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COLD AND WARM DRY MONTHS AND THE ASSOCIATED CIRCULATION IN THE HUMID AND SEMI-HUMID ARGENTINE REGION

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COLD AND WARM DRY MONTHS AND THE ASSOCIATED CIRCULATION IN THE HUMID AND SEMI-HUMID ARGENTINE REGION

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Abstract

This paper studies the climatic conditions of the dry months with extreme temperature (warm or cold) in the humid and semi-humid Argentine region and some aspects of the regional circulation related to these cases. The climatic analysis of the dry months with extreme temperature conditions (temperatures below the 20 percentile and above the 80 percentile of each month) is based on precipitation and temperature data registered at reference stations over a period of at least 70 years while the characteristics of the associated circulation are derived from daily data of geopotential height at 500 hPa corresponding to the NCEP-DOE Reanalysis 2 database. The reference station for the center of the country registered a greater number of dry months with warm temperature conditions during both the warm season (October to March) and the cold season (April to September), whereas the reference stations in the northeast and center-east showed differences according to the time of 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 patterns of the 500 hPa geopotential height anomalies was used to analyze the associated circulation fields. The circulation patterns were obtained by applying principal components analysis and cluster analysis. Findings show that some of the mid-level circulation patterns occur with a significant different frequency during the dry warm months or the dry cold 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.

Keywords: deficit – precipitation –extreme temperatures – circulation patterns

1. Introduction:

The countless activities carried out by human beings take place within a natural environment with its own characteristics depending on the place of residence. The climate of each region is a major feature that defines many of these activities. 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 the yields of crops, among other adverse effects.

From the geographical point of view, droughts are interesting because of the impact they may have, and the 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 in the evaluation of droughts, temperature also plays a major role in the development of these unfavorable conditions, due to its influence on the evapotranspiration and, therefore, on the availability of water 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 of generalized ones (Barrucand et. al. 2007), proving the need of a differentiated analysis by zone of the country. In line with this, Bettolli et. al. (2010) conducted a regionalization of dry days in Argentina, finding 6 homogeneous regions in the country 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 (Naumann 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 responsible agents of 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 (Bidegain and Podesta 2000; 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 the only forcing of the extreme rain events. An example of this can be seen in the study about droughts in Humid Pampa (Barrucand et. al. 2007), showing that most of the months classified as dry occurred under neutral conditions. These aspects foster the study of patterns related to drought conditions that are not necessarily related to the ENSO phases. An example of this kind of study can be found in Scian et. al. (2006), who analyze some characteristics of the large scale circulation related to excesses and deficit of rainfall in the Humid Pampa under non ENSO conditions.

From the viewpoint of synoptic climatology, the first studies to analyze rain deficit conditions were mainly focused on case studies. 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) are some examples of this. This work aims to extend the climatic-synoptic analysis to cover all the dry cases that affected the humid and sub-humid Argentine region in order to find common characteristics in the past decades.

The objective of this work is to develop a climatology of the months with minimum rainfall and specific thermal conditions (cold and warm) 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. In sections 3 and 4 the reader can find a climatology of dry months in relation to their thermal condition and temporal variability. The fifth section shows the results of a synoptic climatology used to analyze the physical conditions related to the dry months and lastly, section 6 analyzes the spatial simultaneity of cold or warm dry conditions and the associated circulation patterns. Section 7 summarizes the main results and conclusions of the work

2. Data and methodology

In order to analyze situations with rain deficit conditions and with extreme temperatures, 3 meteorological stations were taken as references of the humid and semi-humid Argentine zone: Corrientes -representative of the north-eastern region-, Pilar (Córdoba) -representative of the central region- and Buenos Aires (OCBA), representative of the central-eastern region of the country. These meteorological stations were considered to be the most representative based on the calculations of correlations made using different databases (University of Delaware, CMAP, figure 1) and this is consistent with a study on regional droughts in Argentina and Chile (Minetti et. al. 2010b).

The reference stations mentioned have extensive records of temperatures and monthly rainfall, with more of 70 years of information available; this characteristic was taken into account when choosing the representative stations of the different regions analyzed (table 1).

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 in order to obtain typical thresholds with which to classify the months with extreme values of the variables. Due to the presence of trends in the series studied (Castañeda and Barros 1994; Rusticucci and Barrucand 2004), the values of the percentiles turn out to be sensitive to the base period considered for their calculation. This trend is somewhat 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 1998, Camilloni and Barrucand 2012). This encouraged a differentiated analysis, with different base periods. According to the year to be classified, a percentile calculated based 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 20th 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).

Those months with rainfall lower than the percentiles 20 and 10 respectively were classified as dry (D) and very dry (DD) cases, while the temperature percentiles 10, 20, 80 and 90 were used to classify the 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 the differentiation is only kept for case studies. The dry months that did not have any extreme thermal condition associated with it were considered "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 cold and warm dry months were statistically analyzed with the Z-proportions test (Devore 2005).

In a 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 15ºS - 60ºS and 30ºW – 90ºW. The fields of daily anomalies of geopotential height at 500 hPa were calculated and then they were synthesized using the principal components analysis technique, retaining the 5 first main components that account for 82.2% of the total variance of the whole set of data. A cluster analysis on the sub-space defined by these 5 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. at. (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 the months classified as dry, either warm or cold.

