02	38	1963
TAr	Tres Arroyos	38.33	60.25	109	1964

Table II. Agrometeorological indices used.

Indices	Abbreviation	Definition	Unit
First frost day	FFD	Date of first autumn frost	Date
Last frost day	LFD	Date of last spring frost	Date
Frost period	FP	Number of days between FFD and LDF	Days
Number of frost days	NFD	Number of days below freezing	Days
Start of growing season	$\mathrm{SGS}_{5,10,15}$	First 7 d spell with T_{mean} above 5, 10 and 15 °C	Date
End of growing season	$\mathrm{EGS}_{5,10,15}$	Last 7 d spell with T_{means} above 5, 10 and 15 °C	Date
Length of growing season	$\mathrm{LGS}_{5,10,15}$	Number of days between $\mathrm{SGS}_{5,10,15}$ and $\mathrm{EGS}_{5,10,15}$	Days
Growing degree days (monthly)	$\mathrm{GDD}_{5,10,15}$	Accumulated number for temperature degrees above 5, 10 and 15 °C	°C
Diurnal temperature range (monthly)	DTR	Monthly difference between daily maximum and minimum temperature	°C
Chilling hours	CH	Number of hours below 7 °C	Hours
Lowest minimum temperature	LMT	Lowest minimum temperature of the year	°C

chilling temperatures to overcome a dormancy period and to resume the growth in spring. A very common index is the chilling hours (CH) defined as the total number of hours when the temperature is below or equal to 7 °C (Fraisse and Whidden, 2010). The daily CH were accumulated over the five coldest months, considering here from May to September, when the accumulation of chilling temperatures is maximum. CH from daily temperature data was estimated according to Pascale and Damario (2004):

$$\mathrm{CH} = 24 \times \frac{(7 - T_{\min})}{(T_{\max} - T_{\min})} \tag{2}$$

The DTR for each month was calculated as the monthly average of the daily thermal amplitude, i.e. daily difference between $T_{\max}$ and $T_{\min}$. The last index in the analysis is the lowest minimum temperature of the year (LMT) which represents an indication of the risk of lethal temperatures on a given crop (Hall and Sadras, 2009).

2.3. Data analysis

The least squares estimator of a regression coefficient is vulnerable to gross errors and the associated confidence interval is, in addition, sensitive to non-normality of the parent distribution (Sen, 1968). So, in this paper we calculate the presence of a monotonic increasing or decreasing trend in the agrometeorological indices with the nonparametric Mann–Kendall test (Mann, 1945; Kendall, 1975) and the slope of a linear trend is estimated with the nonparametric Sen's method (Sen, 1968). The trend is the median of all possible trend estimates obtained from a pairs of observations obtained at distinctly different observing times. This estimator is statistically robust and unbiased. Missing values are allowed and the data need not conform to any particular distribution. Besides, the Sen's method is not greatly affected by single data errors or outliers.

Zhang *et al.* (2004) confirm that the Mann–Kendall test and Sen's slope estimator are not reliable when applied on time series with serially correlated residuals. The time series analysed in this work have an annual time step; we considered them statistically independent and without autoregressive processes. The level of significance was set to $p < 0.05$. Hereafter, if no level of significance is specified, all trends significant at the level $p < 0.05$ are referred to as significant. The trends were computed for annual time series for all the indices and for each of the monthly time series for GDD and DTR.

3. Results

3.1. Frost indices

Period 1940–2007. The FFD over 0 °C showed a delay in most of the region: in 35 stations (90%) the trends were positive indicating that the FFD occurred later in the year (Table III, Figure 3(a)). In 14 stations (36%), the correlation was statistically significant. For these stations, the occurrence of the FFD was delayed on average 4 d decade^{-1}. On the other hand, the LFD in 28 stations (72%) showed negative trends (33% were statistically significant), indicating a generalized earlier occurrence of the last frost (Table III, Figure 3(c)). Most of the stations with non-statistically significant changes in the LFD index were located north of 30 °S and along 65 °W (Figure 3(c)). On average, the LFD trend statistically significant was −4 d decade^{-1}. The behaviour of both indices has resulted in a decrease of the FP, with a clear negative trend throughout the region, statistically significant in 16 stations (41%) (Table III, Figure 3(e)). The average of the statistically significant trends values was −7 d decade^{-1}.

