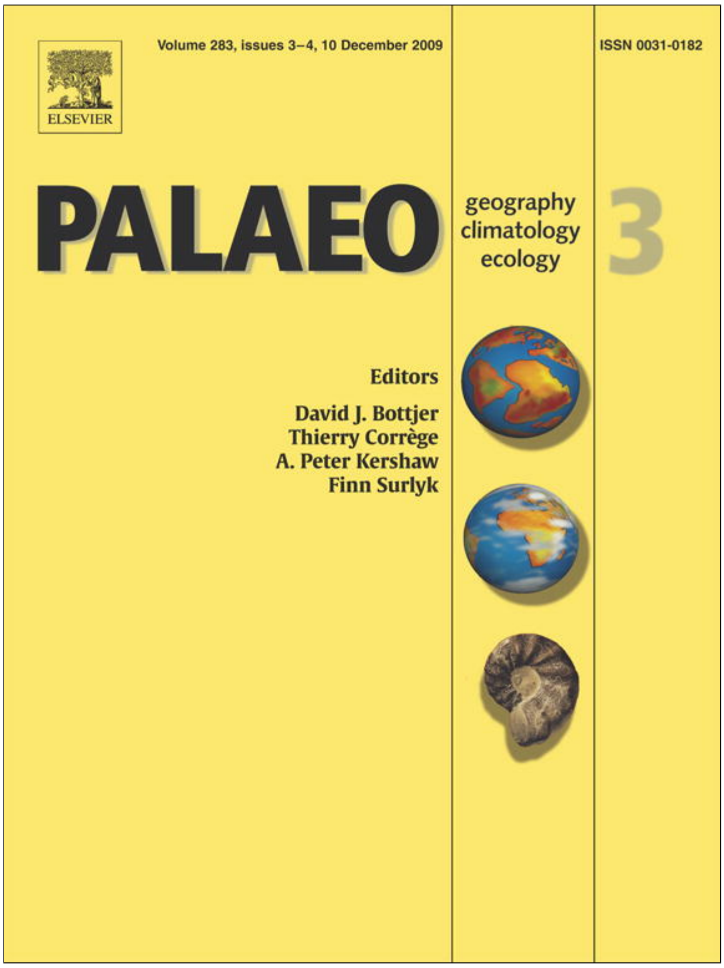

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Historical climatic extremes as indicators for typical scenarios of Holocene climatic periods in the Pampean plain

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ABSTRACT

The Holocene has been marked by two different climatic periods in the Pampas, one (8.5–3.5 kyr B.P.), characterized by temperatures and precipitation higher than today and the other (3.5–1.4 kyr B.P.) semiarid, generating parabolic dunes. The humid period produced intense pedogenesis down to 40° lat. S and a mobilization of iron oxides to 30° lat. S, which means tropical climate with temperatures above 20 °C and precipitation higher than 2000 mm/yr. Sand deflation and development of parabolic dunes occur under climates with 300–400 mm/yr. This contribution is based on geological and physical proxies. Typical weather scenarios of those climates are sporadically reproduced today during extremely humid or dry periods. On that basis, meteorological parameters of years beyond the thresholds of 2000 and 400 mm/yr were processed. Dry periods were characterized by a large thermal amplitude, frosts and stronger winds, reproducing the continental anticyclonic circulation of the Late Holocene. Humid extremes were warmer than normal (lower thermal amplitude), with rains produced by local convection processes. Typical scenarios with precipitation above 2000 mm/yr are: 21 °C mean temperature (ca. 1 °C higher than the Present record); 27 °C maximal annual temperatures; 16 °C minimal annual temperatures (more than 1 °C higher than the Present); as a consequence, thermal amplitude was smaller than today, virtually without frosts. Characteristic parameters of the Late Holocene were: mean annual precipitation ca. 350 mm/yr; 15 °C mean temperature; 22 °C maximal annual temperatures; 8 °C minimal annual temperatures, showing significative shifts in the dry season (lower than normal); monthly maximal and mean temperatures higher than today. The result is a thermal amplitude larger than today. Probably, higher quantity of frosts per year, stronger winds and lower relative air humidity in comparison with the humid climate extreme, complete the scenario.

