Theoretical and Applied Climatology (2019) 136:1371–1386
https://doi.org/10.1007/s00704-018-2565-7

ORIGINAL PAPER

Trends in reference evapotranspiration and associated climate variables over the last 30 years (1984–2014) in the Pampa region of Argentina

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Received: 19 January 2018 / Accepted: 12 July 2018 / Published online: 21 July 2018

Abstract

Agricultural production is sensitive to weather and thus directly affected by climate change. In Argentina, the geographic region known as the "Pampa" is at the heart of agricultural production. In this context, the objective of the present study was to evaluate the presence of long-term trends and abrupt changes in reference evapotranspiration (ETo PM) and associated climate variables in 30 weather stations of the Pampa over the 1984–2014 period. The presence of temporal trends was evaluated using Mann-Kendall's statistical test, whereas abrupt changes were detected through Pettitt test. Significant upward trends were observed in 80 and 43% of maximum temperature (Tmax) and ETo PM time series, whereas relative humidity (RH) and wind speed (WS), in contrast, presented decreasing trends in 57 and 47% of the locations. Abrupt changes were frequently observed in the years 2000–2003 for Tmax, RH, and ETo PM time series, a period that coincides with the occurrence of flooding events in the region. Weather stations of the Pampa region could be divided into two broad categories based on their trends in ETo PM and influencing climate variables: (A) stations exhibiting a rising trend in ETo PM and a concomitant decreasing trend in RH and (B) stations presenting invariant ETo PM and a decreasing trend in WS. The spatial distribution of the two categories of stations did not exhibit any specific geographic pattern. The information provided herein on modern trends in climate and evaporative demand is essential to the development of climate models and future scenarios necessary to evaluate food security prospects both regionally and globally.

1 Introduction

Agricultural production is sensitive to weather and thus directly affected by climate change (Nelson et al. 2014). Studies to date suggest that climate change has reduced growth in crops yields by 1–2% per decade over the past century (Wiebe et al. 2015). However, plausible estimates of these impacts are complicated by interactions between numerous biophysical and regional factors (Nelson et al. 2014; Wiebe et al. 2015). Indeed, climate change modifies not only air temperature, but also a set of climatic variables including precipitation, humidity, wind speed, sunshine duration, and evaporation; the magnitude and direction of these changes varying both locally and regionally (Zhang et al. 2017).

In Argentina, the geographic region known as the "Pampa" is at the heart of agricultural production. Often referred to as the "world's granary," the Pampa region is characterized by temperate climate and fertile deep soils that have favored the establishment of a thriving farming economy (Barros et al. 2014). Although global warming and climate change are pressing topics currently receiving wide attention globally, recent climate trends remain little studied in the Pampa region of Argentina. Indeed, although a number of studies have examined trends in precipitation in the past (Castañeda and Barros 1994; Barros et al. 2008; Re and Barros 2009; Scian and Pierini 2013; Saurral et al. 2017; Maenza et al. 2017), no information is available regarding modern trends in rainfall. For their part, trends in parameters such as evaporation, temperature, wind speed, relative humidity, and solar radiation remain largely unstudied or limited to interpretations emerging from

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continental-scale studies (Grossi Gallegos and Spreafichi 2008; Bichet et al. 2012; McVicar et al. 2012; Rusticucci 2012; Cardoso et al. 2016). Considering the close relationship existing between climate change, water regimes, and agricultural production, it is clearly important to better understand actual regional trends prevailing in the Pampa region in terms of evaporation, rainfall, and other climate parameters.

The potential evapotranspiration (PET) represents the evaporative demand of the atmosphere under given meteorological conditions (Katerji and Rana 2011). To standardize PET estimations, the Food and Agriculture Organization of the United Nations (FAO) has defined reference evapotranspiration (ETo) as "the evaporation of a surface of short, well-watered, grass with a prescribed albedo of 0.23 and surface resistance of 0.7 $s.m^{-1}$" (Allen et al. 1998). Although many equations exist to estimate ETo (McMahon et al. 2013), the Penman-Monteith equation (ETo PM) is considered the most complete, as it accounts for every climatic factor relevant to the evaporative process, namely relative humidity (RH), wind speed (WS), air temperature, and solar radiation (SR) (McVicar et al. 2012).

Water regimes in the Pampa region have in the past been greatly affected by the displacement of the Atlantic Subtropical High in the early 1960s and the climate shift observed in the 1970s over South America (Barros et al. 2014). This shift in climate was driven by a cold-to-warm sea surface temperature (SST) shift in the tropical Pacific Ocean that led to a phase change of the Pacific Decadal Oscillation (PDO) index and separated a "La Niña-like" decadal regime from an "El Niño-like" one (Jacques-Coper and Garreaud 2014). The climate shift was associated with a significant rise in rainfalls (Maenza et al. 2017; Saurral et al. 2017) and was linked to an increase in the number of floods and extreme precipitation events, especially during El Niño years (Re and Barros 2009; Penalba and Rivera 2016). The increase in rainfall was also responsible for the expansion of the agricultural frontier of rainfed agriculture to previously semiarid regions (Pérez et al. 2011, 2015). Although many studies have demonstrated the existence of positive trends or shifts in rainfalls when considering time periods that included the 1970s (Saurral et al. 2017; Maenza et al. 2017), no study has yet examined modern trends in rainfalls from the 1980s up to now.

As stated above, temporal trends in evaporation have been much less studied in the Pampa region than rainfalls. The only study to have previously examined temporal variation in ETo focused on the central sector of Argentina and only included the western limit of the Pampa region (de la Casa and Ovando 2016). Globally speaking, as the capacity of the air to hold water vapor expands with increasing temperatures, the rise in air temperature observed worldwide since the beginning of the twentieth century was expected to bring an acceleration of the hydrological cycle resulting in higher rates of precipitation and evaporation (Huntington 2006). However, contrary to predictions, a number of studies (Peterson et al. 1995; Roderick and Farquhar 2002; Hobbins and Ramirez 2004; McVicar et al. 2012; McMahon et al. 2013) have detected downward evaporation trends and questioned the supposed effect of temperature over evaporation, a debate referred to as the "evaporation paradox" (Roderick and Farquhar 2002).

Some authors believe that these downward trends in evaporation were linked to the complementary relationship proposed by Bouchet in 1963, which states that, when a terrestrial environment is water-limited, the solar energy that cannot be used in the evaporative process is released as sensible heat flux, which, in turn, drives an increase in potential evaporation (i.e., the evaporation in an adjacent water body with ample water supply) (Brutsaert and Parlange 1998). According to these authors, in such water-limited environments, any increase in terrestrial water supply during the trend calculation period would reduce heat flux-driven potential evaporation and generate downward trends in this parameter (Roderick and Farquhar 2002; Roderick et al. 2009; McMahon et al. 2013). Nevertheless, the existence of such downward evaporation trends in regions with unrestricted water supply suggests that other factors are also likely at play. For example, as evaporation is dependent on a number of climate variables, the presence of time trends in any of those variables may create a trend in evaporation (Chattopadhyay and Hulme 1997; Roderick and Farquhar 2002; McVicar et al. 2012). Alternatively, the "evaporation paradox" has also been linked to climate oscillations originating from teleconnections such as El Niño Southern Oscillation (ENSO) or the Pacific Decadal Oscillation (Miralles et al. 2013; Xing et al. 2016).

The objective of the current study was to examine the presence of trends and abrupt changes in ETo, rainfalls, and associated climate variables over the last 30 years (1984–2014 period) in the Pampa region of Argentina. This basic information is essential to the development of climate models and future climate scenarios necessary to the assessment of food security prospects both regionally and globally.

