Meteorol Atmos Phys (2014) 123:143–154
DOI 10.1007/s00703-013-0300-6

ORIGINAL PAPER

Warm and cold dry months and associated circulation in the humid and semi-humid Argentine region

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Received: 5 April 2013 / Accepted: 11 November 2013 / Published online: 26 November 2013

Abstract This paper studies the climatic conditions of warm and cold dry months in the humid and semi-humid Argentine region and some aspects of the regional circulation related to these cases. The climatic analysis of warm (temperatures above percentile 80) and cold (temperatures below percentile 20) dry months is based on precipitation and temperature data registered at reference stations over a period of at least 70 years, while the associated circulation is derived from daily data of geopotential height at 500 hPa from NCEP-DOE Reanalysis 2 database. The reference station for the center of the country registered a greater number of warm dry months during both the warm season (October–March) and the cold season (April–September), whereas the reference stations in the north-east and center-east showed differences depending on the time of the year, with more cold dry months during the April–September season and more warm dry months in the October–March season. A classification of daily fields of geopotential height anomalies at 500 hPa was used to analyze the atmospheric circulation related to warm and cold dry months. The circulation patterns were obtained by applying principal component analysis and cluster analysis. Findings show that some mid-level circulation patterns occur with a significant different frequency during the warm dry months or the cold dry months studied. Finally, cases of spatially extended precipitation-deficit conditions (hereinafter generalized droughts) were studied, noting dominant patterns that are coherent with the previous results.

Responsible editor: C. Simmer.

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1 Introduction

The countless activities carried out by human beings take place within a natural environment that has typical characteristics depending on the place of residence. Many of these activities are defined by the climate of each region. Whenever extraordinary climate conditions occur, the consequences affect the economy and the well-being of human beings. This can be seen, for example, in the cases of rain deficits, which have historically brought about important losses in crop yields, among other adverse effects.

From a geographical point of view, the interest in droughts lies in the impact they may have, and areas of influence can be chosen according to physical (climate) and/or economic criteria (Minetti et al. 2007). Although rainfall is the main climatic element when evaluating droughts, temperature also plays a major role in the development of these unfavorable conditions, due to its influence on the evapotranspiration and, therefore, on water availability in the soil. Hence, it is key to study the cases in which conditions of rain deficits and extreme temperatures co-occur.

In Argentina, previous studies have shown a greater frequency of regional droughts than that of generalized ones (Barrucand et al. 2007), proving the need of a differentiated analysis by country zone. In line with this, Bettolli et al. (2010) conducted a regionalization of dry days in Argentina, finding six homogeneous country regions for the summer season. After analyzing the physical causes of drought conditions, it is possible to find spatial and seasonal differences that must also be taken into account (Minetti et al. 2010a).

The studies about droughts in South America and in the La Plata basin in particular show an overall decrease in the frequency and duration of dry events (Naumman et al. 2008; Llano and Penalba, 2011). However, since mid 2003 until 2009, it was possible to observe a change (increase) in this trend across all the Argentine regions. These droughts have caused significant losses in the production of cereal and derived products based on high technology and in the hydroelectric generation for its development (Minetti et al. 2010b).

According to different authors, remote forcings like ENSO have been identified as one of the agents responsible for most of the interannual variability of rainfall (e.g., Compagnucci and Vargas 1998; Grimm et al. 2000; Boulanger et al. 2005, Mo and Berbery 2011) and temperature (Barros et al. 2002; Rusticucci and Vargas 2002; Rusticucci et al. 2003) in different Argentine regions. However, the ENSO (or any of its phases) cannot be considered as the only forcing of extreme rain events. There is an example of this in the study on droughts in Humid Pampa (Barrucand et al. 2007), which shows that most of the months classified as dry occurred under neutral conditions. The results obtained from other studies show that patterns related to drought conditions are not necessarily related to the ENSO phases. An example of this kind of study can be found in Scian et al. (2006), who analyzed some characteristics of the large-scale circulation related to excesses and deficits of rainfall in the Humid Pampa under non-ENSO conditions.

From the viewpoint of synoptic climatology, the first studies to analyze rain deficit conditions focused mainly on case studies. This is exemplified by the drought that affected most of the Argentine territory in 1962, studied by Malaka and Nuñez (1980), or that which affected the center-east and north-east of Argentina in 1995 studied by Alessandro and Lichtenstein (1996) and Pezza and Ambrizzi (1999). This work aims to extend the climatic-synoptic analysis to cover all the dry cases that affected the humid and sub-humid Argentine region to find common characteristics over the past decades.

The objective of this work was to develop a climatology of warm and cold dry months in the humid and semi-humid Argentine region and to study some aspects of the regional circulation related to these cases with a synoptic climatology analysis. The methodology and the data used in this study are detailed in the following section. Sections 3 and 4 show a climatology of dry months in relation to their thermal condition and temporal variability. Section 5 shows the results of a synoptic climatology used to analyze the physical conditions related to the dry months and lastly, Sect. 6 analyzes the spatial simultaneity of warm or cold dry conditions and the associated circulation patterns. Section 7 summarizes the main results and conclusions of the work.

Table 1 Location of reference station and record data

Station	Latitude (°S)	Longitude (°W)	Height (m)	Period
OCBA	34°35′	58°29′	25	1861–2008
Corrientes	27°28′	58°49′	73	1931–2008[a]
Pilar	31°4′	63°53′	338	1925–2008

[a] January–October data are missing in 1961

2 Data and methodology

In this work, three Argentine regions studied in a previous work (Minetti et al. 2010b) were considered and one reference station was selected which has the longest available record of each region: Buenos Aires (OCBA), Corrientes and Pilar (Table 1). In order to explore the regional representativeness of each station, correlations between the annual precipitation of each selected station and the annual precipitation of each gridded point obtained from University of Delaware and CMAP datasets were performed. High correlations at the gridded point nearest to the station and low correlations far away from the station were expected. This was reflected in Fig. 1. It can be seen that the highest correlation values are near each station location, but the correlation coefficients decrease when the distance from this point increases and the values are not significant among the three stations. Correlation calculations among the three stations considering observed annual precipitation records confirmed this result. Taking into account these aspects, Corrientes was selected as a reference station of the north-eastern region, Pilar Cordoba representative of the central region and OCBA representative of the central-eastern region. The reference stations mentioned above have extensive records of temperatures and monthly rainfall, with more than 70 years of information available. For each of the series of monthly mean temperature and monthly rainfall, the percentiles 10, 20, 80 and 90 of temperature and rainfall were calculated to obtain typical thresholds with which to classify the months with extreme values of the variables. Due to trends seen in the series studied (Castañeda and Barros 1994; Rusticucci and Barrucand 2004), the values of the percentiles will change if a different period is taken to calculate them. This trend is more marked in the case of the OCBA station, which is also an urban station, affected by the urban heat island effect (Camilloni and Barros, 1997; Figuerola and Mazzeo

