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Regionalization of climate over the Argentine Pampas

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ABSTRACT: The aim of this study was to classify and characterize the climate of the Pampas, a vast region in the centre of Argentina. Due to its territorial extension, a climatic zoning of the region was performed, based on the topography and the most relevant climatological parameters. Climate data from 33 stations of the National Meteorological Service were analysed considering the period 1960–2010. A cluster analysis from the hierarchical method of Ward with an interval squared Euclidean distance as a measure of dissimilarity was applied. The obtained clusters responded to the north–south temperature gradient of the Pampas, influenced by geographical features such as the Tandilia and Ventania hills in Buenos Aires Province and the Pampean hills in Córdoba. Precipitation had a northeast–southwest gradient, and the influence of the arid southwest diagonal of the Pampas was appreciated by determining a semi-arid environment. The proximity to the sea marked the average humidity values, whereas the winds of strong intensity were registered in the south and west of the region. On the other hand, the standard precipitation index was calculated to identify wet and dry cycles in each cluster. It allowed to characterize these events considering frequency, periodicity, duration and intensity, resulting in the definition of eight climatic subregions.

KEY WORDS Climatic subregions; Pampas; Ward method; SPI

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1. Introduction

The Pampas is an extensive and fertile plain of Argentina. It has an extension of 613 532 km^2 (Figure 1) and includes various provinces: Buenos Aires, the northeast of La Pampa, the southeast of Córdoba and the south of both Santa Fe and Entre Rios (Labraga *et al.*, 2011). Its economy is based on agriculture and livestock industrialization. Since the late 19th century, it represents the most productive area of the country (Kitoh *et al.*, 2011; Martínez *et al.*, 2016). The region is characterized by the occurrence of long periods of drought and floods, which affect the water availability, the productivity of agricultural systems and other human activities.

The Pampas is located within the region of subtropical and mid-latitudes or temperate climates. In addition, it is next to the Atlantic Ocean; this fact generates lower daily and annual thermal amplitudes than in other regions at similar latitudes in the Northern Hemisphere (Barros *et al.*, 2015). The regional climate of the Pampas is also influenced by the Pacific Ocean. Frontal rains are generated due to latitudinal and longitudinal movements of air masses. Natural cycles in the atmosphere can affect the climate of the region for weeks, months and decades (Scian *et al.*, 2006; Scian and Pierini, 2013). El Niño Southern Oscillation (ENSO) causes inter-annual rainfall variations with more intensity during autumns and summers (the rainy season in South America) (Grimm, 2011). Winds from the northeast are generated by the South Atlantic semi-permanent high-pressure system, bringing humid and warm air. The region under the influence of the South Atlantic high-pressure represents the subtropical area of Argentina. On the other hand, dry westerly winds predominate at the southern extreme of the region. Precipitation decreases from northeast to southwest and determines the passage from warm and humid climate to a semi-arid one (Scian *et al.*, 2006). The eastern area is subtropical humid and subhumid, whereas the northwest is a dry-warm steppe. The west zone is dry and cold, and the southwestern region of the Pampas is arid and cold. Mean annual temperatures decrease from north to south, whereas the continental climate predominates from east to west, causing variations in the thermal regimes.

Climate is a key to determinate different characteristics and distribution of natural ecosystems. Temperature influences the distribution and abundance of patterns of plants and animals due to their physiological limitations (Parmesan *et al.*, 2000; Thomas *et al.*, 2004). Furthermore, precipitation variability on all time scales determines seasonal cycles as well as annual changes (Rosenzweig and Casassa, 2007). Forte Lay *et al.* (2008) analysed two periods of 30 years each (1947–1976 and 1977–2006) and found an increment in annual precipitation all over the region in the latter. Areas with different increases in precipitation were located; these varied between 50 and 200 mm in annual rainfall. One of the consequences of this increase was the augment in soil water supplies, essential

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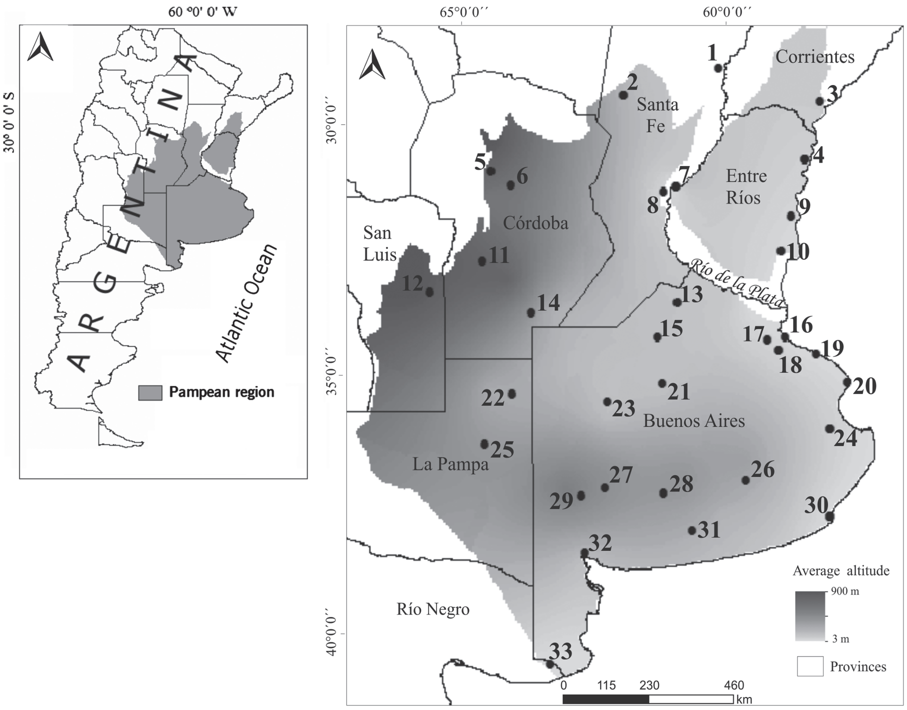

Figure 1. Localization of meteorological stations of the Pampas.

for the development of agricultural activities. Hulme and Sheard (1999) concluded that the mean annual temperature in Argentina increased 1 °C during the last century (1900–2000), being the 1990s the warmest decade. June to August (winter) were the months with the largest increment in temperature. On the other hand, a decrease in the frequency of frosts was also observed. These changes should be studied because even small fluctuations in weather patterns can affect the distribution of the different ecosystems. However, the specific effects may vary among regions.