Table III. Number of stations with positive (Pos) and negative (Neg) trends of the frost indices FFD, LFD FP and NFD, above 0 and 3 °C, for the periods 1940–2007 and 1975–2007.[a]

Period	Indices	Above 0 °C		Above 3 °C	
		Pos	Neg	Pos	Neg
1940–2007	FFD	35 (14)	4 (0)	35 (20)	4 (1)
	LFD	9 (0)	28 (13)	9 (0)	30 (18)
	FP	8 (0)	31 (16)	8 (1)	31 (23)
	NFD	9 (1)	30 (17)	4 (2)	35 (20)
1975–2007	FFD	25 (3)	14 (1)	23 (2)	16 (1)
	LFD	18 (4)	19 (1)	19 (1)	20 (1)
	FP	19 (2)	20 (4)	19 (3)	20 (4)
	NFD	20 (2)	19 (2)	16 (2)	23 (5)

[a] Between parentheses is the number of stations with statistically significant trends.

There were also a lower number of frost days: the NFD decreased in 30 stations (77%), and in 17 (44%) the changes are statistically significant. The NFD statistically significant trends values ranged between −3 and 5 d decade^{-1}, with an average of −2 d decade^{-1}. In summary, from 1940 to 2007, fewer frost days occurred in most of the region. A small area in the SE of the studied region, centred approximately at 37 °S and between 62° and 59 °W (stations CSu and Tan), shows the opposite behaviour, an increase number of frost days, within a longer time period (Figure 3(e) and (g)).

The trends of the frost indices over the 3 °C threshold were statistically significant in a larger number of stations than over the 0 °C threshold (Table III). The spatial variation is similar to the frost indices over 0 °C: an increase number of stations with statistically significant frost indices trends located SE part of the domain (not shown). The mean trend values were also similar to the values over the 0 °C threshold, but the range of variation was larger for the FFD and consequently for the FP. The FFD trends ranged between 2 and 5 d decade^{-1} on average for the 0 °C threshold, compared to between −8 and 12 d decade^{-1} for the 3 °C threshold. The FP trends ranged between −12 and −3 d decade^{-1} for the 0 °C threshold and −16 and 12 d decade^{-1} for the 3 °C threshold.

Period 1975–2007. All the indices in this shorter and recent period showed statistically significant trends in a

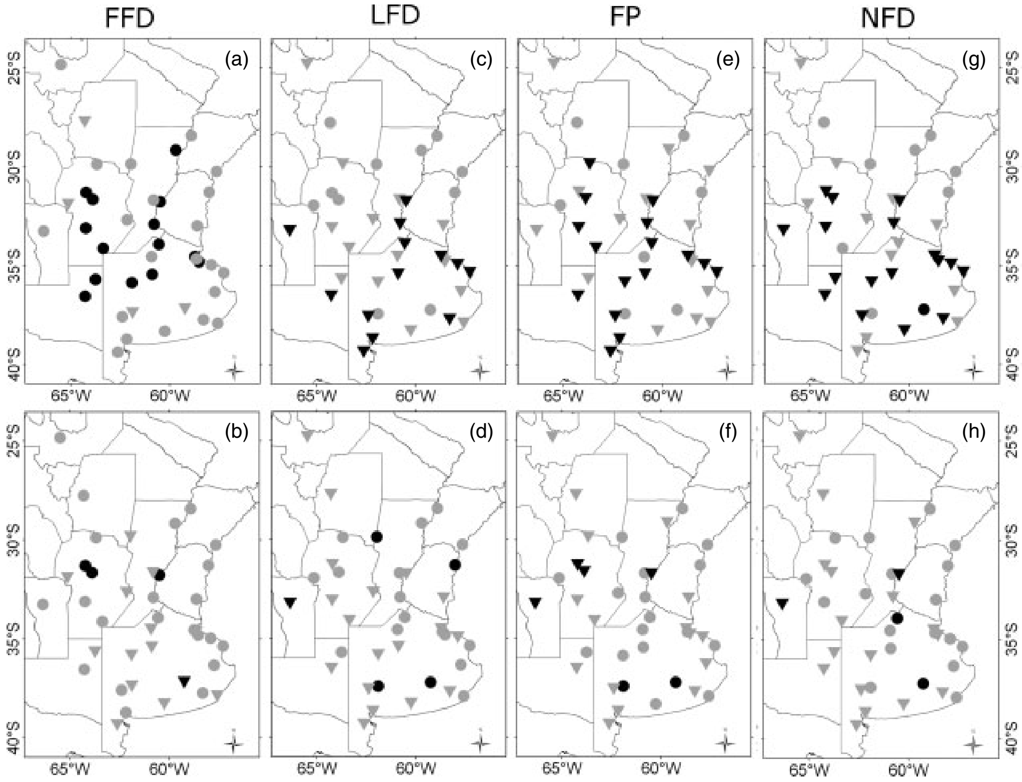

Figure 3. Trend of (a, b) FFD, (c, d) LFD, (e, f) FP and (g, h) NFD, above 0 °C for the periods 1940–2007 (top) and 1975–2007 (bottom). Positive and negative trends are represented with circles and triangles, respectively. Stations with statistically significant trends are shown with closed dark symbols.