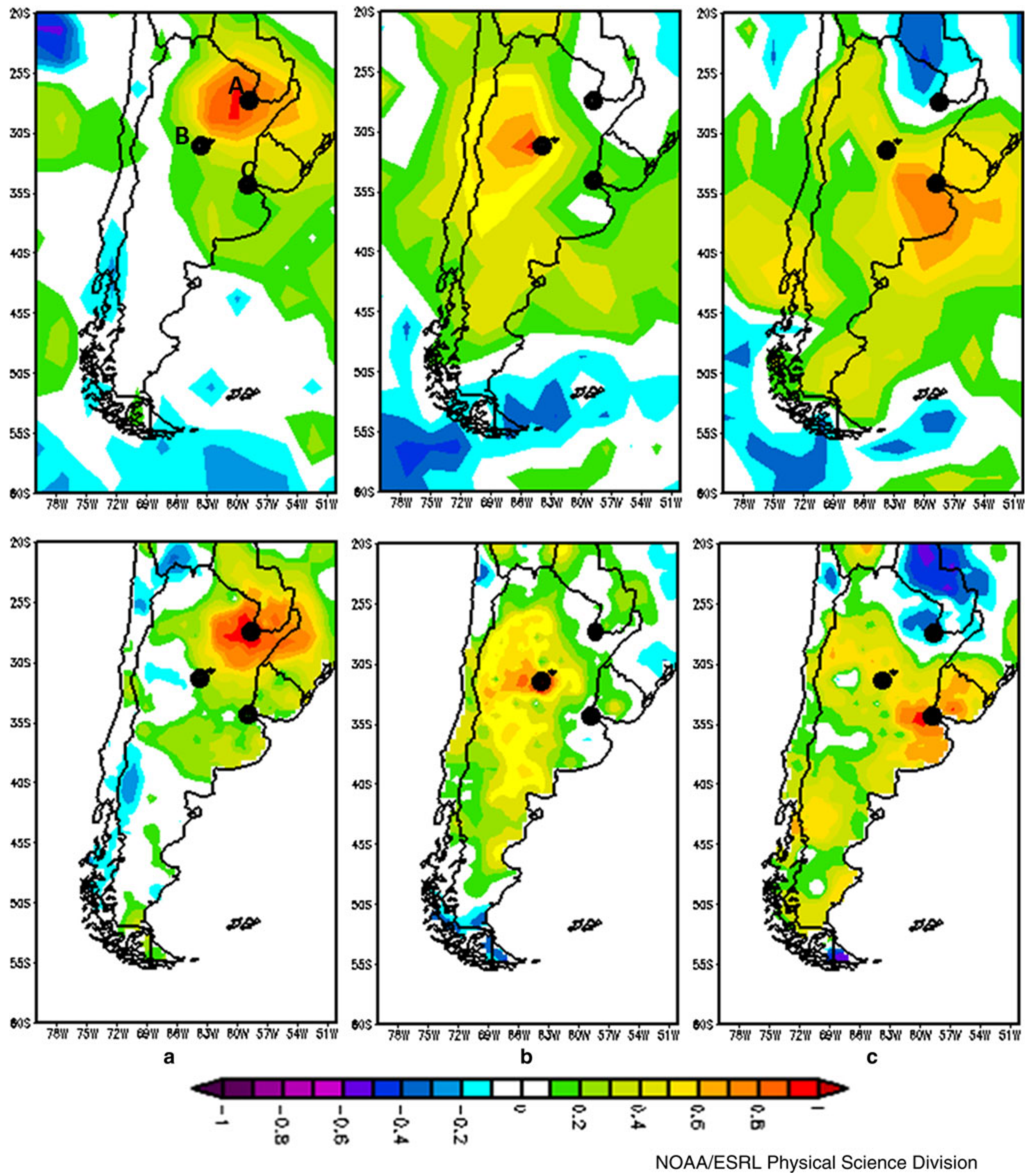


Fig. 1 Correlation between rainfall in the meteorological reference stations and rainfall from the CMAP (*upper panel*) and University of Delaware (*lower panel*) databases. The Corrientes (**a**), Pilar (**b**), OCBA (**c**)

1998; Camilloni and Barrucand 2012). This fostered a differentiated analysis, with different base periods. According to the year classified, a percentile calculated on a determined sub-period was used. These sub-periods were selected according to previous studies that showed changes in temperature and rainfall throughout the twentieth century (Penalba and Vargas 2004; Rusticucci and Penalba 2000). The sub-periods studied were 1861–1910; 1911–1945; 1946–1975; 1976–2008. Due to data availability, the first sub-period was only considered for OCBA, and the starting date of the second sub-period is set according to each station considered (Table 1).

Months with rainfall lower than percentiles 20 and 10, respectively, were classified as dry (D) and very dry (DD), while the temperature percentiles 10, 20, 80 and 90 were classified as very cold (CC), cold (C), warm (W) and very warm (WW) cases. In general, the two cold extremes (CC and C) and the two warm ones (WW and W) are considered as a unit and these cases will be referred to as cold (warm) dry months. The differentiation between DD and D, CC and C, WW and W, is only kept for case studies. Dry months without any extreme thermal condition associated with it were considered as "normal." Once the classification was obtained, the co-occurrence of rain deficit conditions and extreme temperatures in each month was analyzed.

The differences between percentages of warm and cold dry months were statistically analyzed with the Z-proportion test (Devore 2005).