Climate characterization is accomplished through methods based on statistical analyses, which allow to have an objective criterion. Multivariate statistical clustering methods have been widely used in order to establish homogeneous regions from a hydrology (Paris and Zucarelli, 2004), climate (Iyigun *et al.*, 2013) or rainfall (Jones *et al.*, 2014) perspective. Cluster analysis is very useful to generate subsets for classification. In Argentina, the application of cluster analysis has established homogeneous climatic zones, grouping variables such as different types of soil and maize yields, among others (Ravello *et al.*, 2001; Hurtado *et al.*, 2002). Specifically, Díaz and Mormeneo (2002) used this technique to characterize the homogeneous agro-climatic regions of the Pampas, considering only rainfall and temperature for the period 1961–1990. The cluster analysis was performed for each variable individually, then, the overlap of both variable results defined six clusters. However, only four of them were explained by precipitation. In addition, Aliaga *et al.* (2016) applied this method in the Pampas in order to determine six clusters, using monthly rainfall data for the period 1960–2010.

For the above mentioned, the Pampas has been characterized with an agro-meteorological and rainfall criteria, but there is not a delimitation that considers only the climatological variables to define the different climates that take place in it. Thus, this study was addressed to improve the knowledge about the climate subregions of the Pampas (Argentina), using climatic variables and considering its topography as well the increase in the collection frequency and the extension of the period of data register (1960–2010), contributed to reach a more accurate climatic delimitation. Besides, extreme meteorological events (droughts and floods) were analysed as well to generate a more precise climatic regionalization of the area. Once the regions were delimited, it was possible to categorize the areas with the highest risk of dry and wet events.

2. Materials and methods

2.1. Data

Climate data from 33 meteorological stations of the National Meteorological Service (SMN, Argentina) were collected to describe the spatial variability of climate (Figure 1). These data reflect the long-term (1960–2010) climate conditions in the Pampas expressed as monthly means of precipitation, air temperature, wind speed and direction, relative humidity and altitude. Table 1 shows the general setting of the studied area. A total of 2400 monthly records were obtained for each station, so more than 70 000 registers were analysed. Díaz (2001) had already tested the quality of similar data for the Pampas in the period 1961–1990 along with the records of the remaining two decades, normal trend and consistency

Table 1. Climate data from 33 meteorological stations of the SMN (period 1960–2010).

No.	Station	Latitude	Longitude	Altitude (m)	Precipitation (year mm^{-1})	Temperature (°C)	Wind speed (km h^{-1})	Relative humidity (%)
1	RECONQUISTA	−29.11	−59.42	53	1258.8	19.9	11	77
2	CERES	−29.53	−61.57	88	935.5	19.0	12	74
3	MONTE CASEROS	−30.16	−57.39	54	1458.2	19.6	10	74
4	CONCORDIA	−31.18	−58.01	38	1353.4	18.9	10	72
5	CORDOBA	−31.19	−64.13	493	856.8	17.1	11	73
6	PILAR	−31.40	−63.53	338	860.6	17.1	8	68
8	PARANA	−31.44	−60.29	87	937.4	15.3	17	72
7	SAUCE VIEJO	−31.46	−60.49	18	994.5	18.6	12	76
9	CONCEP.URUGUAY	−32.29	−58.14	25	1115.5	18.1	10	73
10	GUALEGUAYCHU	−33.00	−58.37	21	1094.0	17.7	10	74
11	RIO CUARTO	−33.07	−64.14	421	843.9	16.3	16	66
12	VILLA REYNOLDS	−33.44	−65.23	486	714.7	15.7	11	68
13	PERGAMINO INTA	−33.53	−60.34	65	993.8	16.6	11	74
14	LABOULAYE	−34.08	−63.22	137	873.3	16.1	13	71
15	JUNIN	−34.33	−60.55	81	1012.9	15.9	12	74
16	BUENOS AIRES	−34.35	−58.29	25	1180.2	17.7	11	72
17	CASTELAR	−34.40	−58.40	22	1037.4	16.8	8	72
18	EZEIZA	−34.49	−58.32	20	997.2	16.5	13	74
19	LA PLATA	−34.58	−57.54	23	1019.8	15.8	15	78
20	PUNTA INDIO	−35.22	−57.17	22	951.5	16.0	15	81
21	9 DE JULIO	−35.27	−60.53	76	1018.4	16.1	11	73
22	GRAL PICO	−35.42	−63.45	145	862.6	16.2	12	69
23	PEHUAJO	−35.52	−61.54	78	1034.2	18.3	13	75
24	DOLORES	−36.21	−57.44	9	950.4	14.8	11	79
25	SANTA ROSA	−36.34	−64.16	191	706.1	15.5	12	67
26	TANDIL	−37.14	−59.15	175	925.0	13.9	15	76
27	CNEL SUAREZ	−37.28	−61.56	233	779.1	13.5	13	72
28	LAPRIDA	−37.32	−60.49	212	827.3	14.2	10	67
29	PIGUE	−37.37	−62.25	304	894.0	14.2	11	74
30	MAR DEL PLATA	−37.56	−57.35	21	937.3	13.9	17	79
31	TRES ARROYOS	−38.23	−60.16	115	816.3	14.6	13	66
32	BAHIA BLANCA	−38.44	−62.10	83	654.5	15.4	22	69
33	VIEDMA	−40.80	−63.00	7	369.4	14.5	20	61

was tested following the guidance of quality control of climatological data from the World Meteorological Organization (WMO) World Climate Data Program (Klein Tank *et al.*, 2009) and using the methodology set by Rusticucci and Barrucand (2004).