In order to further 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 of days of each cluster, in the three meteorological reference stations. Furthermore, to describe the patterns, the 1000 hPa geopotential height field related to each 500 hPa field was taken into account.

3. Climatology of the dry months in relation to their thermal condition

When analyzing the dry events of all the records of each station, it is possible to see 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 (figure 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 in order to assess if these features could be considered to be homogeneous throughout the year or if they presented some seasonal variability.

In both seasons of the year, the Pilar station shows a predominance of warm and dry events over cold and dry ones, but this is much more marked 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 is 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 was shown at table 1, 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, the months with rain deficit conditions and warm temperatures 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 there is still predominance, although to a lower extent, of dry months with warm thermal conditions over the cold condition, in the other two stations there is a clear predominance of droughts with cold temperatures.

4. Temporal variability of occurrence of dry events and extreme temperatures

After this initial analysis, the temporal variability of the thermal conditions related to 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 initial year of each series. The results from this analysis are presented in figure 3.

The Pilar station shows a stationary behavior, keeping the greatest proportion of warm dry cases that is higher than the cold dry cases throughout the different periods studied. In the case of the Corrientes station it is possible to see that the higher number of cold dry cases vs. the warm ones 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 cold and warm dry cases is similar, except for the 1911-1945 sub-period, when there is a greater proportion of cold cases.

The analysis was repeated, with a considering the season of the year (results not shown). Although there is some agreement between these results and those shown for the total period, there is a significant change in the last two sub-periods considered, which coincides with the climatic jump of 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 the Pilar station and in the warm period in the OCBA station. The cold (April-September) time 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 the 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 times. 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 (Oct-March) of the 1946-1975 period, the cold dry cases had a low occurrence frequency (8.3% of dry cases).

5. Dry months and atmospheric circulation

The following step in this work was to study the relationship between the thermal condition of the month classified as dry and the frequency of occurrence of fields of geopotential height at 500 hPa previously found by a cluster method, as detailed in section 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 the climatology of dry months (1979-2008 period). These 30 years are analyzed with daily temperature and rainfall data from the reference stations, and with daily fields of geopotential height at 500 hPa., as indicated in the data and methodology section. As previously explained, through the synthesis method it was possible to get a set of 10 types of representative structures of the variable. These structures are presented in figure 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 of days of each cluster, in the three meteorological stations used as references (table 3). These results correspond to 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 figure 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, and the results obtained turned out significant.

Each pattern presented in figure 4 has a frequency of climatological occurrence, also indicated in the figure. When analyzing the frequency of occurrence of these patterns for the dry months, it is important for the results 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 (month with warm or cold dry conditions) and the climatological occurrence of the pattern, relativized to the climatology as per:

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

Where

Fdi is the frequency of the occurrence of the pattern i in the warm (w) or cold (c) dry months

Fci is the frequency of climatological occurrence of pattern i

Figure 5 shows the indices calculated considering all the dry months with warm and cold conditions of the period studied. It is interesting to observe those cases in which the frequency of 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 figure 5, it is possible to see that in the warm dry months there has been a high frequency of occurrence of anomalies of geopotential height at 500 hPa with type 6 and 7 structure, while the frequency of occurrence of these structures under cold dry conditions has been the same as or lower than climatologically expected. 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 (figure 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 an 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 anti-cyclone 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 an homogeneous pattern in the three reference stations. From all the above mentioned it is possible to observe that the first of the structures mentioned is more related to the rain deficit condition, while the other is more strongly related to the warm thermal 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. 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 in the three reference stations it is possible to see that during the warm dry months, the type 2 structure is weakened. 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 the 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 rainfall intensities lower than normal. These anomalies in the surface variables are due to a pattern of negative anomalies of geopotential height at 500 hPa centered on the Atlantic Ocean (42S-55W) and positive anomalies on the Pacific Ocean (figure 4). This configuration of anomalies 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 the 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 the pattern 4 is related to cold conditions (table 3). Cluster 4 is represented by a large center of positive anomalies of geopotential height 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 worth of attention is that corresponding to cluster 10. This pattern shows a frequency from normal to higher than normal in the cold dry cases; besides, its frequency 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 (figure 4). This configuration of anomalies 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) semesters separately, taking into account the climatological occurrence of each pattern for each semester separately. Results are shown in figure 6, where it can be observed than the patterns 6 and 7, typical of warm dry cases, are more often seen during the cold semester, while cluster 2 decreases in both segments and in all stations. The participation of cluster 2 in the 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 participation depending on the semester analyzed. It shows greater frequency of occurrence in the cold dry months in OCBA in the Apr-Sept semester, while in Corrientes there is a higher frequency of occurrence in the cold dry months of the Oct-March semester.

6. Analysis of spatial simultaneity of cold or warm 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 3 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, showing 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 occurrence 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". Dry months with cold or warm conditions which have occurred simultaneously in the three stations considered 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), as is shown in table 4.