2 Materials and methods

2.1 Study area

The region known as "the Pampa" consists of a vast grassy plain of about 500,000 km^2 that covers most of central Argentina and is located between the 31st and 39th south parallels of latitude and between the 57th and 65th west meridians of longitude (Fig. 1). The eastern boundary of the region is delimited by the Uruguay River, the La Plata River, and the Atlantic Ocean. The Pampa region of Argentina includes the totality of Buenos Aires and Entre Ríos provinces, the center and south of Santa Fe province, the center and

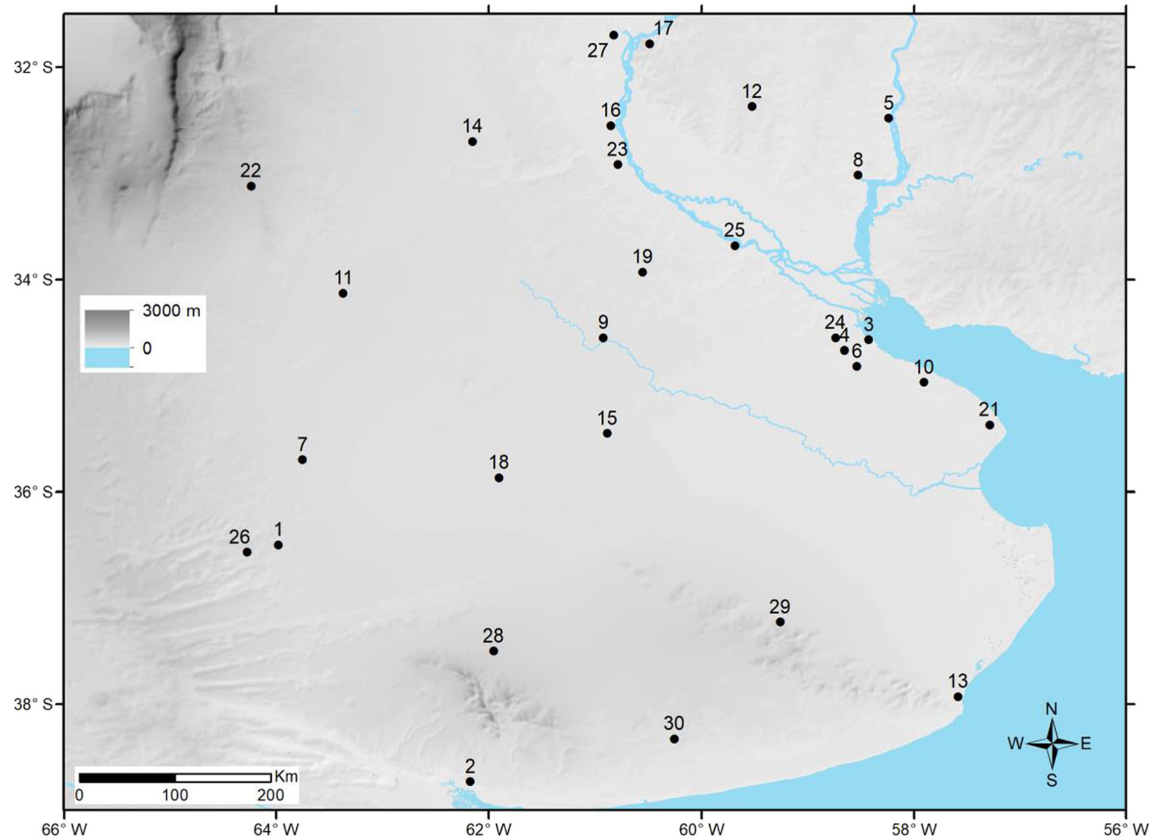

Fig. 1 Geographic locations of the studied meteorological stations within the Pampa region (Argentina). Numbers correspond to weather stations identified in Table 1

southeast of Córdoba province, and the northeast of La Pampa province (Moscatelli 1991).

The Pampa is part of a continental plain known as Pampasia that separates the ancient shields of Guyana–Brasilia from the Andean system and includes the great Amazonas and Chaco regions. The presence of the Andes Mountains to the west prevents moisture from entering from the Pacific Ocean, while Atlantic high-pressure systems bring humid and sometimes warm air from the east and the north (Barros et al. 2014). Mean annual precipitation gradually decreases from 1200 to 600 mm from east to west, whereas mean annual temperatures gradually increase from 14 to 19 °C from south to north (Rubi Blanchi and Cravero 2012). In contrast to other parts of South America where ENSO is linked to reductions in rainfalls, the warm ENSO phase produces above-average rainfalls in Argentina. The extra amount of precipitation received during El Niño years leads to a net increase in soil moisture and groundwater levels, especially during spring and summer months (Labraga et al. 2002; Barros et al. 2014; Penalba and Rivera 2016).

2.2 Data sources

Datasets from three different sources were used: (1) the Argentine National Meteorological Service (Servicio Meteorológico Nacional, SMN), (2) the National Institute of Agricultural Technology (Instituto Nacional de Tecnología Agropecuaria, INTA), and (3) the Hydraulic Management Agency of Entre Ríos Province (Dirección de Hidraúlica de Entre Ríos, DHER). Studied climate variables were maximum temperature (Tmax, °C), minimum temperature (Tmin, °C), wind speed at 10 m (WS, m s^{-1}), RH (%), and precipitation (PP, mm day^{-1}). ETo PM (mm day^{-1}) was calculated according to FAO-56 procedures using the Penman-Monteith Eq. 1 (Allen et al. 1998; Zotarelli et al. 2010).

$$\mathrm{ETo} = \frac{0.408\,\Delta\,(\mathrm{Rn}{-}G) + \gamma\,\frac{900}{\mathrm{Ta}+273}u_2 D}{\Delta + \gamma(1 + 0.34\,u_2)} \quad (1)$$

where Δ is the slope of the saturation vapor curve (kPa °C^{-1}), Rn is the net radiation at the surface (MJ m^{-2} day^{-1}), G is the ground heat flux (MJ m^{-2} day^{-1}), γ is the psychometric constant (kPa °C^{-1}), Ta is the mean daily air temperature calculated as Ta = (Tmax − Tmin) / 2 (°C), u_2 is the daily average wind speed at 2 m above ground level (m s^{-1}), and D is the saturation vapor pressure deficit (kPa) defined as $D = e_s - e_a$, with e_s being the saturation vapor pressure (kPa) and e_a the actual vapor pressure (kPa).

2.3 Data quality

To ensure data quality, available datasets were thoroughly inspected for regularity and consistency. Following a detailed visual inspection, three weather stations were discarded due to abrupt shifts in the mean over time of WS data. To further ensure data quality, the following cautionary measures were also taken: (1) daily temperature data were eliminated from the database when values of Tmin were greater than Tmax, (2) values greater or lower than three standard deviations were considered outliers and removed, and (3) to prevent unbalanced results, the whole month was removed from the database when more than 10 days were missing and the whole year was removed when more than 2 months of data were missing. Stations were also removed from the database if more than 5% of the data was missing or if more than 2 years of data were lacking for one variable. In the case of ETo PM, the percentage of missing data considered for quality control included missing values of Tmax, Tmin, WS, and RH. The implementation of these measures never removed more than 5% of the initial full data set. The final list of the 30 meteorological stations considered in this study is presented in Table 1 and Fig. 1.