2.2. Methods

The methodology consists of four steps summarized in Figure 2. The first one corresponds to the revision of monthly climate data from 33 meteorological stations and their organization in groups considering different climatic variables for further analysis: precipitation and temperature; climatological variables (relative humidity, wind speed) and topography; dry and wet events [standardized precipitation index (SPI)]. The second step corresponds to the regionalization process; the Ward clustering method was applied considering first the time-series of precipitation and temperature, and then the rest of the variables. Precipitation data were also examined with the SPI. The next step corresponds to the interpolation method (Kriging) used to delimit the subregions previously obtained. The last step corresponds to the boundary definition and characterization of the climate patterns in subregions according to the response to climate variability. Each methodological step is described in Sections 2.2.1.–2.2.3.).

2.2.1. *Ward cluster analysis*

In order to determine the spatial climatic subregions, the Ward cluster analysis (Ward, 1963) was used to generate regions considering different climatological variables (temperature, relative humidity, wind speed, precipitation and altitude). The purpose of clustering is the statistical classification of individual objects into groups or clusters. The criterion used for clustering is derived from the similarity and/or dissimilarity of all analysed objects on the basis of their selected characteristics. The 33 meteorological stations were the objects to be grouped according to the measured climatological data. These initial units were forming groups in ascending order until, at the end of the process, all cases were encompassed in the same cluster or until they reached the preset number of groups according to a dissimilarity of 2 %.

For this analysis, the Ward hierarchical method was applied with an interval of squared Euclidean distance as the dissimilarity measurement. It measures the distance between stations. This method groups by stage, joining the groups according to the increment in the total value of

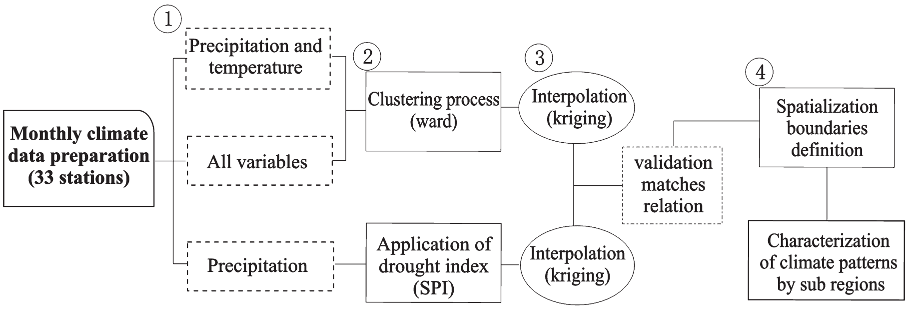

Figure 2. Diagram of the steps used to characterize the climatic subregions of the Pampas.

the sum of squares of the differences of each group to the centroid of each individual group (Equations (1) and (2)).

$$E_k = \sum_{i=1}^{nk}\sum_{j=1}^{n}\left(x_{ij}^{k} - m_j^k\right)^2 = \sum_{i=1}^{nk}\sum_{j=1}^{n}\left(x_{ij}^{k}\right)^2 - n_k\sum_{j=1}^{n}\left(m_j^k\right)^2 \tag{1}$$

where j is the variable, i is the individual and k is the cluster. E_k is the sum of the squared errors of cluster k, which is the squared Euclidean distance between each individual cluster k to its centroid.

$$E = \sum_{k=1}^{h} E_k \tag{2}$$

where E is the sum of the squared errors for all clusters, if we assume that there are h clusters.

The Ward agglomerative hierarchical clustering method has been widely used in weather and climate applications (Knapp *et al.*, 2002; Marzban and Sandgathe, 2005; Jolliffe and Philipp, 2010; Aliaga *et al.*, 2016). This method allowed to arrange the weather stations of the Pampas in groups with significant differences or dissimilarities less than 2 %. The fusion was optimized by minimization of the increment of the variance within the groups. Given the spatial congruence of the data, they could be analysed jointly by the different objectives. First, they were grouped considering only precipitation and air temperature. Then, all climatological variables were crossed for a more complex and representative grouping. In both cases, the study period was 1960–2010. From the analysis of the clusters, eight subregions were obtained representing the spatial distribution of the climate of the Pampas.

2.2.2. *Analyses of dry and wet climatic events with SPI*

After defining the climate of each subregion, the SPI was applied to identify dry and wet events. The SPI (Mckee *et al.*, 1993) is a meteorological drought index based on precipitation. The historical series of monthly rainfall for a specific period is used to calculate the SPI (Edwards *et al.*, 1997). It has been recommended by the Lincoln Declaration on Drought Indices (Hayes *et al.*, 2011) and is the most adequate drought index for South American regions (Penalba and Rivera, 2016). The SPI has been widely applied for the analysis of current and future drought conditions in different spatial and temporal scales (Al-Qinna *et al.*, 2011; Heinrich and Gobiet, 2012; Orlowsky and Seneviratne, 2013). Assuming its focus on precipitation, SPI droughts are the most relevant for rainfall-dependent activities, such as agriculture or water supply, in certain regions like the Pampas (Strzepek *et al.*, 2010). The index allows to identifying different types of drought, so it is a good indicator to evaluate the impact on water resources and different activities such as agriculture and livestock (Mckee *et al.*, 1993; Edwards *et al.*, 1997).

For the calculation of the SPI, the accumulated rainfall series was divided in 12 monthly series of 50 years. It was calculated considering time scales of 1, 3 and 12 months, which enabled the representation of short- and long-term droughts, respectively (monthly, seasonal and annual scales). A drought event was defined when the SPI values were lower than −1.0, which means that precipitation departures from average conditions exceeded one standard deviation. Wet events were represented by the SPI values above 1. Four parameters were considered for dry and wet events through SPI: *frequency* – number of periods; *periodicity* – time between an event and the occurrence of another one; *duration* – average duration of all events; *intensity* – average SPI values of all events. They were calculated separately for dry and wet events for each meteorological station to identify significant differences between subregions.