As in the case of the analysis done in section 5, an index was made which represented the deviations from the occurrence frequency of each circulation pattern under a certain condition (in this case, generalized droughts with different thermal conditions) and the climatological frequency of each pattern, relativized to the latter.

Results presented in figure 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 what has already been shown in the analysis of all the cold dry cases of the stations studied. In the case of the generalized 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 section 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 configuration 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). With regard to the 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 thermal conditions, which was the most frequent condition among the generalized droughts cases. It shows the scarce or null participation 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 anomalies of geopotential height towards the south-eastern extreme of the domain of the study. 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 what was observed in 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 occurrence frequency was lower than the first quartile, the occurrence of the pattern was considered to be low. On the contrary, if the occurrence frequency was higher than the third quartile, the occurrence frequency was considered to be high.

It can be observed that the cases of droughts with normal to cold thermal characteristics typically have a high occurrence of patterns 4 and 2, and a low occurrence 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 participation in the cases of cold droughts, both generalized and non-generalized ones.

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 participation in the months with cold dry conditions. As previously exposed, this pattern favors high temperatures in the region.

7. Summary and conclusions

In a first stage, this work presents a climatology of dry months with extreme temperature conditions (warm or cold) 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 stations analyzed it was possible to find out a greater frequency of months with simultaneity of dry conditions and high temperatures 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 dry and relatively cold conditions 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 patterns of atmospheric circulation which could distinguish the dry months with extreme thermal conditions, a classification of patterns of anomalies of geopotential height at 500 hPa was used on a daily basis, obtained by means of principal components 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 conditions of surface temperature and the rainfall related to these clusters were also studied. It was observed that some of these patterns had a high frequency of occurrence in warm dry months, while others occurred in cold dry cases.

It was found out that the months with a high frequency of occurrence of fields with structures represented through the patterns 6 and 7 have shown a warm thermal condition. The physical analysis of these patterns showed that the first of the cases 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 stations of reference) with a warm thermal condition and a very low one in the cases of cold generalized droughts. Finally, there is a low frequency of the cluster 2 in the months with warm droughts. This is in line with the findings from the analysis of cold dry cases, which show a high frequency of the structures represented by this cluster 2, which has negative anomalies on the Atlantic Ocean, extending towards the continent on the center and north of Argentina. As previously mentioned, this configuration of anomalies 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. Secondly, for these cases pattern 4 stands out, which is represented by a large center of positive anomalies of geopotential height located on the southern extreme of the continent (55S-70W). The circulation caused by 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 dry months under extreme thermal conditions and to improving the entry database at risk and decision models for drought cases. On the other hand, through the results obtained it is possible to develop studies about 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.

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Figures

Fig. 1 correlation between rainfall in the selected meteorological stations and rainfall in Argentina and surrounding areas from the CMAP (upper panel) and University of Delaware (lower panel) databases. The correlations with the data from the Corrientes station are represented in the panels from the left (a), with the Pilar station in the central panels (b) and OCBA station in the right panels (c)

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

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

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

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

Fig. 6 idem figure 5 but results are broken down by semester

Fig. 7 index of relative weight of each pattern of geopotential height at 500 hPa in the months of warm (w) and cold (c) generalized droughts

Fig. 8: idem figure 7 but for generalized droughts with thermal conditions from normal to cold

Tables

Table 1 location of reference station and record data

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

Table 3 Composites of daily mean temperature, daily rainfall intensity and percent frequency of rainy days (relative to the total of days within each cluster) for each cluster and meteorological station. Dark (light) gray shades show the cases of higher (lower) mean temperature

Table 4 generalized droughts and associated thermal conditions

Table 5, Summary of the frequency of the different patterns in cold or warm generalized droughts. H indicates high frequency of occurrence and L indicates low frequency of occurrence