2.4 Trend analysis and breakpoint detection

The nonparametric Mann-Kendall test was used to evaluate the statistical significance of adjusting a monotonic trend to the time series of annual averages of Tmax, Tmin, WS, RH, ETo PM, and PP. The magnitude of the trend was calculated by the Sen's slope estimator considering upper and lower confidence limits of 95%. The presence of a breakpoint in the time series of annual averages of Tmax, Tmin, WS, RH, ETo PM, and PP was examined using the nonparametric test of Pettitt (Pettitt 1979). The Pettitt's test allows detection of abrupt changes, whether artificial or natural, in the mean of the time series (Mallakpour and Villarini 2015). The aforementioned tests and estimator were calculated using the statistical package "trend" of the R software (Pohlert 2016). The hydrological parameters ETo PM and PP were expressed in terms of annual accumulation.

2.5 Relative influence of climatic variables on ETo PM values

A forward stepwise regression was executed in each of the 30 weather stations in order to evaluate and compare the relative influence of Tmax, Tmin, WS, RH, and PP on calculated ETo PM values at each location. Stepwise regressions were executed using SigmaPlot 12.5 software package. ETo PM values were natural log transformed before analysis to insure normality and equal variance of the data. The lack of collinearity of the data was checked using the Durbin-Watson statistic and significance tables (Durbin and Watson 1950; Durbin and Watson 1951).

2.6 Use of SR data for the calculation of a second set of ETo PM (ETo PM-SR)

Sunshine hours (SH) data were generally few or incomplete in most meteorological stations. Only ten stations presented sufficient SH data, according to the aforementioned quality criteria, to allow SR to be estimated from SH using the Angstrom equation and coefficients, as proposed by Penman (1948). For these ten weather stations, a second set of ETo PM data was calculated (according to FAO-56 procedures) using these SR values and referred to as ETo PM-SR (instead of using SR derived from air temperature differences as was the case in previous ETo PM estimations). Trend analysis and breakpoint detection were executed as described above on both the SR and ETo PM-SR datasets from these ten stations to examine whether the type of solar radiation employed influenced calculated values of ETo PM and the outcome of trend and breakpoint analysis. The concordance between ETo PM and ETo PM-SR datasets was further examined by computing the Spearman's rank nonparametric correlation coefficient using the package "stats" from the statistical software R.

3 Results

3.1 Long-term temporal trends and breakpoints

3.1.1 Temperature

Tmax time series displayed a significant upward trend for the 1984–2014 period in 80% of the 30 meteorological stations examined. Time series of the remaining stations failed to present any significant trends (Table 2). An abrupt change or breakpoint was detected in 63% of the series (19 stations out of 30), the break year occurring between 2000 and 2003 in 40% of these series (12 stations out of 19). Of the stations which presented a significant positive trend, 75% also had a significant breakpoint (Table 2).

Notably, most meteorological stations with stable Tmax series were located near major water bodies: the Atlantic Ocean (stations 13 and 21), the Paraná River (station 27), or the Uruguay River (stations 5 and 8) (Fig. 2a). An exception to this rule was the group of stations belonging to the metropolitan area of Buenos Aires (stations 3, 4, 6, 10, and 24) which presented upward trends in Tmax despite their proximity to La Plata River (Fig. 2a). These stations, nevertheless, registered the lowest significant Sen's slope values detected, indicating a trend of a low magnitude (Table 2). Overall, an average increase in Tmax of 0.03 °C per year was observed in the Pampa region for the period 1984–2014.

Table 1 Meteorological stations of the Pampa region (Argentina) used in the current study

	Station	Institution	Latitude (°E)	Longitude (°N)	Elevation (m a.s.l.)	WMO number
1	Anguil	INTA	− 36.50	− 63.98	165	87624
2	Bahia Blanca	SMN	− 38.73	− 62.17	83	87750
3	Buenos Aires	SMN	− 34.57	− 58.42	25	87585
4	Castelar	INTA	− 34.67	− 58.65	22	87575
5	Concepcion	INTA	− 32.48	− 58.23	25	87493
6	Ezeiza	SMN	− 34.82	− 58.53	20	87576
7	General Pico	SMN	− 35.70	− 63.75	145	87532
8	Gualeguaychu	SMN	− 33.02	− 58.52	21	87497
9	Junin	SMN	− 34.55	− 60.92	81	87548
10	La Plata	SMN	− 34.97	− 57.90	23	87593
11	Laboulaye	SMN	− 34.13	− 63.37	137	87534
12	L. Gonzalez	DHER	− 32.37	− 59.52	77	No Id
13	Mar del Plata	SMN	− 37.93	− 57.58	21	87,692
14	Marcos Juarez	SMN	− 32.70	− 62.15	114	87,467
15	Nueve de Julio	SMN	− 35.45	− 60.88	76	87,550
16	Oliveros	INTA	− 32.55	− 60.85	26	87,472
17	Parana	SMN	− 31.78	− 60.48	78	87,374
18	Pehuajo	SMN	− 35.87	− 61.90	87	87,544
19	Pergamino	INTA	− 33.93	− 60.55	65	87,484
20	Pilar	SMN	− 31.40	− 63.53	338	87,349
21	Punta Indio	SMN	− 35.37	− 57.28	22	87,596
22	Rio Cuarto	SMN	− 33.12	− 64.23	421	87,453
23	Rosario	SMN	− 32.92	− 60.78	25	87,480
24	San Miguel	SMN	− 34.55	− 58.73	26	87,569
25	San Pedro	INTA	− 33.68	− 59.68	28	87,494
26	Santa Rosa	SMN	− 36.57	− 64.27	191	87,623
27	Sauce Viejo	SMN	− 31.70	− 60.82	18	87,371
28	Suarez	SMN	− 37.50	− 61.95	233	87,637
29	Tandil	SMN	− 37.23	− 59.25	175	87,645
30	Tres Arroyos	SMN	− 38.33	− 60.25	115	87,688

INTA National Institute of Agricultural Technology, *SMN* National Meteorological Service, *DHER* Hydraulic Management Agency of Entre Ríos Province, *WMO* World Meteorological Organization

In contrast to the large proportion of increasing trends that were observed for Tmax, only 13% of the weather series had a significant upward trend in Tmin, whereas another 13% of the series presented a significant downward trend in this parameter (Fig. 2b). A breakpoint in Tmin was identified in only four of the 30 weather series and the year at which this breakpoint occurred was variable (Table 3).

3.1.2 Relative humidity and wind speed

About half (57%) of the weather stations exhibited a significant downward trend in RH for the period 1984–2014. The location of these stations was dispersed over the territory and without any distinctive geographic pattern (Fig. 2c). Only one station presented a significant upward trend, whereas the rest of the stations (40%) failed to exhibit a trend (Fig. 2c and Table 4). A significant breakpoint was detected in 60% of the stations, the breakpoint taking place between 2000 and 2004 in 72% of these cases (13 stations out of 18). Of the 18 stations presenting a significant trend, 89% also exhibited a breakpoint (Table 4).