2.2.3. *Climate interpolation data*

Interpolation is a common practice in statistical analysis. The interpolation methods usually generate different results, according to the approach they use for determining the output cell values. The choice of the most appropriate method will depend on the distribution of sample points and the phenomenon being studied. In this case, a geo-statistical interpolation technique was adapted because it is based on statistics and is used for more advanced prediction surface modelling such as the *Kriging* method.

Kriging assumes that the distance or direction among sample points reflects a spatial correlation that can be used to explain variation in the area. It fits a function to a specified number of points or all points within a specified radius to determine the output value for each location. Kriging aims to produce a better linear unbiased estimate for an unknown location. It is linear because the projected

Table 2. Mean values of climate parameters in both cases of cluster analysis.

Cluster (case 1)	1	2	3	4	5	6	7	
Precipitation (mm year^{-1})	1357	1056	859	1004	692	883	369	-
Temperature (°C)	19	18	16	16	16	14	15	-
Cluster (case 2)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Precipitation (mm year^{-1})	1357	988	819	1043	829	957	512	814
Temperature (°C)	19	19	17	17	14	15	14	16
Relative humidity (%)	74	74	69	73	70	79	65	69
Wind velocity (km h^{-1})	10	14	11	11	12	15	21	12
Altitude (msl)	48	61	435	47	216	50	43	158

values are weighted linear combinations of the available data, and unbiased because the mean of the error is 0; it aims to minimize the variance of the errors (Menafoglio *et al.*, 2013). The predicted values are derived from the measure of relationship in samples using a sophisticated weighted average technique, which uses a search radius that can be fixed or variable. The generated cell values can exceed the value range of the samples, and the surface does not pass through the samples.

The ordinary Kriging type was chosen for this study because it is the best suited to geo-sciences and has numerous applications in scientific fields, such as fisheries, forestry, civil engineering, image processing, cartography and meteorology (FAO, 2003). This technique has shown the results that best fit the analysis of climatological data (Gong and Richman, 1995; Marzban and Sandgathe, 2005; Keskin *et al.*, 2015; Zhang *et al.*, 2015). This assumes that there is no constant mean for the data over an area (i.e. no trend). Regular spherical and cell size of 0.01 was used.

3. Results

3.1. Climate clusters

The Ward classifications divided the Pampas into several subregions characterized by the different distribution of the climatic variables. There groups or clusters indicated the transition from the continental climate in the south west, with fairly low precipitation and low mean temperatures, to the warm and wet climate toward the northeast. The climatic clusters are described in detail as cases 1 and 2 for each group of climatological parameters (Table 2) in the next section.

3.1.1. Precipitation and temperature cluster

The Ward analysis identified seven clusters from the monthly mean precipitation and temperature of the 33 meteorological stations located in the Pampas (Figure 3). It showed a gradient in the region, where the temperature decreased from north to south, and precipitation from northeast to southwest (Grimm, 2011; Aliaga *et al.*, 2016). The maximum rainfall was registered northeast of the region due to the contribution of warm and wet air from the South Atlantic Ocean. Clusters 1, 2, 4 and 6 showed a progressive decrease in the temperature gradient, with differences of up to 5 °C between the extremes, as well as a decrease in the average rainfall ranging from 1.300 to 900 mm year^{-1}.

To the west, a considerable decrease in rainfall was represented by clusters 3 and 5, where the precipitation decreased between 250 and 200 mm year compared with the neighbouring clusters 2 and 6, respectively. Temperature decreased between clusters 2 and 3 due to the increase of the altitude in Córdoba province (northwest – Figure 1). Cluster 4 showed a northwest–southeast arrangement, which coincided with the arid diagonal of South America in Argentina; this marks a climate limitation on the annual rainfall that matches the isoline of 500 mm year^{-1} (Gabella and Zimmermann, 2016). Clusters 3 and 4 had a longitudinal extension whereas the others are distributed in circular or longitudinal shape. Finally, cluster 7 was the coldest and driest in the Pampas, with rainfall below 400 mm year^{-1}, about 300 mm less than the northeast cluster next to it. Only in this case, the cluster is represented by a single meteorological station called *Viedma* located in the southern limit of the region (Figure 1)

3.1.2. Climatological and topographical variables

The incorporation of new climatological and topographical parameters did not modify cluster 1, characterized by high relative humidity due to the income of wet masses entering the continent from the South Atlantic Anticyclone. During the study period, the wind direction was more frequent from the east, southeast and northeast. Its highest incidence was during spring and summer. This cluster corresponded to a region with a semi-annual cycle as a result of two factors: warming (represented by the annual cycle) and advection of humidity (represented by the semi-annual cycle) (Penalba and Rivera, 2016). Cluster 2 had a reduced area and retained high temperatures whereas the volume of rainfall decreased. The northeast wind direction predominated although there was no marked seasonality. It represented a warm and humid climate with an altitude of 61 masl (Figure 4). The influence of cluster 3 was extended to the northeast, representing an area of abundant rainfall and high temperatures. This cluster comprised the lower basin and the estuary of the Río de la Plata (Figure 1), which coincided with low altitude and high humidity. In this region, the predominant wind direction varied from northeast to southeast as well as the latitude increases.