much lower number of stations (Table III, Figure 3, bottom). Moreover, the trends did not show a clear behaviour and even the spatial pattern changed throughout the region compared to the period 1940–2007 (Figure 3, top). For example, for the FFD index over 0 °C, there were only 3 stations, compared to 14 in the longer period, with statistically significant positive trends. A 36% of the stations (14 stations) presented negative trends, compared to only 10% in the 1940–2007 period (Table III) and most of them located south of 35 °S (Figure 3(b)). This means an earlier occurrence of the first frost during recent years. In general, the mean trend values are larger, in absolute values, than in the longer period 1940–2007. One station, Tandil (Tan), have now statistically significant negative trends. The LFD showed a similar change: 18 stations have now positive trends (9 in the longer period) and only one with a negative statistically significant trend, compared to 13 in the period 1940–2007 (Table III, Figure 3(d)).

Although the FP index over 0 °C, showed a similar behaviour to the total period, the change was strongly weakened, in the slope value and in the number of stations with significant values (Table III, Figure 3(f)). The number of stations with statistically significant negative trends decreased from 16 to 4, and increased from none to 2 the stations with positive trends. Compared to the longer period (1940–2007), more stations show a relative longer FP during the recent years. This is indicated by the changes in the trends between the two periods (Table III): they show a shift from negative to positive values or trends become less negative. Nevertheless, the trends tended to shorten mostly in stations located W and N of the domain (Figure 3(f)).

Finally, for the NFD index over 0 °C, fewer stations have statistically significant negative trends (from 17 to 2 stations, Table III). More stations have now positive trends (20 compared to 9 in the period 1940–2007) mainly in the centre of the domain (Figure 3(h)). This indicates a tendency to more days with frost in the recent period.

Similar changes were found for the frost indices calculated over 3 °C (Table III). For example, only 2 stations have statistically significant positive FFD trends compared to 20 in the longer period. The LFD index that clearly had a negative trend in 77% of the stations (30) during the period 1940–2007, shifted to positive trends in 19 stations (49%), although only 1 is statistically significant. The number of stations with statistically significant negative trends in the FP index drastically decreased (from 23 to 4), but increased the number of stations with positive trends, from 8 to 19, of which 3 are statistically significant. Similar to the NFD over 0 °C, there are more stations with positive trends of the NFD over 3 °C in the recent period 1975–2007.

3.2. Indices based on crop temperature requirements

3.2.1. *Growing season indices (SGS, EGS and LGS)*

Period 1940–2007. In general for both analysed periods there was a fewer number of stations with statistically significant trends in the growing season indices compared to the frost indices (Table IV). Nevertheless, a clear behaviour can be seen for the base temperature of 10 and 15 °C. The SGS_{10} and SGS_{15} indices showed negative trends in 28 (72%) and 30 (77%) stations, although in only 12 and 9 the trends were statistically significant, respectively (Table IV). This indicates an earlier start of the growing season, on an average of -4.1 d decade^{-1} for the SGS_{10} index (only for the statistical significant stations). No station presented statistically significant positive trends (Table IV).

During this period, the trends in the EGS_{10} and EGS_{15} were positive in 33 and 30 stations, in 12 and 5 stations the trends were statistically significant (Table IV). This indicated a tendency to a delayed end of the growing season; the average value is 4 d decade^{-1} for the EGS_{10} index (only for the statistical significant stations). No station had negative statistically significant trends (Table IV).

The combination of both indices led to a general increase of the LGS throughout the region (Table IV). The LGS_{10} and LGS_{15} indices presented positive trends in 34 (87%) and 31 (79%) stations, and they were statistically significant in 18 and 14 stations, respectively. Although eight stations showed negative LGS_{15} trends, none was statistically significant. For the LGS_{10} the average increase is 6.3 d decade^{-1} considering only the statistically significant stations, and 8.3 d decade^{-1} for LGS_{15}. The trends did not have a clear spatial pattern in any of the indices (not shown).