1. Introduction

The use of geological and physical indicators in the reconstruction of past environments is as old as Geological Science. This fact is fixed in the classical principle, which states “*The Present is the key of the Past*”. Indicators offered by Sedimentology, and in a lesser degree by Geomorphology, have probably been the more frequent cases. Such data provide a definitive indicator of extreme climate conditions extending beyond of the historical register.

Proxy data with biological bases were developed in the last few decades with remarkable success and today such techniques are extensively applied in climatic reconstructions, particularly for Holocene and Late Pleistocene times. These developments have the important merit of introducing quantitative criteria in paleoclimatic reconstructions through the introduction of transfer functions and analogue matching into interpretation of pollen diagrams, among others. It often results in interesting advances in regional knowledge. However, as is the case in every methodological tool, these techniques are based on some implicit premises and have limitations as well as evident advantages.

The first requirement for applying a transfer function is the true knowledge of the biology and ecology of the involved species, which at Present is reached only in certain regions of the world, e.g. Europe and some areas of North America. On the contrary, knowledge of the biota is modest in most of South America as well as on other continents. That is a problem that could transform ambitious scenarios into true “mine fields”. According to Markgraf (1993), given the still limited understanding of the modern distribution and ecological significance of many of the principal plant taxa of South America as well as the modern relationship between plant frequency and pollen frequency and the modern climate patterns and their variability, any calibration of pollen frequencies in terms of paleoclimatic parameters may lead to unrealistic conclusions.

We propose in this article to re-assume some robust axioms of Geology with global (not just regional) validity, by developing the rationale to quantitative levels. The basic intention, of course, is to

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offer an independent, complementary tool to already existent techniques. The proposal is applied here in the reconstruction of two Holocene climatic periods that occurred in the central plains of Argentina, a region with relatively abundant multiproxy archives. The main goal is to characterize typical scenarios of both Holocene climates, which are sporadically reproduced at Present during extremely humid or dry seasonal, annual or inter-annual periods.

2. Rationale

This contribution is based on proxies with geological and geomorphological (ultimately physical and chemical) principles, which are complementary to the usual proxies applied in Holocene reconstructions that are dominantly biological. The approach proposed here has some evident advantages: the "samples" used are enormous (dune fields, entire loess formations, zonal soil levels), they are of regional-scale occurrence, and are directly linked to primary external forcing factors, such as temperature, precipitation and evapotranspiration.

The fundamental environmental parameters responsible for the occurrence of geological products such as dune fields or zonal soils have been studied since the first decades of the twentieth century in the field as well as in the laboratory (Davis, 1905; Peltier, 1950; Tanner, 1961; Wilson, 1968; Tricard and Cailleux, 1972). At Present their ranks of occurrence are reasonably well-known and accepted among specialists (Summerfield, 1991).

Dunes are sensitive to modifications in the atmospheric parameters, such as wind direction and intensity and changes in precipitation, that affect the evapotranspiration, soil humidity, percentage of vegetation, and mobility of sediment particles. The areas of dunes tend to accentuate the effects of dry and humid phases (Rognon, 1980) and respond rapidly to climatic changes (Gutiérrez Elorza, 2001). Forman et al. (2001) state that the stratigraphic and geomorphic records of eolian dune deposition on the Great Plains of USA provide proxy information on the timing and magnitude of large-scale droughts when landscape conditions were favorable for the movement and accumulation of eolian sand.

Conversely, in a review of the role of pedogenic processes modifying wind-blown dust (loess), Kemp (2001), indicates that significant changes in climate during past soil-forming intervals might have important consequences for the use of paleosols as proxies of past climatic conditions. According to Morrison (1978), the very presence of a paleosol has paleoclimatic significance in that it is taken to indicate a period of warmer and/or moister conditions between cold and/or arid phases of loess accumulation. Quantitative climatic reconstructions from paleosols normally depend on the establishment of climofunctions, mathematical relationships between climatic variables and measured properties of soils forming at the present surface (Catt, 1991). Sarnthein (1978) summarizes that the past 20 kyrs have witnessed tremendous climatic changes, a glacial maximum at about 18 kyr B.P. (with extensive active sand dunes) and a climatic optimum centered on about 6 kyr B.P., which mark extreme situations for the Quaternary.