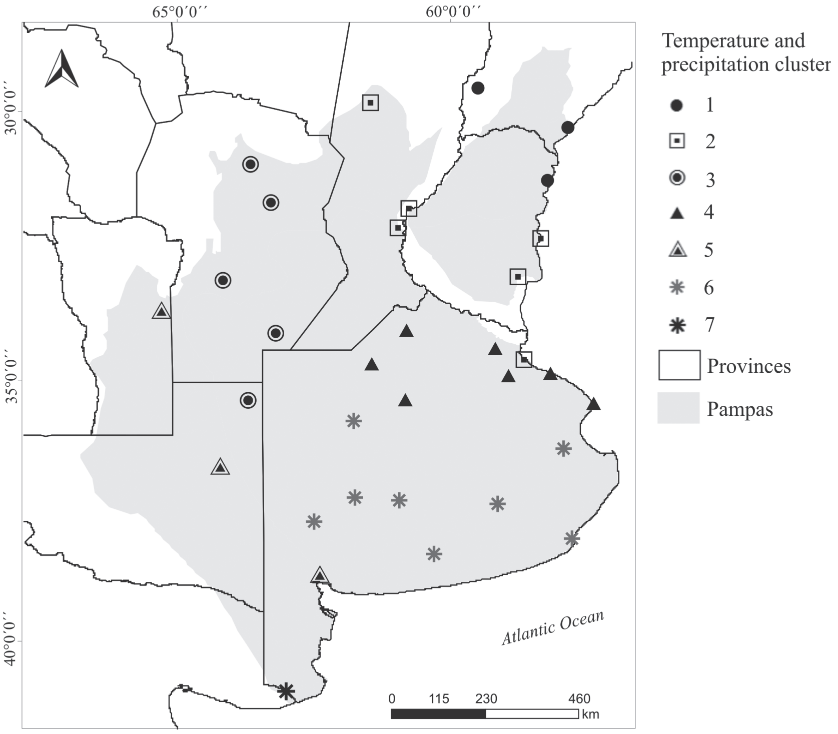

Figure 3. Spatial distribution of clusters considering temperature and precipitation (1960–2010).

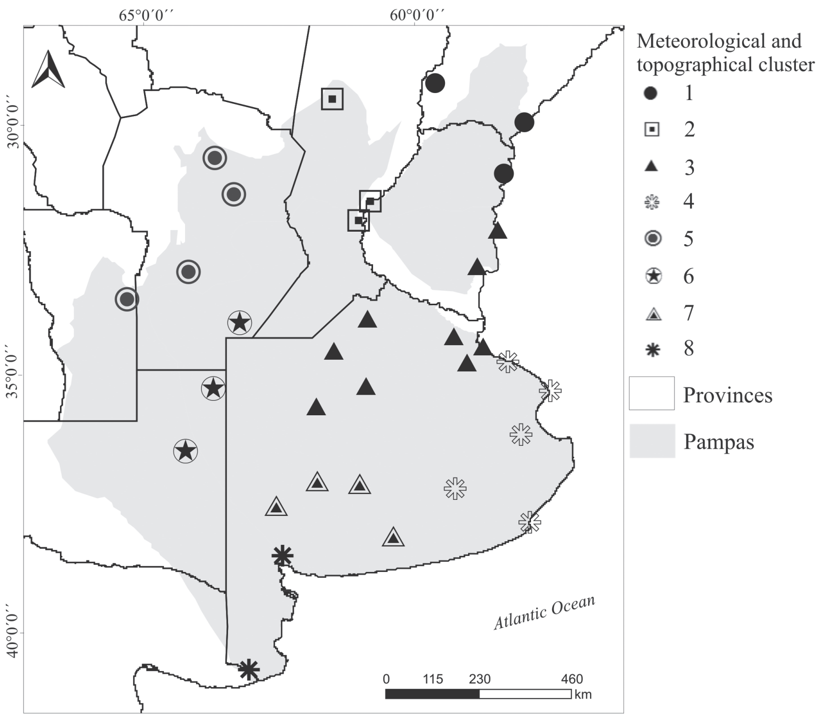

Figure 4. Spatial distribution of cluster considering meteorological and topographical parameters (1960–2010).

To the east, cluster 4 represented the climate of the Pampas within a strong maritime influence, with intense wind speed and rainfall (Table 2). Wind directions from the northeast, east and southeast were frequent from the coast, while inside the continent were from west. Cluster 5 was amended prioritizing the altitude of the area (435 masl), which was the highest of all clusters, unifying Córdoba and San Luis provinces (Pampean hills) (Figures 1 and 4). The continental climate generated a decrease in rainfall and relative humidity. The wind speed in the area of the mountains had an average of 11 km h^{-1}. Northeast wind direction was common throughout the year, whereas the east and south were more frequent in spring and summer. Another cluster, represented in Figure 4 as number 6, had