Period 1975–2007. The number of stations with statistically significant trends decreased during this more recent period, similarly to the frost indices (Table IV). The SGS_{10} and SGS_{15} indices still showed negative trends, although number of stations with statistically significant trends shifted from 12 to none for SGS_{10}, and from 9 to 1 for SGS_{15}.

The EGS trends changed in this more recent period: most of the stations shifted from positive trends to negative trends, i.e., EGS_{15} had 30 stations with positive trends in 1940–2007, with 5 of them statistically significant, and in this more recent period 11 with only one statistically significant (Table IV). The trends values were still low, indicating that the end of the growing season tended to occur earlier.

The LGS_{10} and LGS_{15} indices shifted from predominantly positive trends during the period 1940–2007 (in 34 and 31 stations, respectively) to a lower number of stations with positive trends, (24 stations) for LGS_{10}, and mostly negative trends (24 stations) for LGS_{15} in 1975–2007. The average LGS_{10} value was -5.8 d decade^{-1} for stations with negative trends. There were only two stations with statistically positive trends (Table IV). Similarly to the other growing season indices, the spatial distribution of the trends did not shown a clear pattern, although the largest decrease in LGS tended to be concentrated in the centre of the domain (not shown).

Table IV. Number of stations with positive (Pos) and negative (Neg) trends of the growing season indices SGS, EGS and LGS, above 10 and 15 °C, for the periods 1940–2007 and 1975–2007.[a]

Period	Indices	Above 10 °C		Above 15 °C	
		Pos	Neg	Pos	Neg
1940–2007	SGS	10 (0)	28 (12)	9 (0)	30 (9)
	EGS	33 (12)	6 (0)	30 (5)	9 (0)
	LGS	34 (18)	5 (0)	31 (14)	8 (0)
1975–2007	SGS	18 (2)	20 (0)	18 (2)	21 (1)
	EGS	25 (4)	14 (2)	11 (1)	28 (2)
	LGS	24 (4)	15 (2)	15 (2)	24 (2)

[a] Between parentheses is the number of stations with statistically significant trends.

3.2.2. *Growing degree days*

Period 1940–2007. The trends of the GDD index showed a large variability between months with a generalized increased throughout the year. The GDD_{15} trends in January, March (Figure 4(a)), April and September to December were positive in more than 61% of the stations up to 97%, with no statistically significant negative trend, except in January (Table V). Except in March and October, the rest of the months had less than six stations with statistically significant positive trends. During October (Figure 4(e)), almost all the stations, 38 of 39, had positive trends, and 29 were statistically significant. The opposite pattern was observed in February and May (Figure 4(c)): they had mostly negative trends, with 28 and 33 stations respectively, and in February 7 were statistically significant (Table V).

The GDD_5 showed a similar behaviour than GDD_{15}. In June and August, most of the stations presented positive trends, with two and eight statistically significant (Table V). In July there were 34 stations with negative trends, although no station had statistically significant GDD_5 trend. October had all stations with positive trends and 32 were statistically significant. This was the month with the most spatially homogeneous trends.

Period 1975–2007. Similarly to the previously analysed indices, the number of stations with statistically significant GDD_{15} and GDD_5 trends drastically decreased during this latest period (Table V). The monthly pattern of positive *versus* negative trends mostly remained the same compared to the period 1940–2007. A shift to more negative than positive trends, has occurred for the GDD_{15} and GDD_5 in December. No statistically significant trends, either positive or negative, were found in the GDD_{15} for March (Figure 4(b)), April and May (Figure 4(d)), and in the GDD_5 for March, May, July and August (Table V). The month with the largest number of stations with statistically significant trends was October (Figure 4(f)), although that number decreased from 29 and 32 for the GDD_{15} and GDD_5 during the period 1940–2007 to 7 for this period 1975–2007 (Table V).