In the second stage, the aim was to associate the co-occurrence events of rain deficit and extreme temperature conditions on a monthly basis with different circulation patterns. To do so, daily fields of geopotential heights at 500 hPa were used, obtained from the re-analyses II from the NCEP in the 1979–2008 period. The domain analyzed corresponds to 15°S–60°S and 30°W–90°W. The daily fields of geopotential height anomalies at 500 hPa were calculated and then synthesized using the principal component analysis technique, retaining the first five principal components that account for 82.2 % of the total variance of the whole data set. A cluster analysis on the sub-space defined by these five retained principal components was conducted using the k-means classification algorithm. The optimal number of clusters was set based on the pseudo-*F* statistic, determining 10 types of dominant circulation. In Lattin et al. (2003), more details of this methodology can be found. Once the 10 clusters were determined, each day of the 1979–2008 period was assigned to one of these patterns found. Thus, it was possible to determine those patterns that had a high occurrence in warm dry or cold dry months.

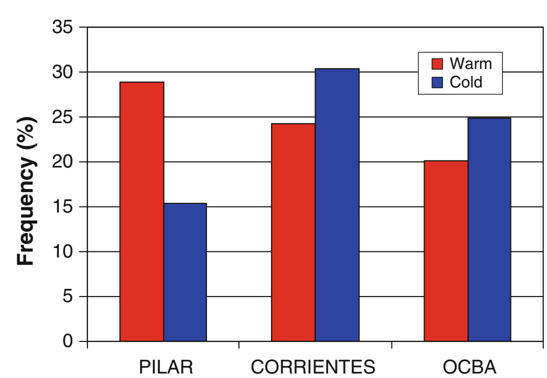
In order to complete this analysis, for each of the 10 clusters, the daily mean temperature values were calculated, along with the daily mean intensity of rainfall and the frequency of rainy days relative to the total number of days within each cluster, in the three meteorological reference stations. Furthermore, to describe the patterns, the 1,000 hPa geopotential height field related to each 500 hPa field was taken into account.

3 Climatology of warm and cold dry months

When analyzing the dry events of all the records of each station, it is possible to find that the most continental station (Pilar) has a greater co-occurrence with warm conditions, while the other two reference stations studied show the opposite, i.e., a greater co-occurrence of cold than warm dry cases (Fig. 2). These differences were statistically tested, and it was found out that they are significant at a 99 % confidence level in the case of Pilar station.

The analysis was repeated considering the warm season (October–March) and the cold season (April–September) separately to assess if these features could be considered homogeneous throughout the year or if they presented a seasonal variability. In both seasons, the Pilar station shows a predominance of warm dry events over cold dry ones, but this predominance is stronger in the warm season (Table 2). The Corrientes and OCBA stations, in turn, show different behaviors depending on the time of the year considered: from April to September, there are a higher number of cold dry months than warm dry ones, while in the warm period (October through March) the opposite occurs. These differences are statistically significant (at between 90 and 99 % confidence level depending on the station and semester analyzed). As it is shown in Fig. 2, when the two semesters are considered together in an annual analysis, there are no significant differences in Corrientes and OCBA stations.

Considering the above said, it can be concluded that in the three stations, warm dry months are much more frequent during the October–March semester, while during the cold season (April–September) there are different characteristics between the most continental station (Pilar) and the other two stations studied. While in the first one,



	PILAR	CORRIENTES	OCBA
Warm	28,8	24,2	20,2
Cold	15,3	30,4	24,9
Difference	**13,5 *****	-6,2	-4,7

Fig. 2 Percentage of dry months related to each type of thermal condition and difference of frequencies (warm–cold). Significant differences (at 99 %) are indicated in bold

Table 2 Percentage of dry months related to each type of thermal condition for the cold (April–September) and warm season (October–March)

Station	Temperature	Apr–Sept	Oct–Mar
Pilar	Warm	25.2	32.7
	Cold	20.0	10.3
	Difference (W − C)	5.2	**22.4*****
Corrientes	Warm	17.5	30.9
	Cold	40.2	20.6
	Difference (W − C)	−22.7***	**10.3***
OCBA	Warm	11.6	28.7
	Cold	32.0	17.7
	Difference (W − C)	−20.4***	**11****

The highest values are highlighted at each station and season. Differences between warm and cold dry cases are indicated. Significant differences at 90 % (*), 95 % (**) and 99 % (***) are displayed

there is still predominance, although to a lower extent, of warm dry months over the cold dry months, in the other two stations there is a clear predominance of cold dry cases.

4 Temporal variability of occurrence of dry events and extreme temperatures

After this initial analysis, the temporal variability of warm and cold dry months was studied, analyzing the different sub-periods separately. Due to the different length of the series, only the 1946–1975 and 1976–2008 sub-periods show a total coincidence in the three reference stations. The previous sub-periods are initiated (and indicated) by the first year of each series. This fact presents a limitation in the analysis. Nevertheless, each station can be analyzed separately to analyze the stability of the results along the total period available for each station. The results of this analysis are presented in Fig. 3.

Pilar station shows a stationary behavior, keeping more warm dry cases than cold dry cases throughout the different periods studied. In the case of Corrientes station, it is possible to see that the higher number of cold dry versus warm dry cases observed annually for the total period is mainly due to the conditions recorded after 1976. In the case of Buenos Aires (OCBA), the proportion of warm and cold dry cases is similar, except for the 1911–1945 sub-period, when there is a greater proportion of cold cases.

The analysis was repeated, considering the two semesters separately (results not shown). Although there is some agreement between these results and the total period results, there is a significant change in the last two sub-periods considered, coinciding with the climatic jump of