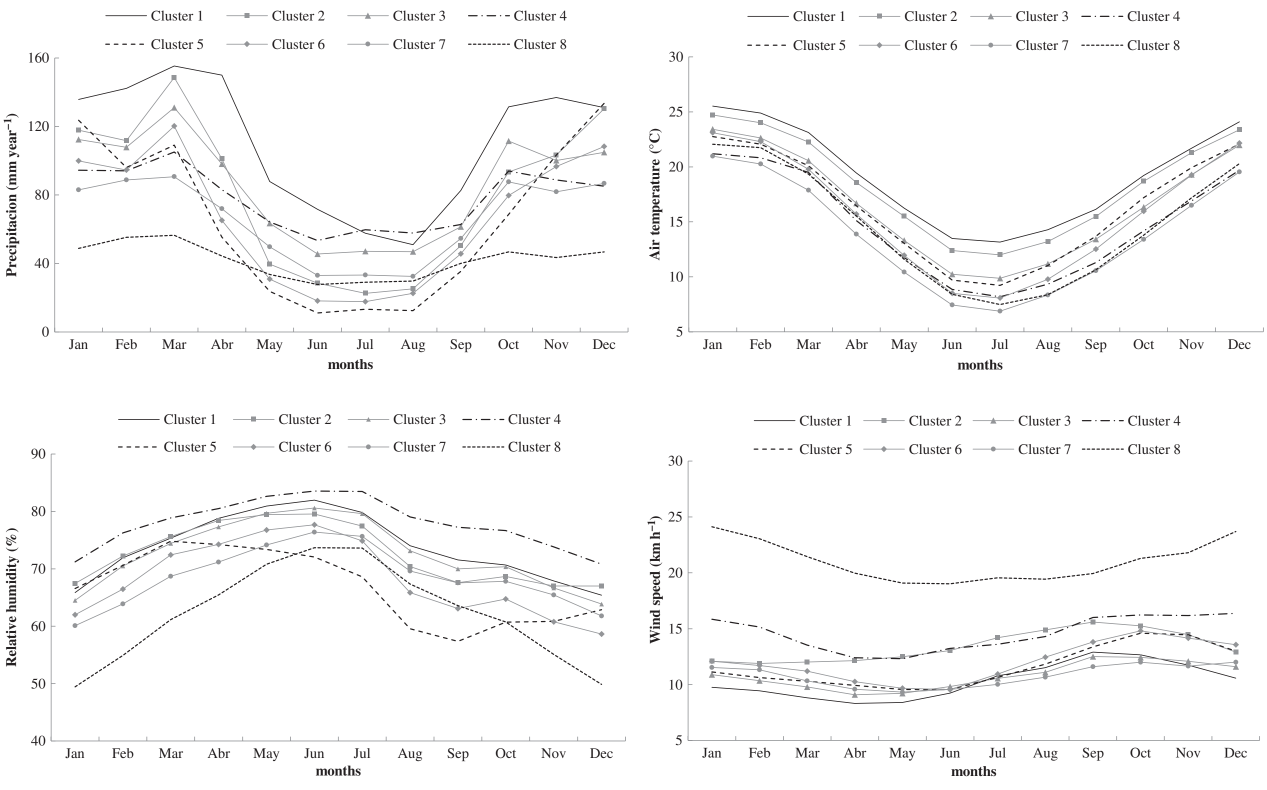

Figure 5. Monthly distribution of precipitation, air temperature, relative humidity and wind speed in each cluster (1960–2010).

similar volume of precipitation but with less altitude and humidity, showing the importance of these parameters in the definition of areas.

To the south of Buenos Aires province, cluster 7 contained the Tandilia and Ventania hill systems (mean altitude of 216 metres), where the temperature decreased 3 °C (Figures 1 and 4, Table 2). Finally, cluster 8, influenced by wind speed, was characterized by being colder and drier than the others clusters and for covering the southern of the Pampas with the lowest precipitation and temperatures. Although the air masses of the northwest dominated in the south entrance of cold winds from the Patagonian region were observed.

According to Barros *et al.* (2015), the most frequent wind directions over the east of Argentina between 35° and 39°S, namely over the Rio de la Plata and Buenos Aires province (Figure 1), rotated from the northeast to the east–northeast and to the east. A weakening of the westerlies and a shift of the maximum zonal wind axis from 46° to 48°S was observed to the south in Patagonia. These changes enhanced the advection of humid air from the Atlantic Ocean over most of the Pampas (Barros *et al.*, 2015). Considering the annual rainfall gradient, it was possible to detect some overlap in the distribution of the clusters. This analysis allowed to observe that most of the Pampas received between 750 and 1100 mm year^{-1} of precipitation. On the other hand, the wind was another factor in the expansion of certain climatic subregions, specially in the south and northeast of the Pampas. It was the case of clusters 3, 4 and 8.

The analysis for the monthly means of climatological variables allowed identifying the seasonality of each cluster (Figure 5). The air temperature showed the seasonality common to temperate zones (warm summers and cold winters). However, cluster 8, located at the southern tip of the study zone, did not present the lowest temperatures. The thermal minimum value was represented by cluster 7, which coincided with the second highest altitudes (Ventania and Tandilia hills). A marked seasonal rainfall was observed in all of the clusters with the highest rainfall peaks in summer and spring. In fact, in seven out of the eight clusters, the maximum of rainfall was observed in March (Figure 5) and the minimum in June–August (winter). Annual and seasonal rainfall amplitude decreased from northeast to the southwest. The minimum records were observed in clusters 5, 6 and 2 with 11, 18 and 23 mm, respectively. These records coincided with the proximity to the coast of Buenos Aires province, highlighting the moderating action of the nearby Atlantic Ocean (Figure 1). Conversely, the largest annual variation was 126 mm, observed in the north and represented by cluster 2 (Figure 5).

The maximum values of relative humidity were distributed between March and June. The clusters with highest humidity were found in the eastern half of the Pampas (1, 2, 3 and 4). Cluster 8 presented more moisture due to the greatest exposure to the sea, whereas the lowest annual average was represented by cluster 5 (Figure 5). Finally, in cluster 8 the minimum percentages of moisture occurred in summer and they had an opposite pattern than the wind speed, which was higher than in the