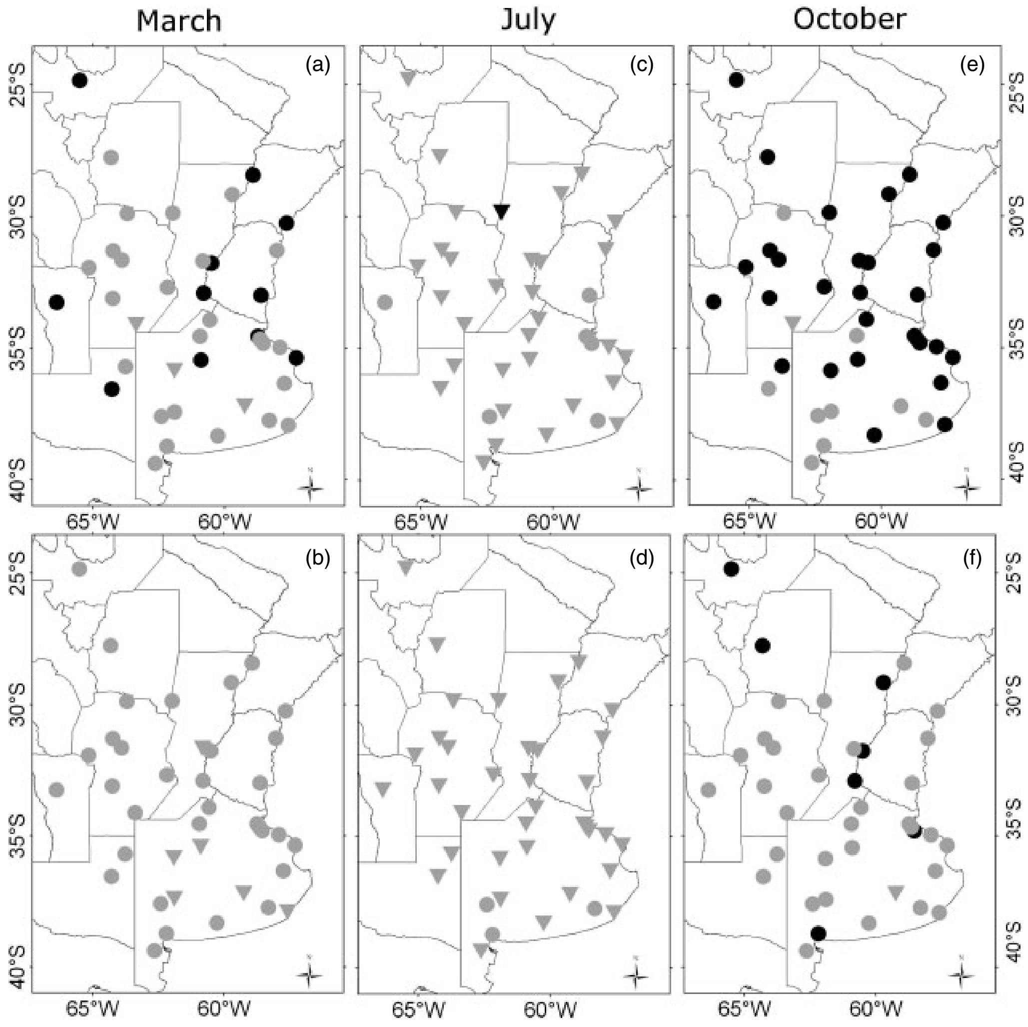

Figure 4. Trend of GDD above 15 °C, for the periods 1940–2007 (top) and 1975–2007 (bottom) for (a, b) March, (c, d) July and (e, f) October. Positive and negative trends are represented with circles and triangles, respectively. Stations with statistically significant trends are shown with closed dark symbols.

Table V. Number of stations with positive (Pos) and negative (Neg) trends of GDD for the periods 1940–2007 and 1975–2007.[a]

	Period 1940–2007				Period 1975–2007			
	GDD_{15}		GDD_5		GDD_{15}		GDD_5	
	Pos	Neg	Pos	Neg	Pos	Neg	Pos	Neg
January	26 (5)	13 (3)	25 (8)	14 (4)	20 (2)	19 (0)	20 (2)	19 (0)
February	11 (0)	28 (7)	12 (0)	27 (8)	10 (0)	29 (2)	10 (0)	29 (3)
March	36 (11)	3 (0)	35 (12)	4 (0)	33 (0)	6 (0)	32 (0)	7 (0)
April	30 (5)	9 (0)	30 (8)	9 (0)	23 (0)	16 (0)	19 (0)	20 (2)
May	6 (0)	33 (1)	11 (0)	28 (1)	3 (0)	36 (0)	3 (0)	36 (0)
June	–	–	32 (2)	7 (0)	–	–	37 (2)	2 (0)
July	–	–	5 (0)	34 (0)	–	–	14 (0)	25 (0)
August	–	–	38 (8)	1 (0)	–	–	30 (0)	9 (0)
September	30 (1)	9 (0)	30 (8)	9 (0)	28 (2)	11 (0)	30 (2)	9 (2)
October	38 (29)	1 (0)	39 (32)	0 (0)	38 (7)	1 (0)	35 (7)	4 (0)
November	26 (4)	13 (0)	26 (4)	13 (0)	36 (4)	3 (0)	31 (3)	8 (0)
December	24 (2)	15 (0)	25 (1)	14 (0)	12 (0)	27 (1)	12 (0)	27 (1)

[a] Between parentheses is the number of stations with statistically significant trends.