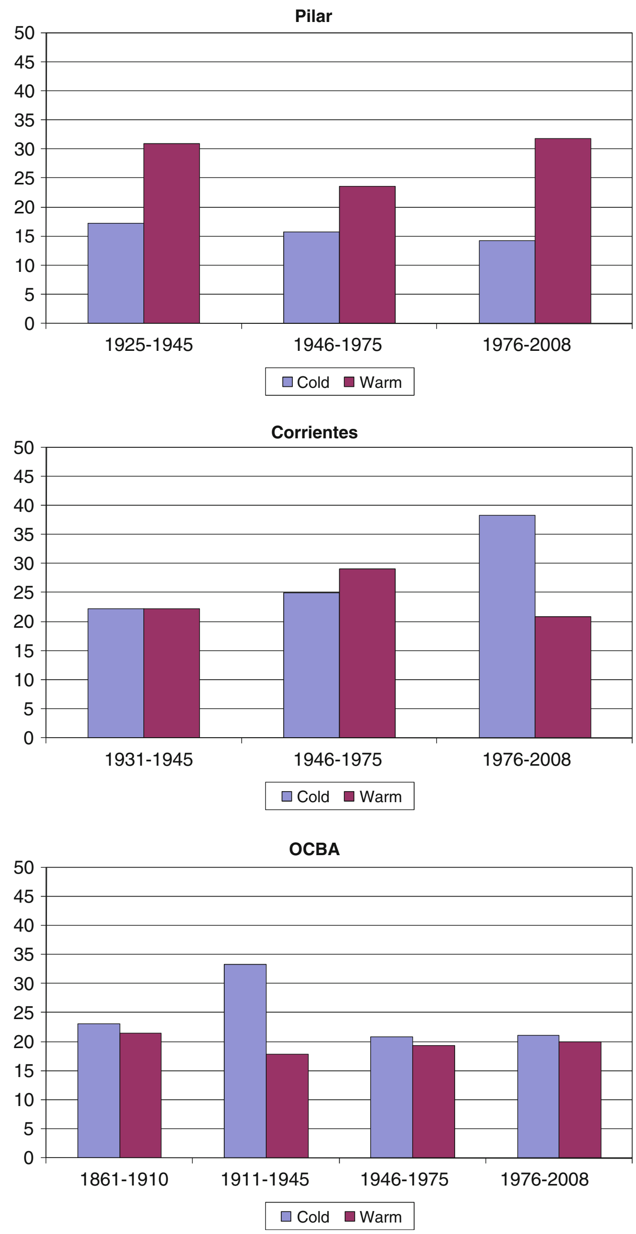


Fig. 3 Percentage of warm and cold dry months for each sub-period analyzed

1976 studied by several authors (Huang et al. 2005; Rusticucci and Tencer 2008, among others). The major changes can be seen during the cold period in Pilar station and in the warm period in OCBA station. The cold (April–September) season of the 1946–1975 period was the only one in which there was a higher number of cold dry cases than warm dry ones in Pilar station; it is possible to observe an inverse proportional relationship (higher number of warm than of cold dry cases) in all the other sub-periods and seasons. In the case of OCBA, although annually it is possible to observe a similar proportion of warm and cold dry cases, it was found out that during the warm season

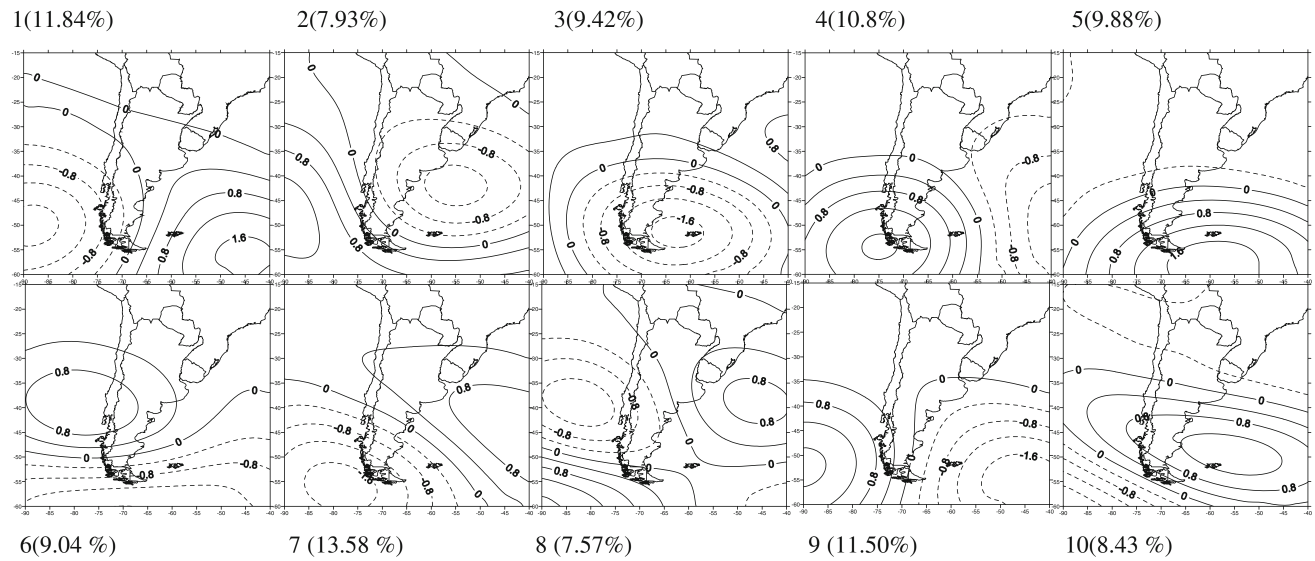


Fig. 4 Daily patterns of geopotential height anomalies at 500 hPa obtained from a principal component analysis and a method of cluster classification. The filled-in lines (*dotted*) indicate positive (*negative*) anomalies. The *parentheses* indicate the frequency of each pattern in the total of months of the 1979–2008 period

Table 3 Composites of daily mean temperature, daily rainfall intensity and frequency of rainy days (relative to the total number of days within each cluster) for each cluster and meteorological station

Group	OCBA			Corrientes			Pilar		
	Tm	Intensity (mm/day)	Frequency (%)	Tm	Intensity (mm/day)	Frequency (%)	Tm	Intensity (mm/day)	Frequency (%)
1	19.2	12	26.2	22.3	15	22.2	18.8	10.8	22.2
2	**15.6**	6.9	24.4	**19.5**	13.5	32.7	**15.2**	7.3	18.8
3	*19.3*	12.9	34.4	*23.3*	19.9	37.5	*19*	9.5	22.3
4	**16**	11.7	22.1	**19.9**	12.6	28.6	**15.8**	8.2	27.3
5	16.9	11.7	31.8	20.4	13.1	28.9	16.3	9.7	27.5
6	18.5	12.8	14.9	20.7	12.5	20.9	18	10	15.6
7	*20*	13.2	28.6	*22.7*	15.5	24.1	*19.4*	13	18.4
8	*19.5*	15.5	47.4	*24*	16.2	26.5	*19.2*	10.2	29.6
9	17.9	10.3	23.7	21.9	15.9	34.8	17.7	9.1	26.8
10	17.9	13.4	22.2	20.3	10.7	25.4	17.2	11.8	20.6
Mean	18.1	12.3	27.2	21.5	14.8	28	17.7	10	22.8

Values in bold and italics shows the cases of high mean temperature, whereas other values show low mean temperature

(October–March) of the 1946–1975 period, the cold dry cases did not occur frequently (8.3 % of dry cases).