Figure

COLD AND WARM DRY MONTHS AND THE ASSOCIATED CIRCULATION IN THE HUMID AND SEMI-HUMID ARGENTINE REGION

Mariana Barrucand

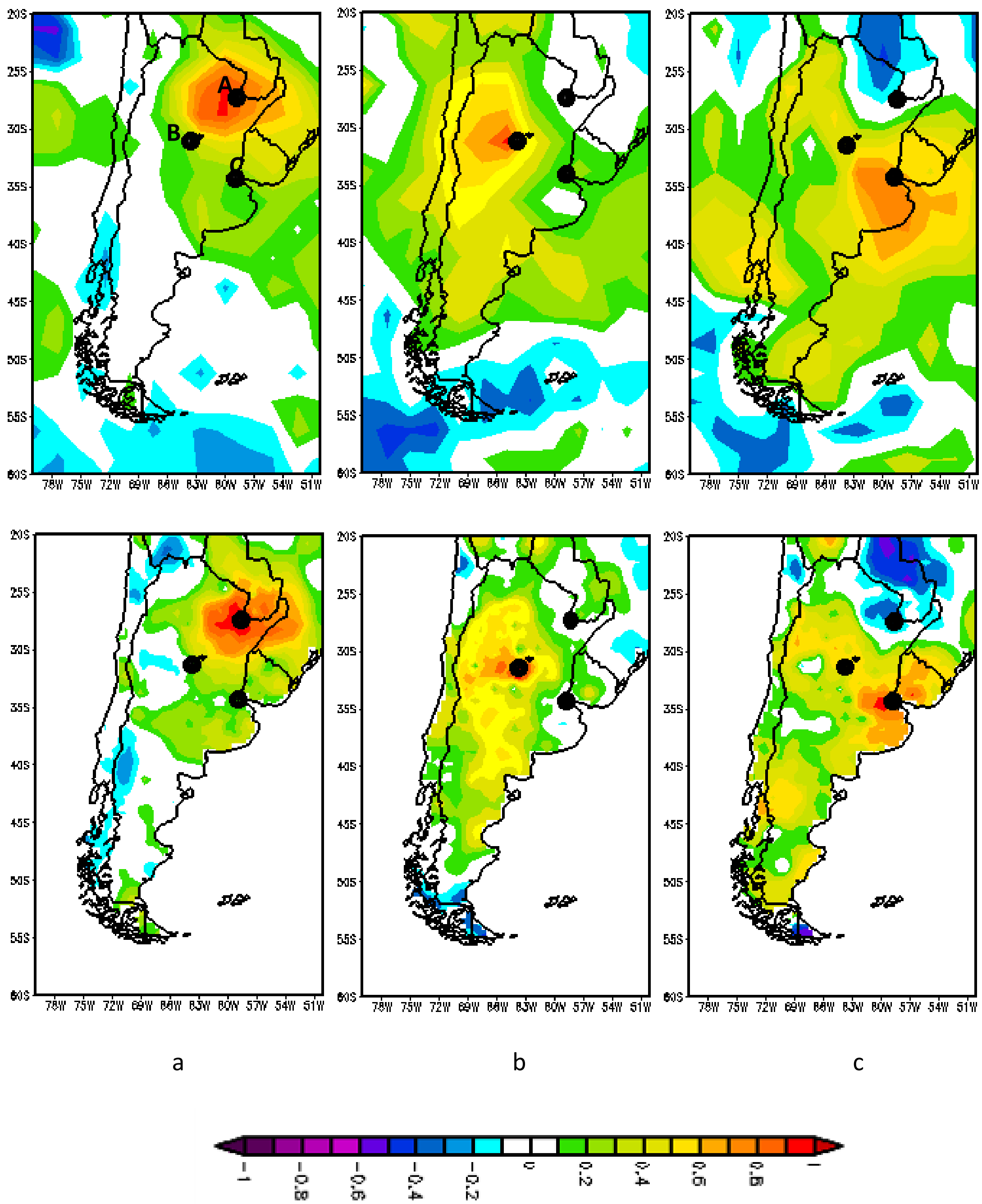
Walter Vargas

María Laura Bettolli

Figures

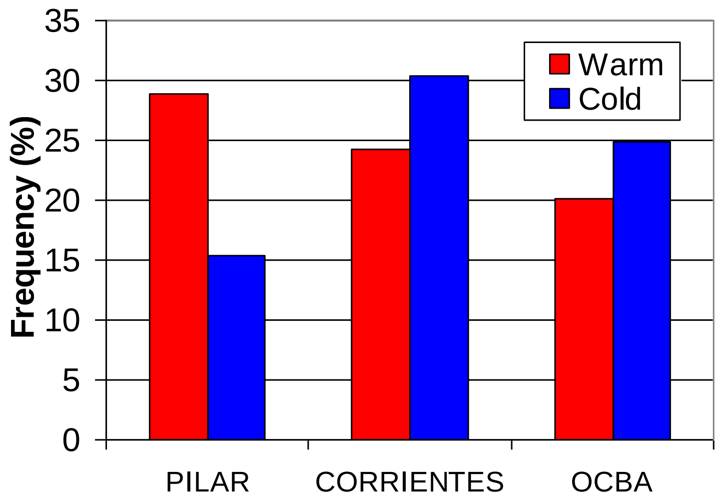
Color figures will be shown on-line

Black and White will be shown in the print version


A
B
C
20S
25S
30S
35S
40S
45S
50S
55S
60S
78W 75W 72W 69W 66W 63W 60W 57W 54W 51W
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