February, with negative trends, also showed a similar behaviour in the recent years, but with less statistically significant trends.

3.3. Other agroclimatic indices

3.3.1. Diurnal temperature range

Period 1940–2007. The DTR presented the higher number of stations with statistically significant trends of all the analysed indices and clearly most of them are negative (Table VI, Figure 5). The DTR clearly decreased from austral spring (September to October to November) to austral autumn (March to April to May) over almost the whole domain. June and July had the lowest number of stations with statistically significant trends.

Period 1975–2007. The number of stations with statistically significant trends drastically decreased in this latest period (Table VI, Figure 5). Moreover, there is not a clear seasonal pattern as in the period 1940–2007. The number of months with statistically significant positive trends increased specially during in April to May (austral autumn) and August to September (austral late

Table VI. Number of stations with positive (Pos) and negative (Neg) trends of DTR for the periods 1940–2007 and 1975–2007.[a]

	Period 1940–2007		Period 1975–2007	
	Pos	Neg	Pos	Neg
January	2 (0)	37 (32)	18 (1)	21 (1)
February	1 (0)	38 (34)	19 (0)	20 (1)
March	1 (0)	38 (23)	18 (0)	21 (1)
April	2 (0)	37 (27)	9 (2)	30 (7)
May	5 (1)	34 (13)	17 (2)	22 (4)
June	12 (2)	27 (2)	8 (1)	31 (2)
July	17 (4)	22 (4)	25 (3)	14 (0)
August	10 (0)	29 (9)	25 (5)	14 (0)
September	11 (0)	28 (7)	22 (3)	17 (0)
October	6 (1)	33 (12)	16 (0)	23 (0)
November	2 (0)	37 (22)	30 (1)	9 (0)
December	2 (0)	37 (25)	29 (1)	10 (0)

[a] Between parentheses is the number of stations with statistically significant trends.