5 Dry months and atmospheric circulation

The following step was to study the relationship between warm and cold dry months and the occurrence of geopotential height fields at 500 hPa previously found by a cluster method, as detailed in Sect. 2. Due to the availability of information from the database used in this paper, it was possible to analyze the last 30 years of the total period previously studied in the analysis on dry months (1979–2008 period). These 30 years are analyzed with daily temperature and rainfall data from the reference stations, and with geopotential height fields at 500 hPa, as indicated in Sect. 2. As previously explained, through the synthesis method, it was possible to get a set of 10 types of structures that represent the variable. These structures are presented in Fig. 4. For each of the 10 clusters, the mean temperature values were calculated, along with the mean daily intensity of rainfall and the frequency of rainy days relative to the total days of each cluster, in the three meteorological stations used as references (Table 3). These results account for the total set of days from the 1979–2008 period.

When considering the months defined as "dry", the frequency of days related to each field presented in Fig. 4 was calculated. The aim was to evaluate if it is possible to associate any field in particular with the "warm" or "cold" dry conditions. The analysis was conducted in the three stations studied, giving significant results.

Each pattern presented in Fig. 4 has a climatological occurrence frequency, also indicated in the figure. When analyzing the frequency of these patterns for the dry months, it is important to refer to these climatological values. That is why a Di index was calculated to represent the difference between the occurrence of each pattern under a certain condition (cold dry or warm dry month) and the climatological occurrence of the pattern, relativized to the climatology as per:

$$Di_{w,c} = \left(Fdi_{w,c} - Fci\right)/Fci \quad i = 1, 10$$

where Fdi is the frequency in which the pattern i occurs in the warm (w) or cold (c) dry months and Fci is the frequency of climatological occurrence of pattern i.

High (low) values of Di index means that the pattern was present for more (fewer) number of days during the month with respect to the expected climatological frequency.

Figure 5 shows the indices calculated considering all the warm and cold dry months of the period studied. It is interesting to observe those cases in which the occurrence deviates more than climatologically expected (either by excess or by default), and the index with opposite sign between the warm and cold dry cases. By looking at Fig. 5, it is possible to see that, in the warm dry months, there has been a high frequency of occurrence of geopotential height anomalies at 500 hPa with type 6 structure, particularly in Pilar and OCBA stations, while cluster 7 shows higher frequencies than normal in the three stations. Cluster 6 shows a center of positive anomalies over the Pacific Ocean and south-west of South America (with center at 40S–80W), which causes an intensification of westerlies to the south of 45S (Fig. 4). This center of positive anomalies is related to a ridge that favors the subsidence downstream and the action of a surface anticyclone, generating stable conditions. When analyzing the relationship with the surface conditions in the three reference stations, it is possible to see that this pattern gives rise to days with temperature within the normal values and very low frequencies of rainy days with intensity within the normal values (Table 3). Cluster 7 is characterized by a center of negative anomalies positioned towards the south-western extreme of the continent over the Pacific Ocean and a center of positive anomalies over the Atlantic Ocean that extends towards the center of the continent. This location of anomalies induces an anomalous flow from the north-west over the region and is related to an intensification of the semi-permanent anticyclone of the South Atlantic and a front type disturbance in the Patagonic region. This type of systems favors the flow with a north component that causes the high temperatures mainly in Pilar and OCBA (Table 3). Unlike cluster 6, its influence on rainfall (intensity and frequency) does not show a homogeneous pattern in the three reference stations. From all the above mentioned, it is possible to observe that the first structure mentioned is more related to the dry condition, while the other is more strongly related to the warm condition. Pattern 8 has a structure of anomalies that responds to shorter wavelengths and which can be related to the disturbances that cause the lifting mechanisms needed for rainfall. This is connected to a trough on the Pacific Ocean with a cold front at surface over the continent responsible for the higher-than-normal values in the rainfall frequency in Pilar and OCBA, generating the highest values of rainfall intensity in the latter.

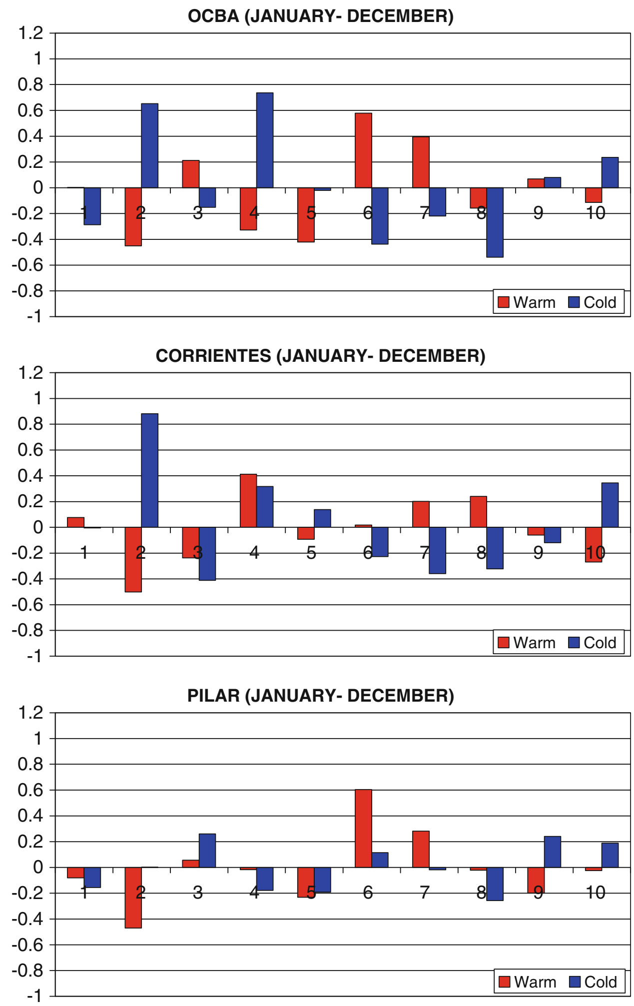


Fig. 5 Differences between the frequency of each pattern in warm and cold dry months and the climatological frequency of each pattern, considering all the months of the year. Values relativized to the climatological frequency of each pattern (Di index)

This pattern favors warm conditions with rainfall from normal to higher-than-normal, so its presence in the cold dry months is inhibited.