With respect to WS, 47% of the meteorological stations examined presented a significant downward trend over the study period. Another 43% of the stations failed to display any significant trends, while a mere 10% exhibited an upward trend (Table 5). Interestingly, three out of four stations presenting an upward trend were located to the southwest of the region (Fig. 2d). Most weather stations (73%) had a breakpoint. The year of the break was more variable for WS than for any other parameter examined. The break occurred in the period 2000–2006 for 30% of the stations (9 of 30 stations), in the period 1991–1994 for 20% of them (6 of 30

Table 2 Results of trend analyses and breakpoint detections for annual average maximum temperature (Tmax) time series of meteorological stations of the Pampa region (Argentina) for the period 1984–2014

Stations		Mann-Kendall trend test			Pettitt breakpoint test	
		Trend intensity Sen's slope estimator (°C year^{-1})	*p* value	Trend direction	Breakpoint year	*p* value
1	Anguil	0.04	0.007**	Up	2002	0.006**
2	Bahia Blanca	0.03	0.011*	Up	1992	0.026*
3	Buenos Aires	0.03	0.003**	Up	2003	0.035*
4	Castelar	0.02	0.013*	Up	–	0.051
5	Concepcion	0.02	0.209	None	–	0.373
6	Ezeiza	0.02	0.028*	Up	2003	0.025*
7	General Pico	0.06	0.001**	Up	2002	0.003**
8	Gualeguaychu	0	0.825	None	–	1.000
9	Junin	0.05	< 0.0001**	Up	2002	0.002**
10	La Plata	0.02	0.003**	Up	2003	0.017*
11	La boulaye	0.05	0.014*	Up	2007	0.020*
12	L. Gonzalez	0.03	0.020*	Up	–	0.145
13	Mar del Plata	0.01	0.126	None	–	0.205
14	Marcos Juarez	0.03	0.045*	Up	–	0.153
15	Nueve de Julio	0.04	0.005**	Up	2003	0.011*
16	Oliveros	0.07	0.0002**	Up	2000	0.001**
17	Parana	0.03	0.018*	Up	–	0.122
18	Pehuajo	0.05	0.001**	Up	2005	0.004**
19	Pergamino	0.02	0.040*	Up	1993	0.039*
20	Pilar	0.03	0.074	None	2007	0.030*
21	Punta Indio	0.01	0.221	None	–	0.214
22	Rio Cuarto	0.05	0.021*	Up	–	0.062
23	Rosario	0.04	0.0007**	Up	1993	0.033*
24	San Miguel	0.03	0.005**	Up	2007	0.019*
25	San Pedro	0.02	0.038*	Up	–	0.145
26	Santa Rosa	0.06	0.002**	Up	2002	0.003**
27	Sauce Viejo	0.02	0.144	None	–	0.284
28	Suarez	0.04	0.012*	Up	2002	0.018*
29	Tandil	0.04	< 0.0001**	Up	2003	0.003**
30	Tres Arroyos	0.04	< 0.0001**	Up	2002	0.001**

$^{*}p < 0.05$, $^{**}p < 0.01$, level of statistical significance

stations) and between 1995 and 1999 in another 23% (7 of 30 stations) (Table 5).

3.1.3 Reference evapotranspiration and precipitation

Forty-three percent of the weather stations examined within the Pampa region displayed a significant upward trend in ETo PM over the 1984–2014 period (Table 6). The remaining stations (57%) failed to display a trend, and no downward trend was observed (Table 6). Stations exhibiting a significant upward trend were dispersed over the region and no specific pattern of spatial distribution could be detected (Fig. 3a). Most stations showing a significant upward trend also exhibited a significant breakpoint (Table 6), the break year occurring in 2002 or 2003 in all cases. With respect to cumulative precipitations, no significant trends or breakpoints was detected over the 1984–2014 period in any of the stations (Fig. 3b and Table 7).

3.2 Influence of climate variables on ETo PM

To facilitate interpretation of the data, trend and breakpoint results are summarized in Table 8 by cluster of stations exhibiting either an upward trend (group A) or lacking a significant trend (group B) in ETo PM. Grouping stations in this manner facilitate visualizing that

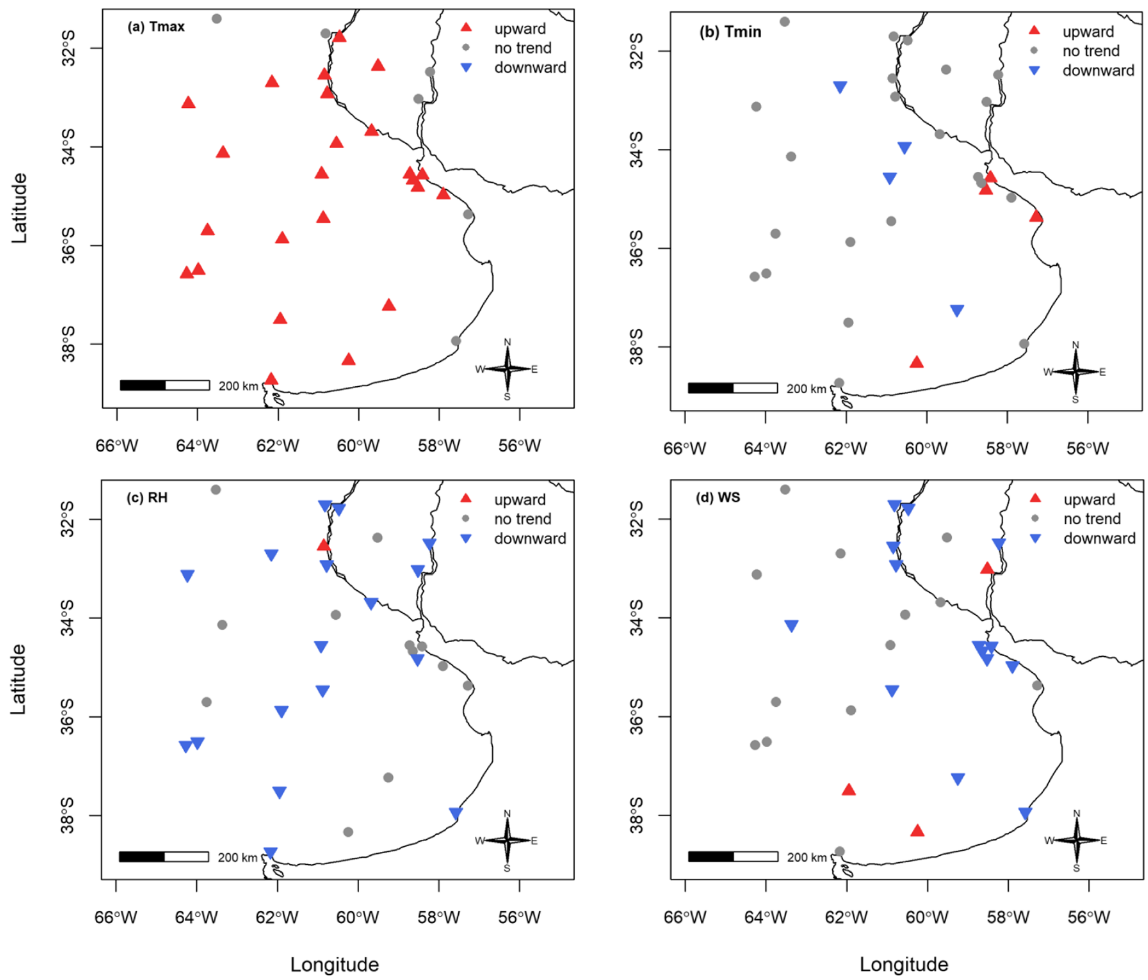

Fig. 2 Trends in **a** annual average maximum temperature (Tmax), **b** annual average minimum temperature (Tmin), **c** relative humidity (RH), and **d** wind speed at 10 m (WS) time series of weather stations from the Pampa region (Argentina) for the period 1984–2014. An upward triangle indicates a significant upward trend ($p < 0.05$), a downward triangle indicates a significant downward trend ($p < 0.05$), and a circle represents the absence of a significant trend

most stations (85%) with an upward trend in ETo PM (group A) present a concomitant downward trend in RH. In contrast, stations lacking a trend in ETo PM (group B) mostly present a downward trend in WS (71%). Table 8 also shows that most weather stations exhibit an upward trend in Tmax regardless of whether or not they present a trend in ETo PM.