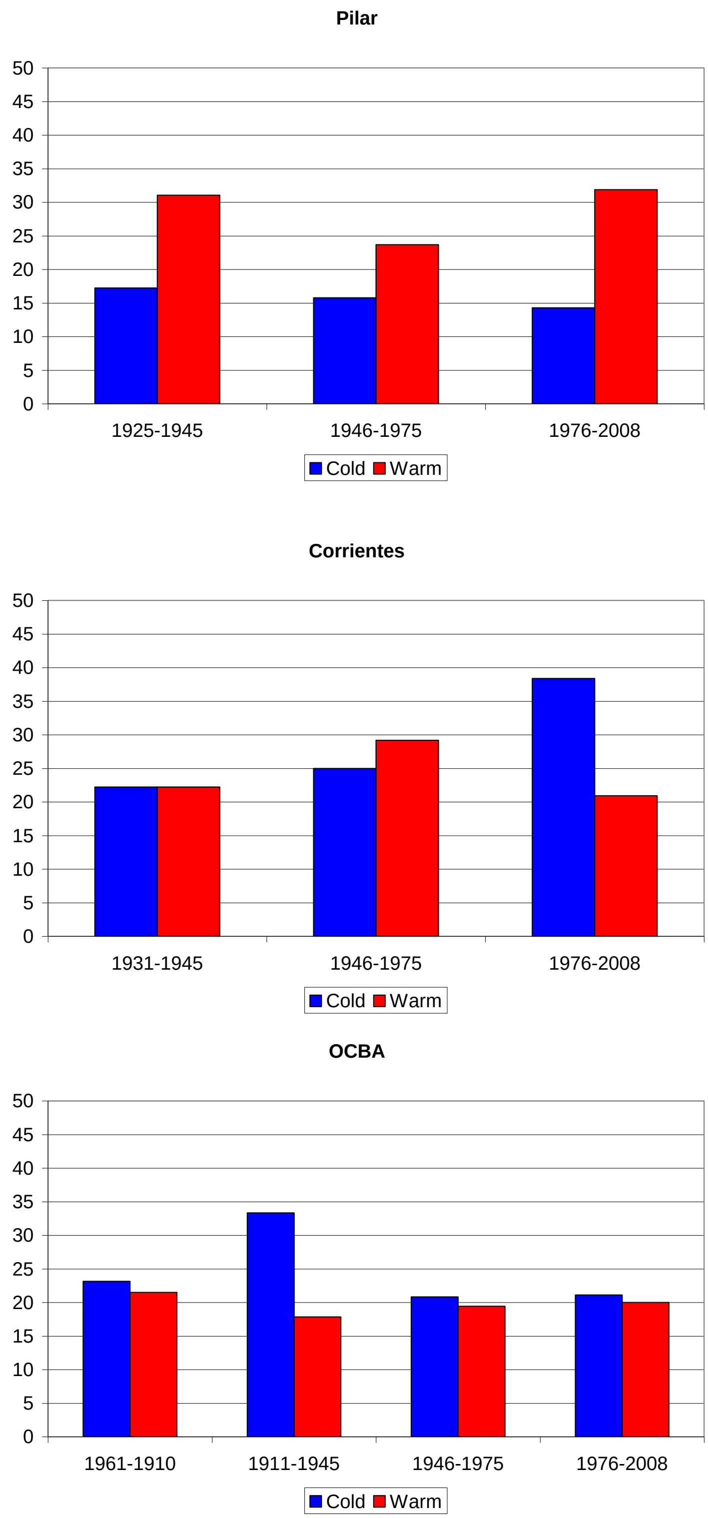
a b c

Figure 1



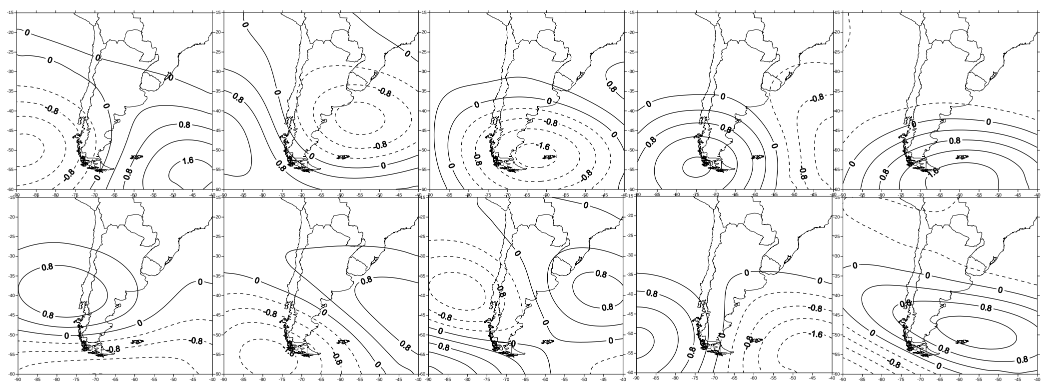
Warm	28,8	24,2	20,2
Cold	15,3	30,4	24,9
Difference	**13,5 *****	-6,2	-4,7

Figue 2


Pilar
50
45
40
35
30
25
20
15
10
5
0
1925-1945
1946-1975
1976-2008
Cold
Warm
Corrientes
50
45
40
35
30
25
20
15
10
5
0
1931-1945
1946-1975
1976-2008
Cold
Warm
OCBA
50
45
40
35
30
25
20
15
10
5
0
1961-1910
1911-1945
1946-1975
1976-2008
Cold
Warm

Figue 3

1 (11.84%) 2 (7.93 %) 3 (9.42 %) 4 (10.8 %) 5 (9.88 %)



6 (9.04 %) 7 (13.58 %) 8 (7.57 %) 9 (11.50 %) 10 (8.43 %)