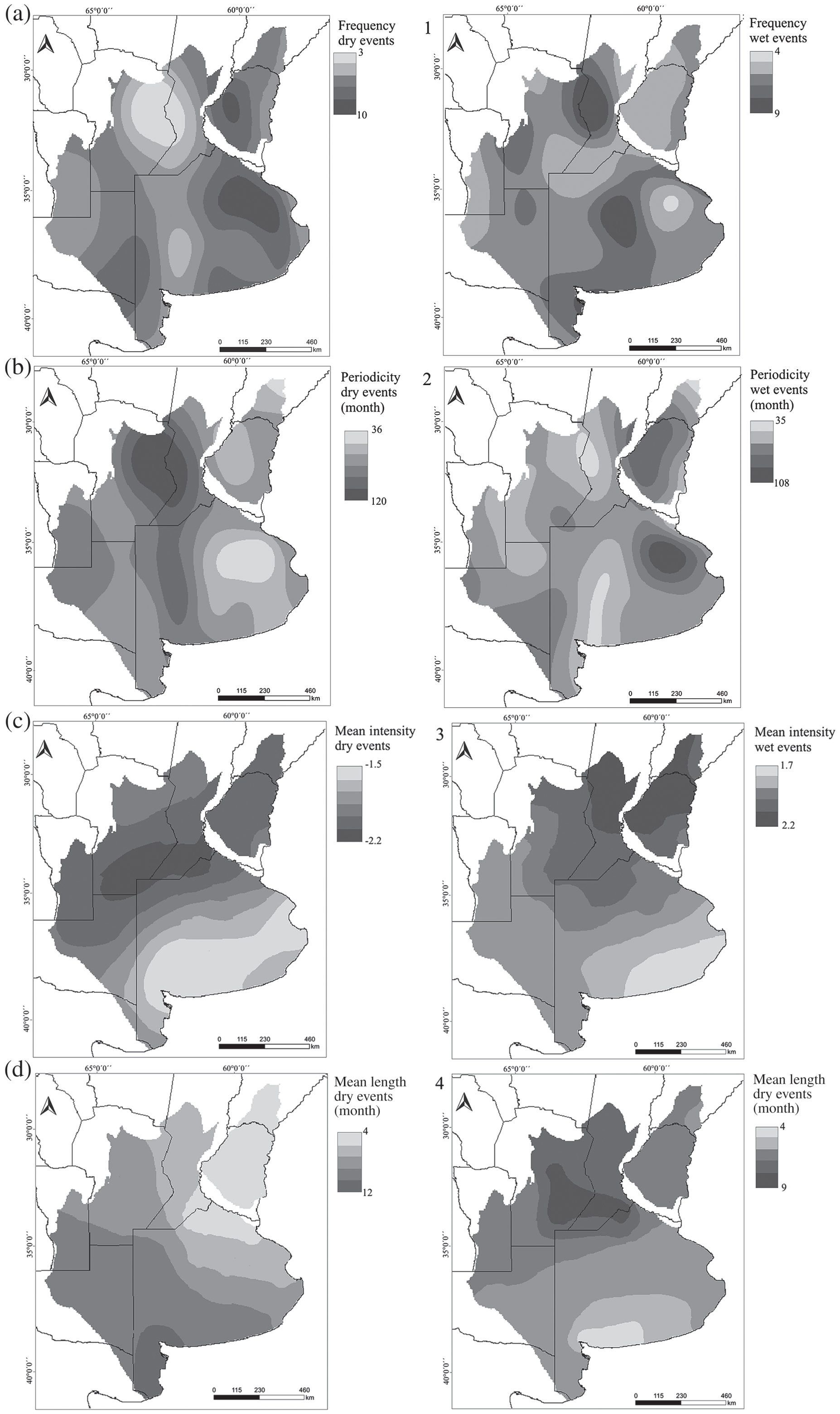

Figure 6. Spatial distribution of dry (a–d) and wet (1 to 4) events by frequency, periodicity, mean intensity and duration in the Pampas (period 1960–2010).

rest of the Pampas throughout the year, with an average of 21 km h^{-1}, whereas in the other clusters varied between 10 and 15 km h^{-1} (Figure 5). Throughout the Pampas, the maximum wind speed occurred in spring, with the exception of cluster 8 located in the south.

3.2. Wet and dry events (SPI analysis)

The regional characteristics of wet and dry events for the 1960–2010 period are presented in Figure 6. Dry events were more frequent in the north-central region, in the northeast of Buenos Aires and in the southeast of La

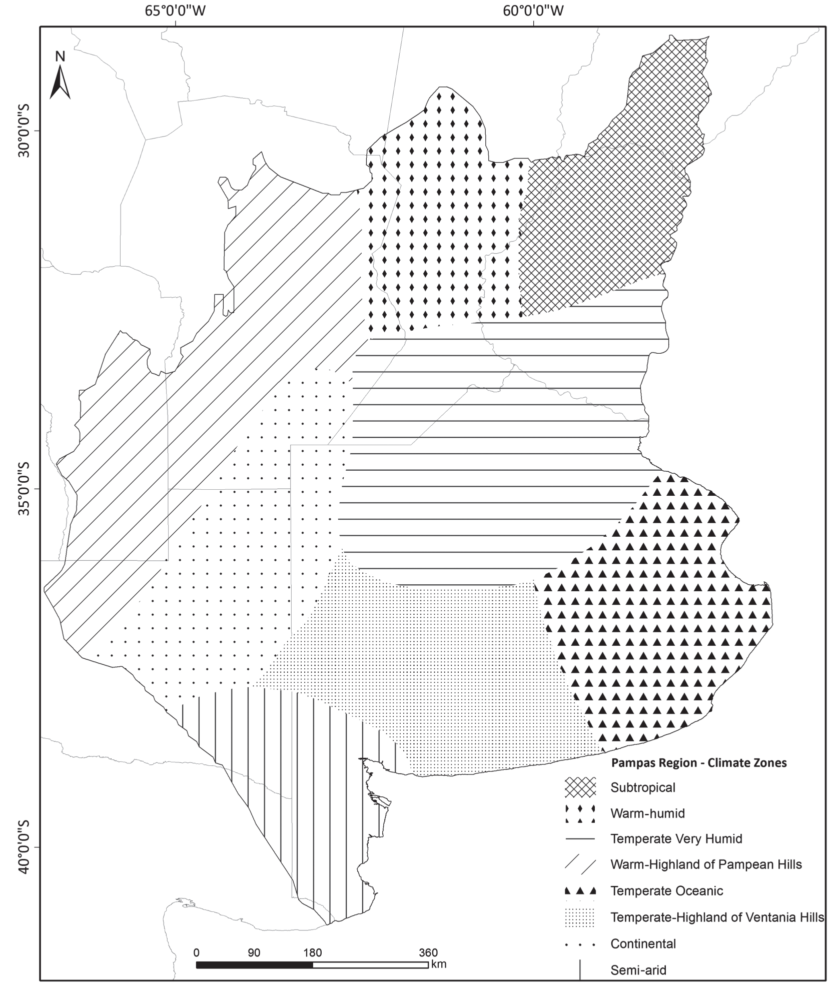

Figure 7. Regionalization of climate in Pampas (period 1960–2010). [Correction added on 8 May 2017, after first online publication: The semi-arid zone in Figure 7 was incorrect and it has been replaced in this current version.]