Another important aspect that should be highlighted is that during the warm dry months, the type 2 structure is weakened in the three reference stations. On the contrary, it has a normal frequency (Pilar) and high frequency of occurrence (OCBA and Corrientes) in the cold dry months.

The participation of cluster 2 in the cold dry cases is shown in Table 3. This cluster is related to the lowest daily mean temperature values, and to lower-than-normal rainfall intensities. These anomalies in the surface variables are due to negative geopotential height anomalies at 500 hPa centered on the Atlantic Ocean (42S–55W) and positive anomalies on the Pacific Ocean (Fig. 4). This pattern is related to the entrance of a postfrontal surface anticyclone (not shown) that affects the whole southern region of South America, generating stable conditions and causing cold air advection.

Cluster 4 also has a major participation in the cold dry cases although only for OCBA and Corrientes stations. Even if, in the particular case of Corrientes, this pattern has a similar frequency as in the warm dry cases, climatologically pattern 4 is related to cold conditions (Table 3). Cluster 4 is represented by a large center of positive geopotential height anomalies centered on the southern extreme of the continent (55S–70W). This structure of anomalies represents a ridge, whose axis extends towards the Pacific Ocean and is related to a surface anticyclone with a center on the province of Buenos Aires, which dominates the low-level circulation favoring the anomalous flow from the south-east in the region studied (not shown). The circulation induced by this pattern favors days with temperatures and rainfall intensities lower than normal in OCBA and Corrientes (Table 3).

The last pattern that must be paid attention to is that corresponding to cluster 10. This pattern shows a frequency from normal to higher-than-normal in the cold dry cases, which goes from normal to lower-than-normal in the warm dry cases in the three reference stations. Cluster 10 has a center of positive anomalies with a NW–SE axis extending from the Pacific Ocean towards the Atlantic Ocean (Fig. 4). This pattern is related to the action of a ridge centered on the same direction and with a surface anticyclone centered towards the south-east of the province of Buenos Aires. The analysis of the related surface conditions shows a non-homogeneous pattern, generating lower-than-normal temperatures in the three reference stations, and less frequent rainfall.

The analysis was repeated considering the cold (April–September) and the warm (October–March) seasons separately, taking into account the climatological occurrence of each pattern for each semester separately. Results are shown in Fig. 6, where it can be observed that the patterns 6 and 7, typical of warm dry cases, are more often seen during the cold season, while cluster 2 decreases in both semesters and in all stations. The contribution of cluster 2 in cold dry cases is important in both semesters for the OCBA and Corrientes stations, while cluster 10, typical of cold dry cases, has a different contribution depending on the semester analyzed. It shows greater frequency in the cold dry months in OCBA in the Apr–Sept semester, while in Corrientes there is a higher occurrence in the cold dry months of the Oct–March semester.

6 Analysis of spatial simultaneity of warm or cold dry conditions: predominant patterns

The spatial homogeneity of rainfall differs from that of temperature due to the physical characteristics of each variable: discrete and more localized in the first case, and continuous in the second case. This becomes evident in the correlation between the variables of the three stations considered, with low values in the case of rainfall and significant values in the case of temperature (results not shown). When analyzing both variables by season of the year, the cold season shows the highest correlation values, with a greater spatial homogeneity at this time of the year.

The months classified as “dry” in each station do not necessarily coincide. Although there are several months in which the three stations have recorded low rainfall levels, in other months the records are clearly different: deficit in one or two reference stations and excess in the rest, although these situations have had a low frequency (3 % of the total of months analyzed).

The cases of greatest interest in this study are related to the spatially most extended extreme conditions, which we will call “generalized droughts.” Warm and cold dry months which have occurred simultaneously in the three stations were analyzed. In the 1979–2008 period, two cases of warm droughts (January 1989 and March 1991) were recorded along with one case of cold drought (May 1988). These cases were particular because they were classified as “very dry and very warm (DDWW)” and “very dry and very cold (DDCC)”, respectively, in the three reference stations simultaneously. This is in line with studies that show the correlation between drought intensity and spatial extension (Minetti et al. 2010b). Other months with generalized droughts had normal thermal or mixed (normal and cold or normal and warm depending on the meteorological station) condition, as is shown in Table 4.

As in the case of the analysis in Sect. 5, an index was made which represented the deviations from the frequency of each circulation pattern under a certain condition (in this case, generalized droughts with different thermal