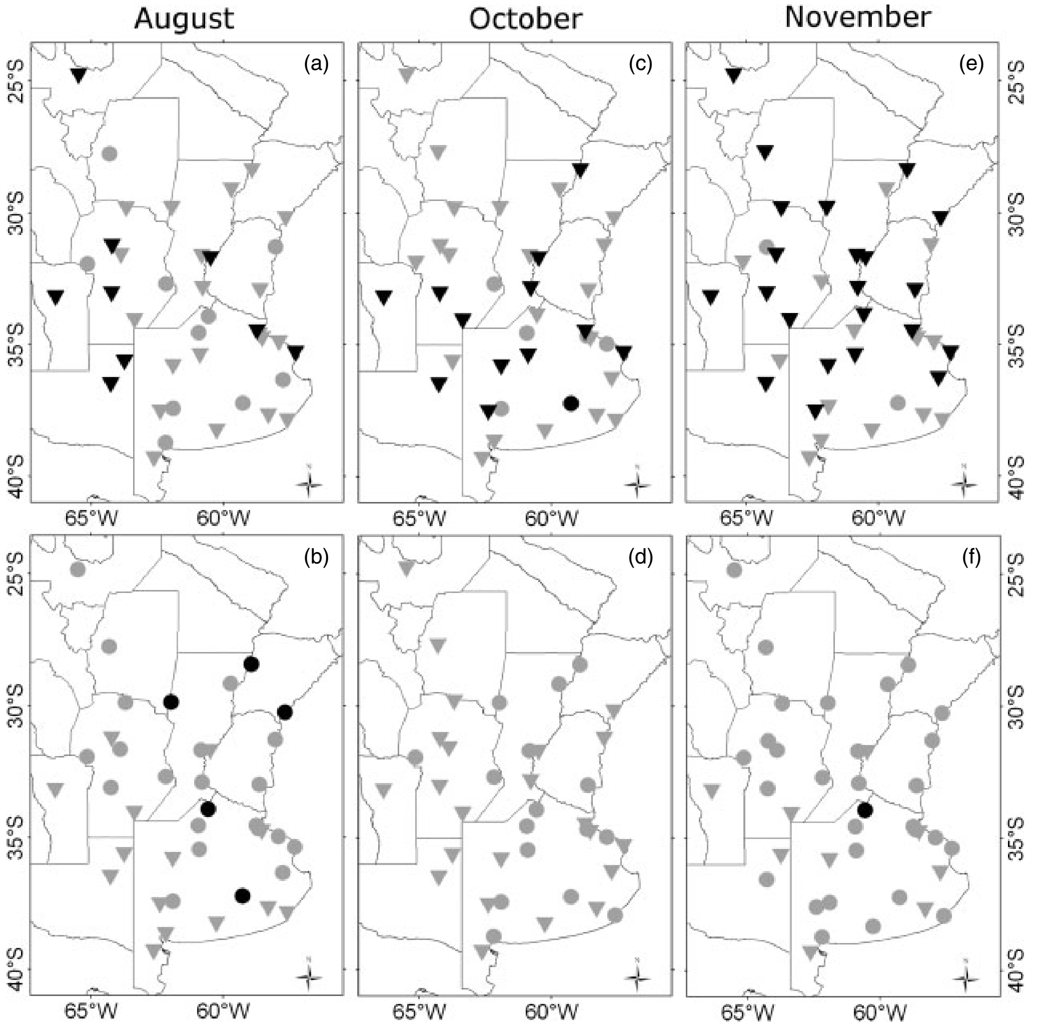

Figure 5. Trend of DTR for the periods 1940–2007 (top) and 1975–2007 (bottom) for (a, b) August, (c, d) October and (e, f) November. Positive and negative trends are represented with circles and triangles, respectively. Stations with statistically significant trends are shown with closed dark symbols.

winter – early spring). The pattern of trends started to shift to more positive than negative trends in August and extended to December, with the exception of October (Figure 5).

3.3.2. *Chilling hours and lowest minimum temperature*

Period 1940–2007. Negative trends in the CH were observed in 35 stations and in 11 were statistically significant (Table VII). Only four stations showed positive trends, and none statistically significant. This general decrease is due mostly to higher nighttime temperatures.

The LMT trends were positive in 30 stations, with 11 statistically significant (Table VII). Only two stations, CSu and Tan, showed negative statistically significant trends (not shown).

Period 1975–2007. Similarly to the rest of the indices, the number of stations with CH and LMT statistically significant trends decreased (Table VII). The pattern remained the same in both indices although the number of stations with CH negative trends decreased from 35 to 25 (Table VII).

4. Discussion and conclusions

In this work, we analysed the trends for the main temperature-based agroclimatic indices for two periods, 1940–2007 and 1975–2007 over the main agricultural area of Argentina. Overall, the trends changed between both studied periods, in absolute values and direction, although tendencies were mostly non-statistically significant in the short-term 1975–2007 period.

The occurrence of frost showed a clear decreasing trend in the long-term period 1940–2007 throughout the region. The FFD occurred later and the LFD occurred earlier during recent years compared to the 1940s and therefore, the frost period shortens during this total period 1940–2007. Conversely, a non-spatially homogeneous behaviour is observed during the recent 1975–2007 period. Most of the trends decreased. Moreover, in some stations located in the southern and central areas showed negative LFD trends, i.e. the last frost occurring later in the year. Although only few stations show statistically significant trends in this short-term period, the frost risk is still present with the consequent potential crop damage (Fernández-Long *et al*., 2005; Magra *et al*., 2005). During 2007 and 2008, frosts in November greatly affected the wheat production in the southern Pampas (Ross *et al*., 2007; Quiroz and Maneiro, 2007) and some areas with soya bean had to be re-sown due to frost damage (Downes, 2007).

Table VII. Number of stations with positive (Pos) and negative (Neg) trends of CH and LMT for the periods 1940–2007 and 1975–2007.[a]

Period	Indices	Pos	Neg
1940–2007	CH	4 (0)	35 (11)
	LMT	30 (11)	9 (2)
1975–2007	CH	14 (0)	25 (1)
	LMT	31 (5)	8 (3)

[a] Between parentheses is the number of stations with statistically significant trends.

The long-term tendencies of the SGS and EGS were mostly negative and positive, respectively, indicating an earlier start and a delayed end of the growing season, respectively. Therefore, the LGS presented a positive trend for the two temperature thresholds used. These results are similar to the ones observed in other parts of the world, like in Germany (Menzel *et al*., 2003), China (Song *et al*., 2010), and in mid-latitudes in the Northern Hemisphere (Frich *et al*., 2002). Increases of the LGS could also shift the productive area to higher latitudes, and also increase the number of potential harvest opportunities (ACIA, 2004). In addition, a longer LGS could add more flexibility to some agricultural practices which could lead to maximize yields (Rinaldi, 2004; Grassini *et al*., 2011). The sowing date for summer crops is usually delayed due to high probabilities of occurrence of the last frost; therefore an earlier start of the growing season would allowed for an earlier sowing date of summer crops which would increase the possibility of double-cropping, for example, wheat–soya bean, as found for the south-eastern Pampas (Monzón *et al*., 2007). They also found that a longer growing season, due to higher temperatures, resulted in increased simulated soya bean yield in the double-cropping management.