A stepwise regression was conducted in each weather station to further examine and compare the influence of the various climate variables on ETo PM. RH was by far the most influential parameter, explaining more than 50% of the variability in 90% of the weather stations (Fig. 4). Consistent with previously-described results, RH was inversely related to ETo PM, the regression coefficient of RH being negative in all cases (data not shown). In most stations, WS was the second most influential factor, generally explaining 10 to 20% of the variability, followed by Tmax which normally explained in general between 2 and 10% of the variability (Fig. 4). Tmin was significant in the regression of 11 out of 30 stations, while PP was significant in only one case (station 18, Pehuajo). When significant, the relationship between ETo PM and WS, Tmax, Tmin, or PP was positive in all cases (data not shown), meaning that ETo PM values increase when these parameters increase. While the aforementioned pattern of influence on ETo PM was the most commonly observed, some exceptions existed. For example, Tmax was more influential than RH in stations 20 and 21, whereas Tmax and WS did not significantly influence ETo PM in stations 28 and 29. No specific geographic pattern could be associated to these exceptional cases (Fig. 4).

3.3 Influence of the type of solar radiation values used to calculate ETo PM

A significant increasing trend in SR was detected in six out of ten stations (Table 9). Trend analyses performed on ETo PM-SR brought about the exact same results as those

Table 3 Results of trend analyses and breakpoint detections for annual average minimum temperature (Tmin) time series of meteorological stations of the Pampa region (Argentina) for the period 1984–2014

	Stations	Mann-Kendall trend test			Pettitt breakpoint test	
		Trend intensity Sen's slope estimator (°C year^{-1})	*p* value	Trend direction	Breakpoint year	*p* value
1	Anguil	0.02	0.208	None	–	0.189
2	Bahia Blanca	0.02	0.056	None	–	0.171
3	Buenos Aires	0.01	0.049*	Up	–	0.273
4	Castelar	0.01	0.341	None	–	0.472
5	Concepcion	− 0.01	0.276	None	–	0.437
6	Ezeiza	0.03	0.006**	Up	1995	0.046*
7	General Pico	0.01	0.174	None	–	0.095
8	Gualeguaychu	0.01	0.444	None	–	0.648
9	Junin	− 0.03	0.041*	Down	–	0.054
10	La Plata	− 0.004	0.807	None	–	1.000
11	Laboulaye	0.002	0.892	None	–	1.000
12	L. Gonzalez	0.01	0.454	None	–	0.592
13	Mar del Plata	0.005	0.671	None	–	0.968
14	Marcos Juarez	− 0.03	0.025*	Down	–	0.069
15	Nueve de Julio	0.02	0.057	None	–	0.063
16	Oliveros	0.02	0.126	None	–	0.067
17	Parana	0.01	0.143	None	–	0.195
18	Pehuajo	0.01	0.475	None	–	0.439
19	Pergamino	− 0.04	0.003**	Down	2002	0.020*
20	Pilar	− 0.01	0.414	None	–	1.000
21	Punta Indio	0.04	0.003**	Up	1999	0.006**
22	Rio Cuarto	− 0.01	0.350	None	–	0.539
23	Rosario	0.01	0.300	None	–	0.273
24	San Miguel	− 0.001	0.915	None	–	1.000
25	San Pedro	− 0.002	0.825	None	–	1.000
26	Santa Rosa	0.005	0.646	None	–	0.610
27	Sauce Viejo	− 0.02	0.103	None	–	0.126
28	Suarez	− 0.02	0.126	None	–	0.173
29	Tandil	− 0.04	0.001**	Down	1993	0.006**
30	Tres Arroyos	0.02	0.016*	Up	–	0.052

*$p < 0.05$, **$p < 0.01$, level of statistical significance

obtained with ETo PM (Table 10). The high level of coherence between ETo PM and ETo PM-SR was confirmed by the significant and always greater than 0.9 Spearman correlation coefficients calculated between the two datasets. In practically all cases, the breakpoint years coincided for both ETo estimates (Table 10).

4 Discussion

The large prevalence of positive trends in Tmax over the whole territory highlights the existence of a climate warming trend over the 1984–2014 period in the Pampa region of Argentina. Furthermore, the presence in most stations of a positive relationship between Tmax and ETo PM values shows that this rise in temperatures acted as a driving force towards an increase in ETo PM over the region, as predicted by the Clausius-Clayperon relationship. Nevertheless, in spite of this climate-led pressure towards increased evaporation, only 43% of the meteorological stations presented statistically significant upward trends in ETo PM, due to counteracting decreasing trends in WS in many locations.

Indeed, significant downward trends in WS were observed in most weather stations in which ETo PM did not significantly increase, highlighting the stabilizing effect of decreasing WS on ETo PM in a subgroup of the stations examined (Table 8). The downward influence on ETo PM

Table 4 Results of trend analyses and breakpoint detections for relative humidity (RH) time series of meteorological stations of the Pampa region (Argentina) for the period 1984–2014

Stations		Mann-Kendall trend test			Pettitt breakpoint test	
		Trend intensity Sen's slope estimator (% $year^{-1}$)	*p* value	Trend direction	Breakpoint year	*p* value
1	Anguil	− 0.343	0.0009**	Down	2002	0.006**
2	Bahia Blanca	− 0.277	0.0005**	Down	2002	0.006**
3	Buenos Aires	− 0.071	0.059	None	–	0.110
4	Castelar	0.024	0.734	None	–	0.648
5	Concepcion	− 0.160	0.036*	Down	–	0.077
6	Ezeiza	− 0.096	0.023*	Down	1994	0.044*
7	General Pico	− 0.033	0.683	None	–	0.610
8	Gualeguaychu	− 0.187	0.007**	Down	2002	0.014*
9	Junin	− 0.197	0.0009**	Down	2002	0.014*
10	La Plata	0.020	0.852	None	–	0.307
11	Laboulaye	− 0.112	0.126	None	–	0.082
12	L. Gonzalez	0.014	0.865	None	–	0.945
13	Mar del Plata	− 0.103	0.007**	Down	1994	0.008**
14	Marcos Juarez	− 0.199	0.0004**	Down	2002	0.002**
15	Nueve de Julio	− 0.177	0.007**	Down	2002	0.020*
16	Oliveros	0.272	0.001**	Up	2000	0.001**
17	Parana	− 0.121	0.030*	Down	–	0.110
18	Pehuajo	− 0.290	0.0009**	Down	2002	0.001**
19	Pergamino	0.085	0.061	None	–	0.166
20	Pilar	− 0.020	0.786	None	–	0.307
21	Punta Indio	0.019	0.852	None	–	0.063
22	Rio Cuarto	− 0.251	0.0003**	Down	2002	0.006**
23	Rosario	− 0.206	0.0002**	Down	1994	0.003**
24	San Miguel	− 0.158	0.101	None	2006	0.003**
25	San Pedro	− 0.199	0.007**	Down	2003	0.005**
26	Santa Rosa	− 0.263	0.005**	Down	2002	0.014*
27	Sauce Viejo	− 0.377	<0.0001**	Down	2003	0.002**
28	Suarez	− 0.208	0.007**	Down	2002	0.007**
29	Tandil	− 0.026	0.646	None	–	0.344
30	Tres Arroyos	− 0.114	0.106	None	2005	0.010*

*$p < 0.05$, **$p < 0.01$, level of statistical significance

of decreasing WS is exemplified by the positive coefficient existing between the two variables in stepwise regressions. Similar downward trends in WS have recently been described over terrestrial surfaces in a number of regions worldwide, including the southern portion of South America (Bichet et al. 2012; McVicar et al. 2012; Cardoso et al. 2016). The phenomenon is known as "stilling" and is believed to result from either changes in large-scale atmospheric circulation (Rayner 2007; Jiang et al. 2010) or changes in surface roughness caused by urbanization or agricultural land cover (Vautard et al. 2010; Bichet et al. 2012; McVicar et al. 2012). In this respect, it is interesting to note that downward trends in WS were clearly notable in the group of stations belonging to the Metropolitan Area of Buenos Aires and La Plata cities, an extended urban area that doubled its extension from 937.16 to 1835.47 km^2 over the study period (Li 2017).