Figure 4

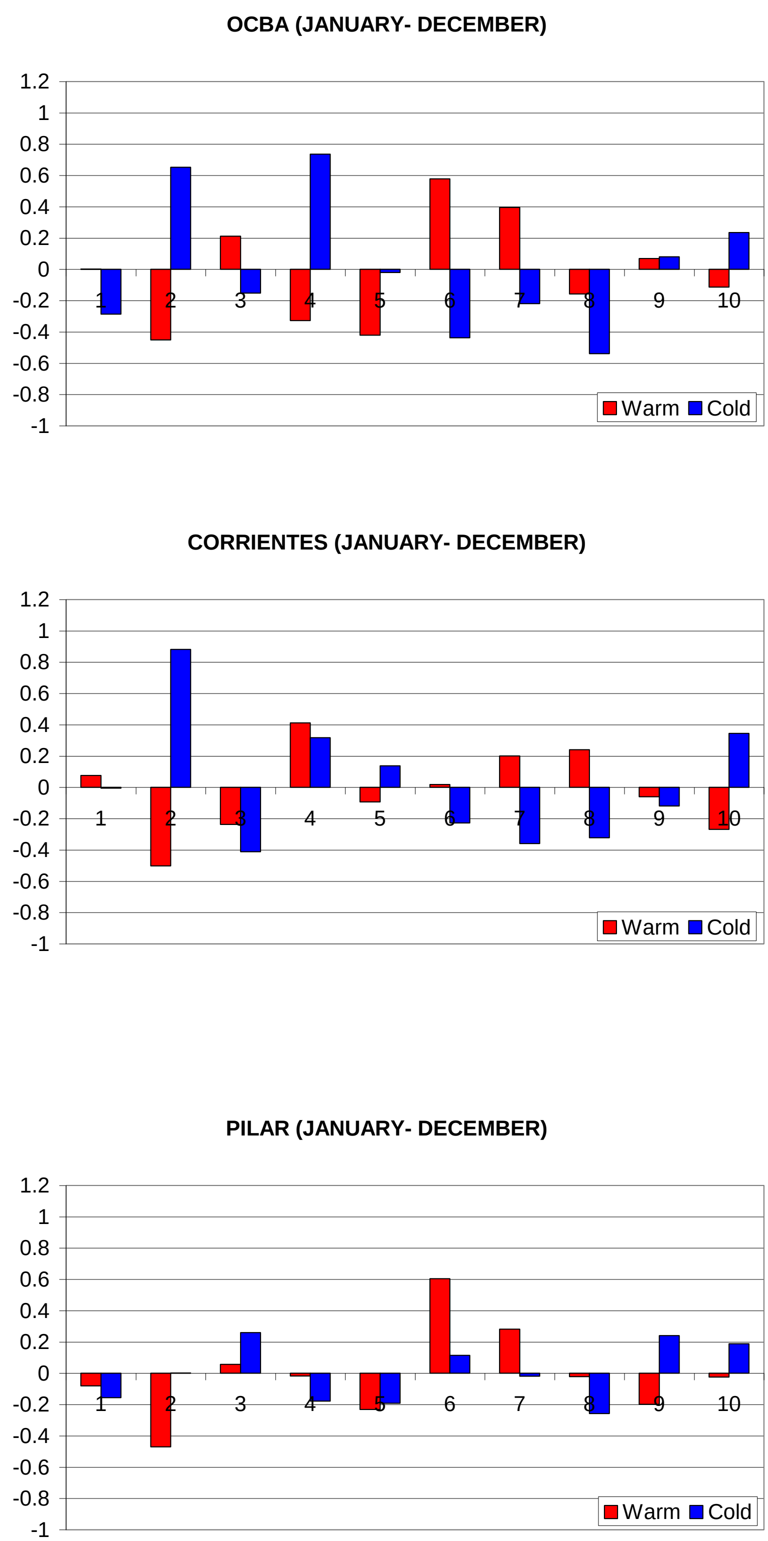