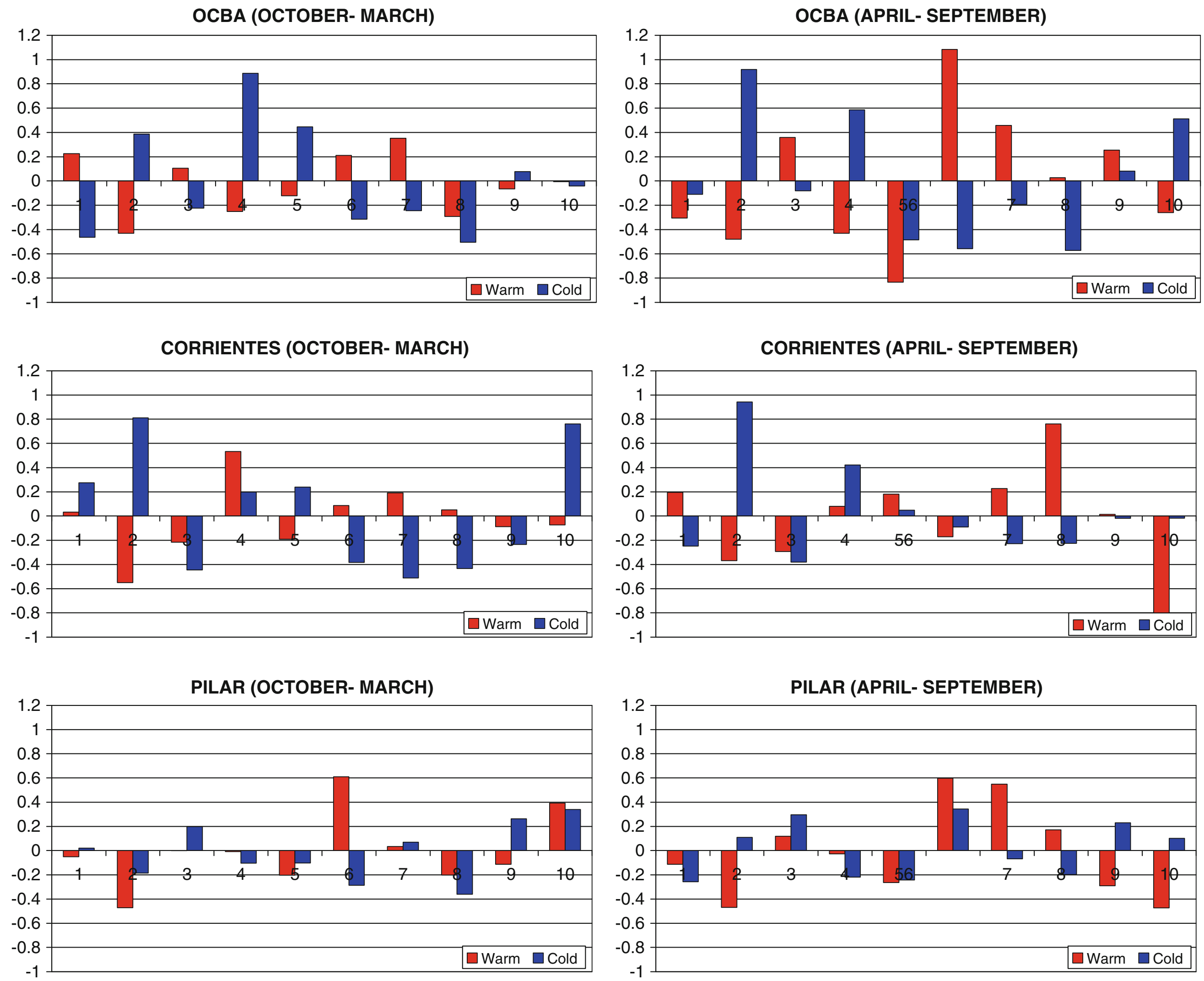


Fig. 6 Same as Fig. 5 but results are shown by semester

Table 4 Generalized droughts and associated thermal conditions

Thermal condition of generalized drought	Months		
Warm	Mar 1991–Jan 1989		
Normal–warm	Apr 2008		
Normal	Aug 2006		
Normal–cold	May-79	Jan-82	Jul-96
	Feb-04	Dec-2005	Nov-07
Cold	May-88		

conditions) and the climatological frequency of each pattern, relativized to the latter.

Results presented in Fig. 7 correspond to the three extreme cases: generalized droughts with warm conditions (January 1989 and March 1991) and generalized drought with cold conditions (May 1988). It shows the predominance of cluster 2 for the cold case, which coincides with the findings from the analysis of all the cold dry cases of the stations studied. In the case of the generalized

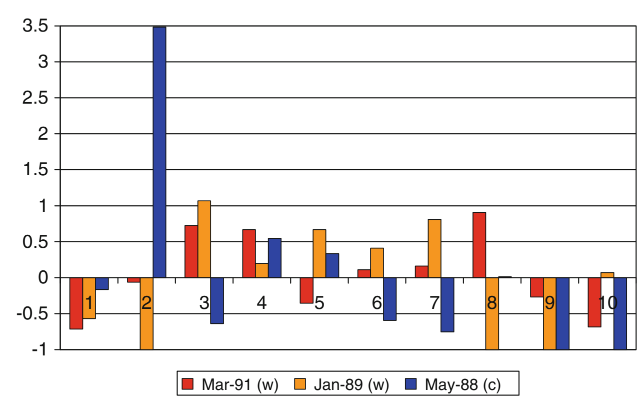


Fig. 7 Same as Fig. 5, but for months of warm (w) and cold (c) generalized droughts

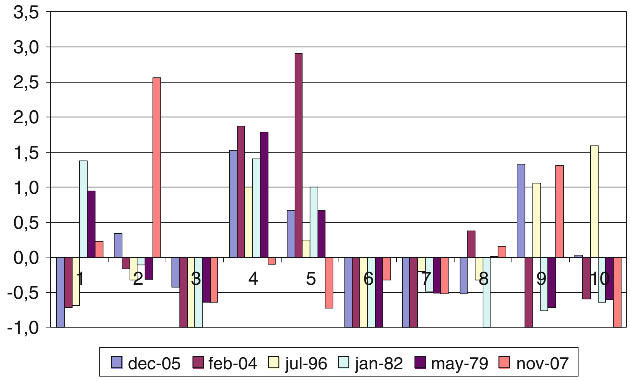


Fig. 8 Same as Fig. 5 but for months of normal to cold generalized droughts

droughts with warm conditions, although it is possible to see a predominance of structures 6 and 7 (and a decrease of frequencies in cluster 2) as was observed in the analysis of Sect. 5, cluster 3 has a higher frequency than the climatological one in the two warm extreme cases studied, while its participation in the cold extreme case is weakened. Cluster 3 presents a center of negative anomalies located on the south-eastern border of the continent and positive anomalies in the subtropical latitudes of both oceans. This pattern favors the intensified flow from the west in middle latitudes and from the north-west in subtropical latitudes of the south of South America. The latter induces an anomalous advection with a north component that is responsible for the high temperatures associated with this pattern (Table 3). As to its relationship with rainfall in the three reference stations, it is observed that this cluster favors higher-than-normal values of rainfall intensity and frequency in Corrientes, while in Pilar and OCBA both properties keep close to the normal values. This pattern might be mainly favoring the extreme temperature condition, while the rain deficit condition in January 1989 and March 1991 must be explained by means of other factors.