Alternatively, in locations where WS remained stable, climate warming and the associated upward trend in ETo PM were linked to a downward trend in RH (Table 8). No specific geographic pattern could be distinguished regarding the spatial distribution of the two different groups of stations: (A) those with rising ETo PM and decreasing RH and (B) those presenting invariant ETo PM and stilling. In this first group of stations, the opposite relationship existing between RH and ETo PM is clearly noticeable by the negative coefficient existing between the two variables in stepwise regressions. Similar scenarios of

Table 5 Results of trend analyses and breakpoint detections for wind speed (WS) time series of meteorological stations of the Pampa region (Argentina) for the period 1984–2014

Stations		Mann-Kendall trend test			Pettitt breakpoint test	
		Trend intensity Sen's slope estimator (m s^{-1} $yr.^{-1}$)	*p* value	Trend direction	Breakpoint year	*p* value
1	Anguil	− 0.003	0.789	None	–	0.408
2	Bahia Blanca	− 0.03	0.055	None	2003	0.026*
3	Buenos Aires	− 0.03	0.0003**	Down	2002	0.0005**
4	Castelar	− 0.02	< 0.0001**	Down	1997	0.0003**
5	Concepcion	− 0.02	0.0002**	Down	2000	0.0010**
6	Ezeiza	− 0.02	< 0.0001**	Down	1997	< 0.0001**
7	General Pico	− 0.01	0.261	None	1996	0.016*
8	Gualeguaychu	0.03	< 0.0001**	Up	1992	0.005**
9	Junin	0.01	0.163	None	–	0.158
10	La Plata	− 0.03	0.005**	Down	2002	0.004**
11	Laboulaye	− 0.03	0.016*	Down	1992	0.002**
12	L. Gonzalez	0.01	0.125	None	2001	0.015*
13	Mar del Plata	− 0.03	0.0006**	Down	1996	0.0002**
14	Marcos Juarez	− 0.01	0.241	None	–	0.166
15	Nueve de Julio	− 0.04	< 0.0001**	Down	2001	0.0003**
16	Oliveros	− 0.01	0.003**	Down	2000	0.022*
17	Parana	− 0.02	0.043*	Down	1995	0.0006**
18	Pehuajo	0.01	0.125	None	–	0.254
19	Pergamino	− 0.002	0.681	None	–	0.337
20	Pilar	0.02	0.144	None	–	0.284
21	Punta Indio	0.02	0.086	None	–	0.057
22	Rio Cuarto	− 0.01	0.587	None	–	0.855
23	Rosario	− 0.05	0.0001**	Down	1995	0.0001**
24	San Miguel	− 0.02	0.0005**	Down	2000	0.0002**
25	San Pedro	0.004	0.424	None	1991	0.010*
26	Santa Rosa	0.02	0.055	None	2006	0.003**
27	Sauce Viejo	− 0.02	0.011*	Down	1994	0.021*
28	Suarez	0.02	0.010*	Up	1997	0.011*
29	Tandil	− 0.03	< 0.0001**	Down	1991	0.003**
30	Tres Arroyos	0.02	0.0001**	Up	1994	0.0003**

*$p < 0.05$, **$p < 0.01$, level of statistical significance

warming-led downward trends in RH have recently been reported in a number of regions worldwide (Simmons et al. 2010; Willett et al. 2014; Xing et al. 2016; Byrne et al. 2016), including the La Plata River Basin in the Pampa region of Argentina (Vicente-Serrano et al. 2017). These observations may be somewhat counterintuitive at first because, as established in the Clausius-Clayperon relationship, the capacity of the air to hold moisture increases as a function of temperature. Nevertheless, such a linear increase in air moisture can only take place when water availability is unlimited as, for example, in oceanic areas. In water-restricted terrestrial environments, as land evapotranspiration becomes more and more supply-limited, RH is reduced and ETo PM is amplified due to this negative feedback (Jung et al. 2010; Sherwood and Fu 2014; Vicente-Serrano et al. 2017). Interestingly, although observed downward trends in RH would seem to indicate some level of restriction in surface water availability for evaporation, no decreasing trends in evaporation comparable to previously reported cases of "evaporation paradox" were observed in the current study.

On the other hand, the timing of the abrupt changes in evaporation observed in the current study does suggest an association between this parameter and ENSO. In the Pampa region, Niño years are characterized by large and intense rainfall episodes causing flooding events. Over the time period considered in the current study (1984–2014), important Niño-dependent flooding episodes occurred on

Table 6 Results of trend analyses and breakpoint detections for annual average reference evapotranspiration (ETo PM) time series of meteorological stations of the Pampa region (Argentina) for the period 1984–2014

	Stations	Mann-Kendall trend test			Pettitt breakpoint test	
		Trend intensity Sen's slope estimator (mm year^{-1})	*p* value	Trend direction	Breakpoint year	*p* value
1	Anguil	4.81	0.0004**	Up	2002	0.004**
2	Bahia Blanca	5.52	0.026*	Up	–	0.113
3	Buenos Aires	0.21	0.708	None	–	0.074
4	Castelar	− 1.08	0.163	None	–	0.132
5	Concepcion	0.51	0.678	None	–	0.385
6	Ezeiza	1.34	0.077	None	–	0.263
7	General Pico	2.33	0.318	None	–	0.204
8	Gualeguaychu	4.45	0.0002**	Up	2003	0.005**
9	Junin	4.09	0.0003**	Up	2002	0.008**
10	La Plata	− 0.54	0.750	None	–	0.506
11	Laboulaye	0.56	0.838	None	–	0.263
12	L. Gonzalez	0.93	0.248	None	–	0.263
13	Mar del Plata	0.90	0.163	None	–	0.331
14	Marcos Juarez	4.19	0.008**	Up	2002	0.009**
15	Nueve de Julio	0.02	1.000	None	–	0.539
16	Oliveros	− 1.99	0.055	None	–	0.115
17	Parana	1.67	0.187	None	–	0.364
18	Pehuajo	8.44	0.0002**	Up	2002	0.001**
19	Pergamino	− 1.46	0.187	None	–	0.223
20	Pilar	1.44	0.455	None	–	0.441
21	Punta Indio	4.97	0.025*	Up	–	0.223
22	Rio Cuarto	6.42	0.002**	Up	2002	0.005**
23	Rosario	2.19	0.020*	Up	–	0.111
24	San Miguel	0.37	0.721	None	–	0.128
25	San Pedro	3.15	0.002**	Up	2003	0.009**
26	Santa Rosa	7.68	0.0005**	Up	2002	0.003**
27	Sauce Viejo	6.10	< 0.0001**	Up	2002	0.003**
28	Suarez	1.85	0.324	None	–	0.945
29	Tandil	0.16	0.760	None	–	0.284
30	Tres Arroyos	5.74	0.0007**	Up	2002	0.009**

*$p < 0.05$, **$p < 0.01$, level of statistical significance

three occasions in 1993, 2001, and 2002 (Vigglizo et al. 2009; Scarpati and Capriolo 2011; Barros et al. 2014; Houspanossian et al. 2016). Interestingly, these dates correspond to periods during which abrupt changes in Tmax, RH, and ETo PM time series were most frequently observed, namely between 1992 and 1994 and 2000–2003. In addition to linking ETo PM variations with teleconnections, this coincidence provides further evidence that surface water availability influences temperature-driven variations in ETo PM and RH. Indeed, a possible explanation for this coincidence is that as a greater amount of surface water is present during flooding events, RH reductions are limited, and the subsequent potentiation of ETo PM is nullified or damped. This interpretation is also supported by the fact that the largest RH values occurred over the 1991–1993 and/or 2000–2001 period, which corresponds to a Niño event, while the lowest RH values were concomitant with the Niña period of 2008–2009 (data not shown).