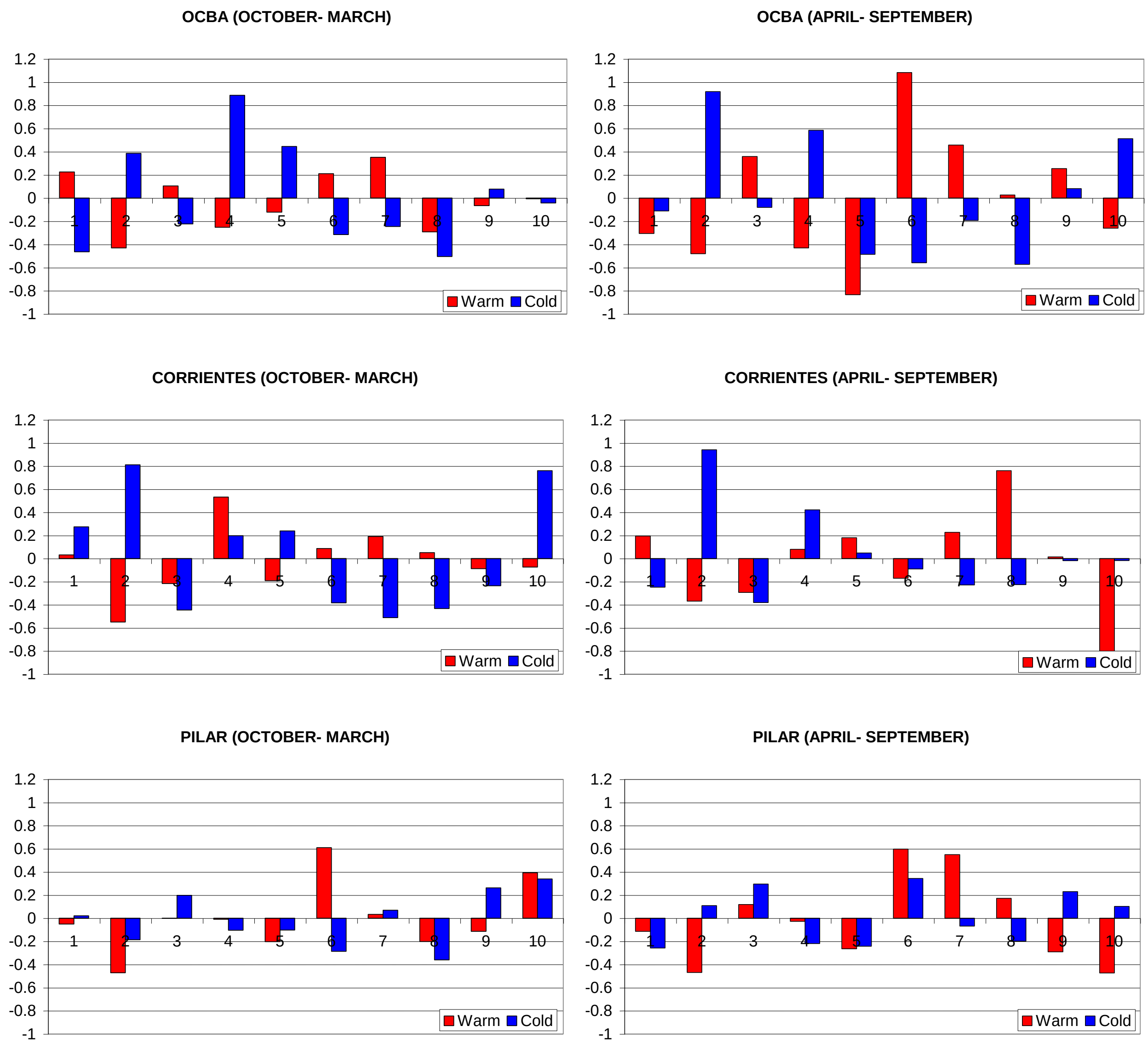