Nevertheless, during the recent 1975–2007 period, the EGS reverses the sign in many of the stations, and therefore, the growing season length shorten, which could have a negative impact on yield. Again, these short-term trends are statistically significant in few stations.

The GDD index trends showed a high inter-monthly variability. In the long-term period, an increase in temperature and therefore in GDD was found during the transitional months March and October (in more than 90% of the stations) while a temperature decrease was found during the extreme months July and February (in more than 69% of the stations). This means a seasonal change in the GDD index, with more availability of temperature in the sowing season and less for the reproductive season (February) of summer crops (i.e. maize and soya bean). More energy available during wheat flowering (October) could shorten the critical period and therefore potentially diminishing yields (Slafer and Rawson, 1994; Calderini *et al*., 2001).

The GDD trends smoothed out during the recent period 1975–2007 compared to the total period and the number of stations with statistically significant trends drastically decreased in this latter period. GDD trends during austral summer months December and January SGS_{10} and SGS_{15} shifted from mostly positive to mostly negative values, indicating a decreasing of temperature accumulation during the first development stages of summer crops.

Similar behaviour was found for the DTR monthly index. In the long-term period, during austral summer, in more than 64% of the stations the trends were negative and statistically significant. During austral winter, although a large number of stations showed negative trends, only a few were statistically significant. These results are similar to those found by Nuñez *et al.* (2008), Rusticucci and Barrucand (2004) and Vincent *et al.* (2005) and they can be explained by the increase in minimum temperature. The increase of T_{min} (and the decrease of T_{max}) can be explained by the increase of precipitation mainly during the summer semester (Forte Lay *et al.*, 2008). In the short-term period 1975–2007 there was a tendency to reverse the sign of the trends, especially during the warm spring-summer months, although similarly to the GDD index, the number of statistically significant trends drastically decreased. The annual precipitation trends showed a similar behaviour to the temperature-based indices, but of opposite value: all the analysed stations showed statistically significant positive values in the long-term annual precipitation tendency (Figure not shown). No station showed statistically significant precipitation tendencies for the short 1975–2007 period. A thorough analysis of the seasonal and monthly precipitation trends and their relationship with temperature trends is beyond the scope of the present work. We are deferring the analysis for a later study.

Instrumental observations over the past 157 years show that temperatures at the surface have risen globally, with important regional variations. For the global average, warming in the last century has occurred in two phases, from the 1910s to the 1940s (0.35 °C), and more strongly from the 1970s to the present (0.55 °C) according to the latest IPCC report (Trenberth *et al.*, 2007). Our results showed a different behaviour respect to the global increase in temperature: we found that the warming for the more recent 1975–2007 period was weaker than in the long-term 1940–2007 period, opposite to the global findings. For example, the LGS_{15} trends in 31 of the 39 analysed stations were positive (in 14 stations the trends were statistically significant) during the long-term period; the sign of the trends reversed for the recent short-term period, and 24 stations had negative trend values (and only 2 were statistically significant).

The behaviour of the trends and the changes between the long- and short-term periods were mostly spatially homogeneous with a clear exception of the stations Tandil (Tan) and Coronel Suárez (CSu) located in the southern Pampas. They showed a decrease in the minimum temperature, especially during the short-term 1975–2007 period and a statistically significant increase of the frost period. This shows that changes at local and sub-regional scales can greatly differ from those of the overall region. The temporal evolution, long- and short-term, of agroclimatic indices and extreme temperatures, and their effects on agricultural production and management should be locally assessed.

In summary, long-term 1940–2007 trends of several temperature-based agroclimatic indices for eastern Argentina show a generalized indication of regional warming, mainly due to increases in the minimum temperatures. For a recent period 1975–2007, the trends mostly weakened or reversed direction in some stations. Although those short-term trends are predominantly non-statistically significant, as Liebmann *et al.* (2010) found to be the case for short-term global surface temperature, they could potential affect management decisions and crop yields. In particular, frost is still an important hazard in agricultural activities and within the context of our results short- and long-term characterization of frost risk might need to be considered at local and sub-regional scales.

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