In spite of the above-described timing between flooding events and ETo PM and RH variations, no trends nor abrupt changes were observed in the PP time series. Although this observation is somewhat confusing given the occurrence of flooding events within the examined time period, it is important to bear in mind that PP values were here expressed in terms of annual accumulation. Indeed, rather than annual accumulation, it is the frequency and intensity of extreme rainfalls, as well as the

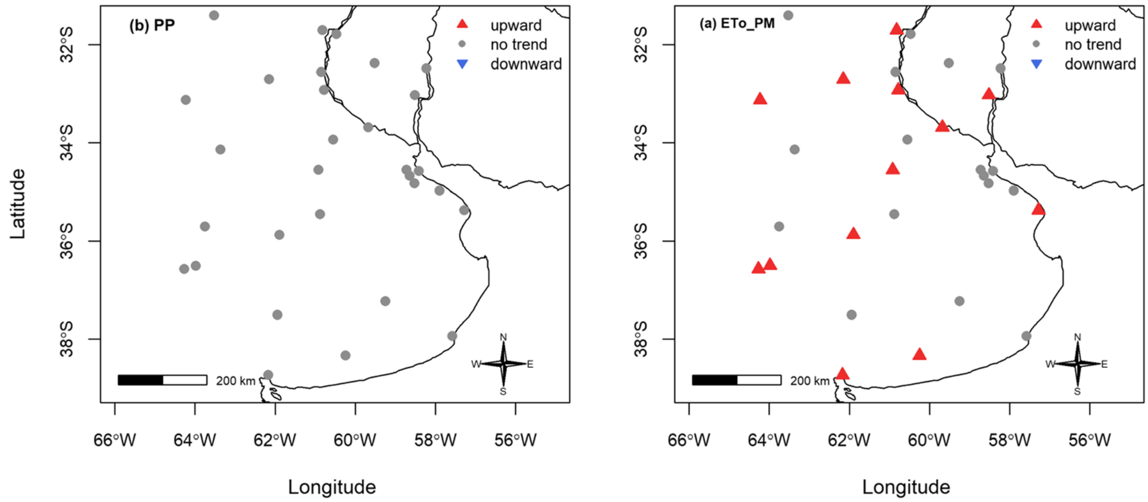

Fig. 3 Trends in **a** annual average reference evapotranspiration by Penman-Monteith (ETo PM) and **b** annual cumulative precipitation (PP) time series of weather stations from the Pampa region (Argentina) for the period 1984–2014. An upward triangle indicates a significant upward trend ($p < 0.05$), a downward triangle indicates a significant downward trend ($p < 0.05$), and a circle represents the absence of a significant trend

Table 7 Results of trend analyses and breakpoint detections for annual precipitation (PP) time series of meteorological stations of the Pampa region (Argentina) for the period 1984–2014

Stations		Mann-Kendall trend test			Pettitt breakpoint test	
		Trend intensity Sen's slope estimator (mm year^{-1})	*p* value	Trend direction	Breakpoint year	*p* value
1	Anguil	− 3.03	0.52	None	–	0.47
2	Bahia Blanca	− 2.37	0.40	None	–	0.26
3	Buenos Aires	2.97	0.48	None	–	0.41
4	Castelar	− 0.89	0.95	None	–	1.00
5	Concepcion	5.45	0.59	None	–	0.77
6	Ezeiza	− 1.30	0.79	None	–	1.00
7	General Pico	− 7.46	0.14	None	–	0.24
8	Gualeguaychu	12.91	0.07	None	–	0.10
9	Junin	3.88	0.52	None	–	0.73
10	La Plata	− 3.25	0.54	None	–	0.90
11	Laboulaye	− 2.02	0.76	None	–	0.65
12	L. Gonzalez	2.55	0.61	None	–	0.61
13	Mar del Plata	− 1.19	0.71	None	–	0.69
14	Marcos Juarez	0.68	0.92	None	–	1.00
15	Nueve de Julio	− 7.92	0.07	None	–	0.11
16	Oliveros	− 3.76	0.52	None	–	0.90
17	Parana	6.47	0.21	None	–	0.21
18	Pehuajo	− 5.68	0.21	None	–	0.17
19	Pergamino	− 2.53	0.66	None	–	0.99
20	Pilar	− 5.56	0.10	None	–	0.14
21	Punta Indio	7.37	0.16	None	–	0.28
22	Rio Cuarto	− 1.93	0.66	None	–	1.00
23	Rosario	3.05	0.56	None	–	0.90
24	San Miguel	− 7.76	0.18	None	–	0.07
25	San Pedro	− 5.09	0.34	None	–	0.54
26	Santa Rosa	− 4.83	0.23	None	–	0.14
27	Sauce Viejo	2.93	0.45	None	–	0.36
28	Suarez	− 9.34	0.06	None	–	0.31
29	Tandil	− 1.07	0.81	None	–	0.54
30	Tres Arroyos	− 3.71	0.29	None	–	0.50

$^*p < 0.05$, $^{**}p < 0.01$, level of statistical significance

Table 8 Summary of trends and breakpoints detected in meteorological stations presenting: (A) an upward trend in ETo PM and (B) no trend in ETo PM

A	Station	ETo PM	PP	TMax	TMin	RH	WS10
1	Anguil	UP 2002		UP 2002		DOWN 2002	
2	Bahia Blanca	UP		UP 1992		DOWN 2002	2003
8	Gualeguaychu	UP 2003				DOWN 2002	UP 1992
9	Junin	UP 2002		UP 2002	DOWN	DOWN 2002	
14	Marcos Juarez	UP 2002		UP	DOWN	DOWN 2002	
18	Pehuajo	UP 2002		UP 2005		DOWN 2002	
21	Punta Indio	UP			UP 1999		
22	Rio Cuarto	UP 2002		UP		DOWN 2002	
23	Rosario	UP		UP 1993		DOWN 1994	DOWN 1995
25	San Pedro	UP 2003		UP		DOWN 2003	1991
26	Santa Rosa	UP 2002		UP 2002		DOWN 2002	2006
27	Sauce Viejo	UP 2002				DOWN 2003	DOWN 1994
30	Tres Arroyos	UP 2002		UP 2002	UP	2005	UP 1994
B	Station	ETo PM	PP	TMax	TMin	RH	WS10
3	Buenos Aires			UP 2003	UP		DOWN 2002
4	Castelar			UP 2003			DOWN 1997
5	Concepcion					DOWN	DOWN 2000
6	Ezeiza			UP 2003	UP 1995	DOWN 1994	DOWN 1997
7	General Pico			UP 2002			1996
10	La Plata			UP 2003			DOWN 2002
11	Laboulaye			UP 2007			DOWN 1992
12	L. Gonzalez			UP			2001
13	Mar del Plata					DOWN 1994	DOWN 1996
15	Nueve de Julio			UP 2003		DOWN 2002	DOWN 2001
16	Oliveros			UP 2000		UP 2000	DOWN 2000
17	Parana			UP		DOWN	DOWN 1995
19	Pergamino			UP 1993	DOWN 2002		
20	Pilar			2007			
24	San Miguel			UP 2007		2006	DOWN 2000
28	Suarez			UP 2002		DOWN 2002	UP 1997
29	Tandil			UP 2003	DOWN 1993		DOWN 1991