OCBA (JANUARY- DECEMBER)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
1 2 3 4 5 6 7 8 9 10
Warm
Cold
CORRIENTES (JANUARY- DECEMBER)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
1 2 3 4 5 6 7 8 9 10
Warm
Cold
PILAR (JANUARY- DECEMBER)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
1 2 3 4 5 6 7 8 9 10
Warm
Cold

Figure 5


OCBA (OCTOBER- MARCH)
OCBA (APRIL- SEPTEMBER)
CORRIENTES (OCTOBER- MARCH)
CORRIENTES (APRIL- SEPTEMBER)
PILAR (OCTOBER- MARCH)
PILAR (APRIL- SEPTEMBER)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
1
2
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4
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7
8
9
10
Warm
Cold

Figure 6

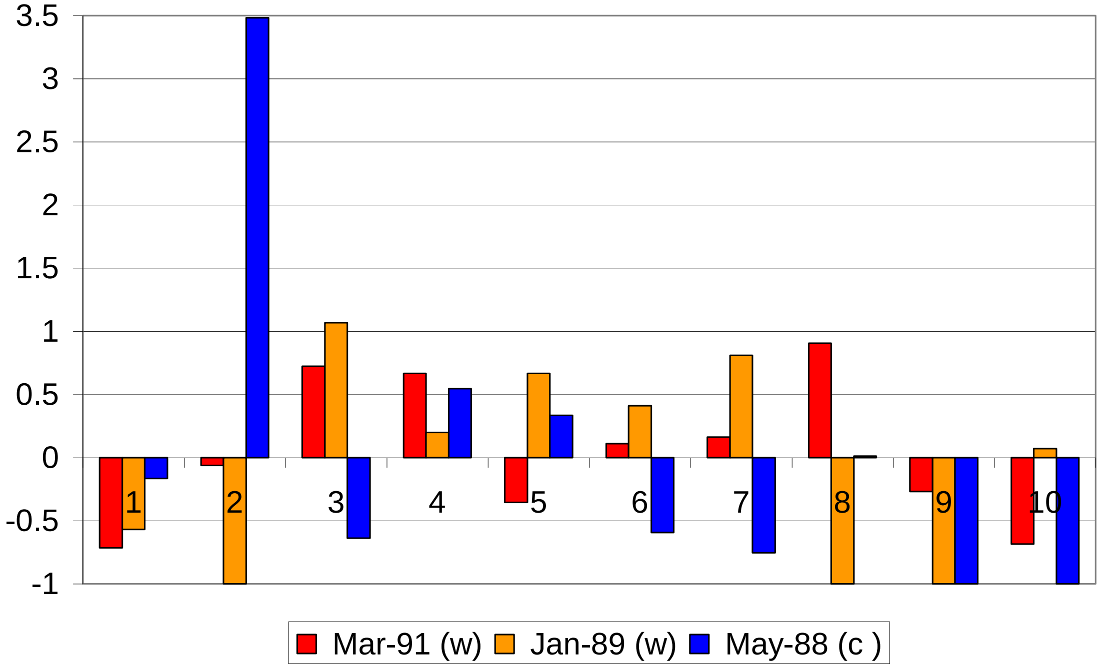
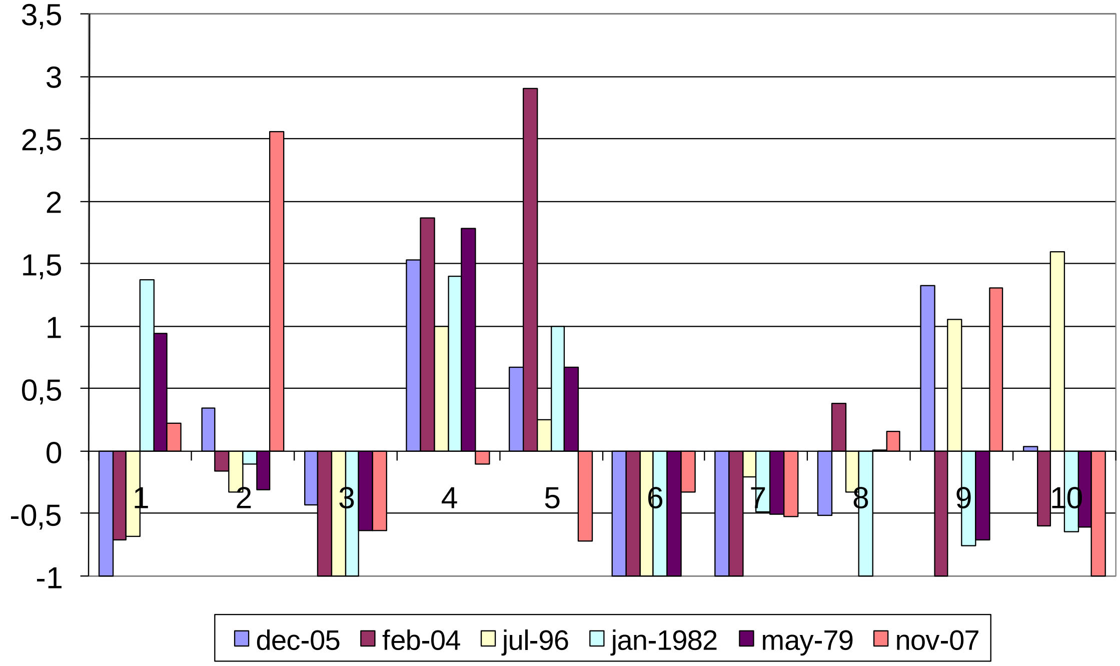


Figure 7



3,5
3
2,5
2
1,5
1
0,5
0
-0,5
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1
2
3
4
5
6
7
8
9
10
dec-05
feb-04
jul-96
jan-1982
may-79
nov-07

Figure 8

COLD AND WARM DRY MONTHS AND THE ASSOCIATED CIRCULATION IN THE HUMID AND SEMI-HUMID ARGENTINE REGION

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Tables

Table 1: location of reference station and record data

STATION	LATITUDE	LONGITUDE	HEIGHT	PERIOD
OCBA	34º 35'	58º 29'	25	1861-2008
CORRIENTES	27º 28'	58º 49'	73	1931-2008*
PILAR	31º 4'	63º 53'	338	1925-2008

**January to October data are missing in 1961*

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

Station	Temperature	Apr-Set	Oct-Mar
Pilar	Warm	25.2	32.7
	Cold	20.0	10.3
Corrientes	Warm	17.5	30.9
	Cold	40.2	20.6
Ocba	Warm	11.6	28.7
	Cold	32.0	17.7

Table 3 Composites of daily mean temperature, daily rainfall intensity and percent frequency of rainy days (relative to the total of days within each cluster) for each cluster and meteorological station. Dark (light) gray shades show the cases of higher (lower) mean

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

Table 4 generalized droughts and associated thermal conditions

Thermal condition of generalized drought	Month
Warm	Mar 1991- Jan 1989
Normal to warm	Apr 2008
Normal	Aug 2006
Nomal to cold	may-79 Jan´-82 jul-96 feb-04 dec- 05 nov-07
Cold	may-88

Table 5 Summary of the frequency of the different patterns in cold or warm generalized droughts. H indicates high frequency of occurrence and L indicates low frequency of occurrence

Cluster	Dy months nomal/cold							Dry months normal/wam		
	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	L	L	
2	**H**	**H**	**H**					H		L
3	L	L	L	L	L	L		H	H	H
4			**H**	**H**	**H**	**H**	**H**	L	H	
5		L	L	H		H		L		
6				L	L	L	L			
7	L	L	L			L	L	L		H
8			L	L				L	H	L
9	L	H	**H**	L	**H**	L	**H**	H		L
10	L	L		L	**H**	L		H	L	