Figure 8 shows the results for the cases of generalized droughts with normal to cold conditions, the most frequent condition. It shows the scarce or null contribution of clusters 3, 6 and 7, typical of the cases with warm conditions, in line with previous results. Cluster 2, typical of cold conditions, had an outstanding participation only in November 2007; it was the only case of this subsample with cold conditions in 2 of the 3 stations studied. The rest of the months had a high frequency of occurrence of 4 and 5 type structures.

Cluster 5 shows a center of positive geopotential height anomalies towards the south-eastern extreme of the domain studied. This center is related to a surface ridge extended on the center-eastern region of the country inducing an east-southeastern flow that mainly favors temperatures lower than normal in the three reference stations (Table 3).

The case of generalized drought with normal to warm thermal condition (April 2008) coincides with the cases of warm droughts regarding the participation of cluster 3, while the case of drought with normal thermal condition shows no significant results (results not shown).

Table 5 presents a summary of results, showing the importance of each pattern in the different dry cases studied. As previously specified, each cluster has a climatological frequency of occurrence. If the frequency was lower than the first quartile, the occurrence of the pattern was considered to be low. On the contrary, if the frequency was higher than the third quartile, the frequency was considered to be high.

It can be observed that the droughts with normal to cold thermal characteristics typically have a high frequency of patterns 4 and 2, and a low frequency of patterns 6 and 7. It must be pointed out that cluster 2 is one of the least probable patterns with a 7.9 % climatological occurrence (Table 4). However, this cluster shows a clear contribution in the cases of cold droughts, both generalized and non-generalized.

In the case of droughts with normal to warm thermal characteristics, only cluster 3 shows a greater frequency in all cases under that thermal condition; it also has a low contribution in the months with cold dry conditions. As previously exposed, this pattern favors high temperatures in the region.

Table 5 Summary of the frequency of the different patterns (clusters) in normal to cold or normal to warm generalized droughts

cluster	Normal/Cold							cluster	Normal/Warm		
	may-88	nov-07	may-79	jan-82	jul-96	feb-04	dec-05		apr-08	mar-91	jan-89
1				**H**	L	L	L	1	L	L	
2	**H**	**H**	**H**					2	H		L
3	L	L	L	L	L	L		3	H	H	H
4			**H**	**H**	**H**	**H**	**H**	4	L	H	
5		L	L	H		H		5	L		
6				L	L	L	L	6			
7	L	L	L			L	L	7	L		H
8			L	L				8	L	H	L
9	L	H	**H**	L	**H**	L	**H**	9	H		L
10	L	L		L	**H**	L		10	H	L	

H and L indicate high and low frequency of occurrence, respectively. Clusters with normal or high (low) frequency in all the generalized droughts have a dark (light) shade

7 Summary and conclusions

In the first stage, this work presents a climatology of cold and warm dry months for the humid and semi-humid zone of Argentina. For that purpose, temperature and rainfall data from three reference stations were used, encompassing more than 70 years of recorded data. These stations are Buenos Aires (reference for the center-eastern zone), Pilar (reference for the central zone) and Corrientes (reference for the north-eastern region). Months with rainfall lower than the 20 percentile were considered as dry. An equivalent criterion was used to classify the thermal condition of each month, taking the percentiles 20 and 80 of the monthly mean temperature to determine the cold or warm months. In the three reference stations, it was possible to find out a greater frequency of warm dry months in the warm semester (October through March), but differences were found when analyzing the cold semester (April through September): while the north-eastern and center-eastern stations recorded a greater number of cold dry months, the central zone station kept a higher frequency of warm dry cases than cold ones. This characteristic remained stable during the different sub-periods analyzed. As to the north-eastern station, it is possible to highlight an increase in the frequency of cold dry months after 1976, while in the case of the central-eastern station, there is a similar number of annual warm and cold dry cases over three of the four sub-periods analyzed.

In order to study some atmospheric circulation patterns which could distinguish the warm and cold dry months, a classification of daily patterns of geopotential height anomalies at 500 hPa was used, obtained by means of principal component analysis and clusters analysis. Due to the availability of information, the analysis was conducted for the last 30 years of the series analyzed (1979–2008 period). The surface temperature conditions and the rainfall related to these clusters were also studied. It was observed that some of these patterns had a high frequency in warm dry months, while others occurred in cold dry cases.

Warm dry months have shown a high frequency of occurrence of patterns 6 and 7. The physical analysis of these patterns showed that the first case was more related to the rain deficit, since it favors stability conditions, while the other was more connected to the high temperatures, since it favors the flow from the north. Pattern 3 is also related to warm dry cases, and its structure favors an intensified flow from the west in middle latitudes and from the north-east in subtropical latitudes of the south of South America, inducing an anomalous advection with a north component that is responsible for the high temperatures related to this pattern. Climatologically, this pattern is not associated with low rainfall levels, so its participation in the warm droughts must take place along with other physical conditions favoring the rain deficit. Its frequency was outstanding in the cases of generalized droughts (rain deficit in the three reference stations) with a warm condition and a very low one in the cases of cold generalized droughts. Finally, there is a low frequency of the cluster 2 in warm dry months. This is in line with the findings from the analysis of cold dry cases, which show a high frequency of this pattern, which has negative anomalies on the Atlantic Ocean, extending towards the continent on the center and north of Argentina. As previously mentioned, this pattern is related to the entrance of a postfrontal surface anticyclone that affects the whole southern region of South America, generating stable conditions and inducing cold air advection. This is the clearest and most significant pattern related to cold droughts, with a high frequency of occurrence during the only case with generalized cold drought (simultaneity of cold and dry condition in the three reference stations). Secondly, for these cases pattern 4 stands out, which is represented by a large center of positive geopotential height anomalies located on the southern extreme of the continent (55S–70W). The circulation related to this pattern favors days with temperatures and rainfall intensity lower than normal in center-eastern and north-eastern stations.

All these results contribute to developing a synoptic climatology of cold and warm dry months and improving the entry database at risk and decision models for drought cases. On the other hand, through the results obtained it is possible to further study the hydric availability in differentiated cases of droughts in the humid and semi-humid zone of Argentina, which is an area of major international participation in the cereal and oilseed trade.

Acknowledgments UDel_Precip and CMAP data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/data/correlation/. Support for carrying out this work was provided by the following grants: UBA 20020100200165-20020100100789-20020100100628; CONICET PIP 112-200801-00762/0227 and PICT 2008-1820.

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