Significant upward trends are reported as UP and significant downward trends as DOWN. Numbers shown under each climatic variable represent the years when a significant breakpoint is detected. The significance level was $p < 0.05$ in all cases

ETo PM evapotranspiration, *PP* precipitation, *Tmax* maximum temperature, *Tmin* minimum temperature, *RH* relative humidity, *WS* wind speed

presence of seasonal trends, that are the determinant factors in the formation of flooding events.

Finally, the existence of previous reports of both upward and downward trends in SH in the region (Grossi Gallegos and Spreafichi 2008) led us to further examine the influence of this parameter on ETo PM in spite of the limited availability of data among studied stations. For this reason, SR and ETo PM-SR were calculated for a subset of ten stations which presented sufficient SH data. A significant increasing trend in SR was detected in six out of ten stations. Nevertheless, the high coherence and correlation existing between ETo PM and ETo PM-SR values and trends suggest that the magnitudes of the trends in SR were not sufficient to critically influence ETo PM.

In conclusion, although an increase in Tmax could be observed over the 1984–2014 period at most weather stations from the Pampa region, this increase led to a significant upward trend in ETo PM in only 43% of the stations, the remaining stations failing to present a trend in this climatic parameter. Overall, weather stations of the

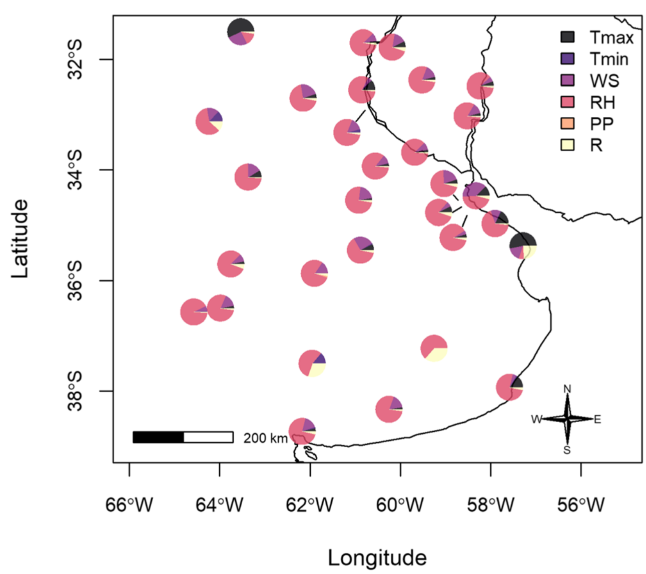

Fig. 4 Percent of variability explained by the different climate variables in a stepwise regression with average reference evapotranspiration by Penman-Monteith (ETo PM). PP = precipitation, Tmax = maximum temperature, Tmin = minimum temperature, RH = relative humidity (RH), WS = wind speed, and R = residuals of the regression

Table 9 Results of trend analyses and breakpoint detections for annual average solar radiation (SR) of meteorological stations of the Pampa region (Argentina) for the period 1984–2014

Stations		Mann-Kendall trend test			Pettitt breakpoint test	
		Trend intensity Sen's slope estimator (MJ m^{-2} $year^{-1}$)	*p* value	Trend direction	Breakpoint year	*p* value
1	Anguil	0.03	0.004**	Up	2004	0.019*
4	Castelar	− 0.02	0.135	None	–	0.067
9	Junin	0.05	0.004**	Up	2002	0.005**
11	Laboulaye	0.04	0.002**	Up	2002	0.011*
12	L. Gonzalez	0.02	0.099	None	–	0.166
16	Oliveros	0.04	0.0009**	Up	1994	0.006**
19	Pergamino	− 0.02	0.185	None	–	0.331
20	Pilar	0.04	0.007**	Up	2002	0.023*
21	Punta Indio	0.05	0.002**	Up	2002	0.017*
25	San Pedro	0	0.773	None	–	0.991

$^*p < 0.05$, $^{**}p < 0.01$, level of statistical significance

Pampa region could be divided into two broad categories based on the direction of their trends in ETo PM and influencing climate variables: (A) stations presenting a time invariant ETo PM due to a concomitant decreasing trend in WS and (B) stations exhibiting a rising trend in ETo PM with the presence of a simultaneous decreasing trend in RH. No specific geographic pattern could be distinguished regarding the overall spatial distribution of the two categories of stations. In the second group of stations, the decrease in RH that was observed with increasing ETo PM probably reflects a restriction in the amount of surface water available for evaporation in the context of increasing air temperature. The existence of a coincidental occurrence of ENSO-related flooding events and the abrupt changes in Tmax, RH, and ETo PM links variation in ETo PM with climate oscillations and provides further evidence of the influence of surface water availability on temperature-driven variations in ETo PM and RH. These findings on modern trends in climate and evaporative demand are essential to the development of climate models and future scenarios necessary to evaluate food security prospects both regionally and globally.

Acknowledgments We gratefully thank Graciela Cazenave, Vanesa Ramis, and Maria Victoria Feler of the "Instituto de Clima y Agua," INTA, for their help with data gathering and interpretation. We are also indebted to Nestor Garciarena from the agrometeorological station of INTA-Paraná and Hector A. Casa from the Hydraulic Management Agency of Entre Ríos Province for facilitating local data and information.

Table 10 Results of trend analyses and breakpoint detections for annual average reference evapotranspiration calculated using SH data time series (ETo PM-SR) of the studied meteorological stations of the Pampa region (Argentina) for the period 1984–2014

Stations		Mann-Kendall trend test			Pettitt breakpoint test		Correlation coefficient
		Trend intensity Sen's slope estimator (mm $year^{-1}$)	*p* value	Trend direction	Breakpoint year	*p* value	
1	Anguil	5.73	0.0005**	Up	2002	0.004**	0.98
4	Castelar	− 1.61	0.174	None	–	0.158	0.97
9	Junin	5.03	0.0005**	Up	2002	0.002**	0.98
11	Laboulaye	1.68	0.335	None	–	0.095	0.96
12	L. Gonzalez	1.51	0.135	None	–	0.242	0.95
16	Oliveros	− 0.51	0.587	None	–	0.855	0.94
19	Pergamino	− 2.16	0.094	None	–	0.287	0.93
20	Pilar	2.66	0.164	None	–	0.439	0.96
21	Punta Indio	6.22	0.007**	Up	–	0.110	0.98
25	San Pedro	3.29	0.010*	Up	–	0.054	0.98

$^*p < 0.05$, $^{**}p < 0.01$, level of statistical significance

We are grateful to Priscilla Minotti for help with GIS images and to an anonymous reviewer for comments on a previous version of the manuscript. We thank the National Meteorological Service for its collaboration. The first author would like to acknowledge the financial support of Global Affairs Canada for a scholarship awarded through the Emerging Leaders in the Americas Program.

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