Pampa provinces. Frequency had a pattern inversely proportional to periodicity (Figures 6(a) and (b)). On the other hand, wet events were more frequent in the southwestern and northeastern regions of Buenos Aires province and the north-central area of the Pampas. Periodicity had not fit with frequency; its higher values were found in the northeast and were lower in the southwest of the Pampas (Figure 6, 1 and 2).

The intensity of dry events was higher to the north and decreased to the south. The intensity of wet ones presented a higher gradient in the northeast, and they decreased to the southwest. The mean length of dry events was higher to the southwest of the Pampas and decreased to the northeast (Figures 6(c) and (d)). As regards the wet events, the mean length was higher to the north and lower to the south of the Pampas (Figure 6, 3 and 4).

3.3. Characterization of regional climates in the Pampas

From the results of the cluster analysis and the evaluation of the variables, the following climatic areas were defined and assigned as: cluster 1: *subtropical*; cluster 2: *warm–humid*; cluster 3: *warm of the highland of Pampean hills*; cluster 4: *temperate and very humid*; cluster 5: *temperate-highland of Ventania hills*; cluster 6: *temperate oceanic*, cluster 7: *semi-arid* and cluster 8: *continental* (Figures 4 and 7). These subregions were named considering altitude and previous classifications (i.e. Kottek *et al.*, 2006).

Three areas with a *subtropical influence* were identified (clusters 1, 2 and 3), where annual precipitation decreased to the west whereas the average temperature was high. In these three subregions, the warm air masses enter permanently through the north, northeast and east. However, they can be interrupted by cold fronts of the southwest, mainly in winter.

- Subtropical (1): It was the warmest and rainiest region of the Pampas, with the lowest average wind speed. Dry events were rare with short duration and intermediate intensity. Wet events had low intensity but longer duration.
- Warm–humid (2): It had similar characteristics to *subtropical*, but with lower annual rainfall due to the continental effect. Seasonal thermal and rainfall patterns were more pronounced. Wet periods were more frequent and intense than dry ones. The wind presented its maximum speeds in spring and in the northern region.

- Warm of the highland of Pampean hills (3): It coincided with the highest point of the region. It had high average temperature, but rainfall decreased compared with the previous regions and concentrated in spring and summer. It was the area least affected by the dry events but, when they occurred, they had a high intensity and a mean duration of 8 months. The wet events were more frequent, intense and longer.

Then, the following areas with *temperate* climates were identified:

- Highly rainy (4): It was the second rainiest area in the region (above 1000 mm year^{-1}, similar to *subtropical*). This type of subregion was originated by the entry of moist masses from the South Atlantic Ocean. Dry events were very frequent but with low duration and intensity, whereas wet ones were less frequent but with an intermediate intensity and longer duration.
- Temperate-highland of Ventania hills (5): It represented the area of Ventania hills, the second highest altitude of the Pampas. It was similar to highland, *warm of Pampean hills*, but with lower temperature. In this area prevails the winds of the northwest, although it is crossed by the cold fronts of the southwest mainly in winter. Droughts were unusual, with low intensity and duration. It was frequently wet, with low intensity and short duration.
- Oceanic (6): It was the wettest area of the region because of its proximity to the sea. It was the second windiest area of the Pampas. Wet and dry events were usual, with low intensity and long duration. The abundant rains are associated with the movement and proximity to the stationary cyclones of the South Atlantic.
- Semi-arid: It represented the southern region, with the lowest altitude. It was the zone with lower rainfall and considerably more windy than the rest of the study area. There was a strong rainfall variability, affected by the alternation between wet and dry events. Both were frequent with long duration and low intensity.
- Continental: It showed intermediate conditions between *semi-arid* and subtropical. The wind, the altitude and the proximity to the sea had a scarce influence. Both dry and wet events occurred, although the area was more affected by dry events.

4. Conclusions

This study proposes an improvement of climate regionalization in the Pampas. Using cluster and SPI analyses, eight subregions of the Pampas general climate were identified considering the main climate elements such as rainfall, air temperature, humidity and wind speed as well as the altitude and the alternation between dry and wet events in the area. Thermal and precipitation gradients were clearly marked in the Pampas as well as the distribution of winds and humidity.

Although precipitation and air temperature are the basic parameters to describe the climate of the Pampas plain, and most of the published studies considered those parameters (Díaz and Mormeneo, 2002; Grimm, 2011), other climatological and topographic variables give more insight into climate differences. Our first statistical analysis was performed using only precipitation and temperature as in the previous studies, which allowed to determine the very well known climatic subregions in the Pampas. However, the added new variables were useful to describe the regional climate more accurately.

The results of the cluster method generated areas with different patterns and responses to different climates. Wet and dry events also have a great importance in the Pampas. In both cases, the intensity and the duration of the event had an inverse relationship, i.e. when the event was of short duration, it was more intense according to the range of the SPI. This coincides with the studies from Penalba and Rivera (2016) which started that, in recent years, there has been a tendency for droughts to be shorter. This also coincides with increased seasonality of precipitation. As described in Figure 6, in both types of events the same intensity decreased with the increasing latitude and the proximity to the sea. With respect to the duration, dry events showed a descendant gradient of northeast to southwest, whereas for wet ones it was from north–northwest to southeast.

The different tool analyses applied in this study allowed to obtain a clearer understanding and specify to the climate distribution in the Pampas. This knowledge is useful for regional planning, allowing to assess more precisely the climate effect on the activities taking place in the numerous subregions.

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