A concept applied in this paper is that of sedimentological or geomorphological "thresholds", above (or below) which a process starts (Monastersky, 1994). These thresholds are associated with a high rate of geomorphic activity, which is a dominant element in determining whether a landscape is formed by the prevailing climate (Summerfield, 1991). Some processes depend on the amount of precipitation, for example transport of sand and dust (Wiggs, 1997; Iriondo and Kröhling, 2007). Others, like glacial and nival processes, are basically linked to a temperature threshold. Another group of processes, such as different zonal soils, are produced mainly by a specific combination of temperature and humidity (Catt, 1990, among others). In consequence, the occurrence of some types of sediments and landforms are robust indicators of paleoclimates (Gutiérrez Elorza, 2001; Berta, 2005).

Another basic characteristic of climate at a regional scale is also useful for reconstructions. It is the repetition of synoptic meteorological structures along successive climatic periods in the same region. The crucial parameters in the theory appear to be the length of the cycle, rather than its magnitude, the length of time that positive feedback processes can operate once they are established and the thresholds are crossed (Monastersky, 1994). An example of a structure is the "Pampero" wind, a cold and dry SSW wind which occasionally blows in the region transporting Patagonic air masses into the Pampas and conveying dust clouds; according to the orientation of longitudinal megadunes of the OIS 4 (marine oxygen isotopic stage 4) age, such wind was the dominant synoptic structure during that period (Iriondo, 1999). Another example is the anticyclonic circulation over the Pampas in extremely dry years, a phenomenon dominant in the Late Holocene (Iriondo, 1990a). Climatic changes in the Pampas during the Holocene can be explained by assuming relatively minor shifts in present atmospheric circulation systems. It is assumed that such fluctuations occur at Present at variable intervals.

Hence, it can be supposed with reasonable certainty that climatic parameters not preserved in the sedimentological/geomorphological record have also occurred in coherence with the preserved ones. Some of those parameters, such as relative air humidity, frosts frequency, maximal temperatures, etc., are undoubtedly important in the reconstruction of past environments. A first approach of this rationale was proposed by Iriondo and García (1993). Benn and Evans (1998) suggested that changes in solar radiation provoke significant changes in the atmospheric circulation, oceans and hydrologic cycles. Those changes can produce shifts in the limits of climatic provinces (Iriondo and García, 1993). By using well-known geological and geomorphological indicators, present atmospheric patterns can be used as a baseline for the reconstruction of past climates, at least those of the Holocene and Late Pleistocene.

3. Present climate in the Pampas

The present climate in the Pampas varies from subtropical in the northeast to temperate in the southwest. Adapting a classical system (Strahler, 1997), the eastern area is subtropical humid and sub-humid (warmest month mean over 22 °C); the northwest area belongs to a dry hot steppe with mean annual temperature over 18 °C; the west is a dry and cold steppe with mean annual temperature under 18 °C and the southwestern region of the Pampas is an arid and cold area (Fig. 1). Other classifications based on morphoclimatic zones as defined by mean annual temperature, mean annual precipitation and the relative importance of geomorphic processes can be adapted from Summerfield (1991). Tropical wet–dry climate in the northeastern zone is characterized by a low temperature range (mean annual temperature 12–30 °C), mean annual rainfall between 1000 and 1800 mm, high chemical weathering, moderate/low wind action, udic soils and few night frosts in winter. It has a Brazilian biota and a thick vegetation cover. By contrast, the central portion of the Pampas is a subtropical semiarid zone characterized by mean annual temperature 8–30 °C, mean annual rainfall 300–1000 mm, moderate/low chemical weathering and moderate/high wind action. This central province has a long dry season occurring between March and September. The vegetation cover is more or less continuous and soils are ustic and aridic (Iriondo and García, 1993). The southwestern part is a subtropical arid region having mean annual temperature 5–30 °C, mean annual rainfall 0–300 mm, low chemical weathering and high wind action.

From the point of view of the climate dynamics, the regional pattern reflects the dominance of both Atlantic and Pacific Oceans on the region. Major influences are the South Atlantic Anticyclone which introduces warm and humid winds from the north and northeast and the South Pacific Anticyclone whose air masses arrive cold and dry from the SSW. Meridional movements or air masses are produced, which provoke frontal rains. In addition, the South American Low-Level Jet (SALLJ) is a relevant feature of the warm season low-level circulation and represents a poleward transport of warm and moist air concentrated

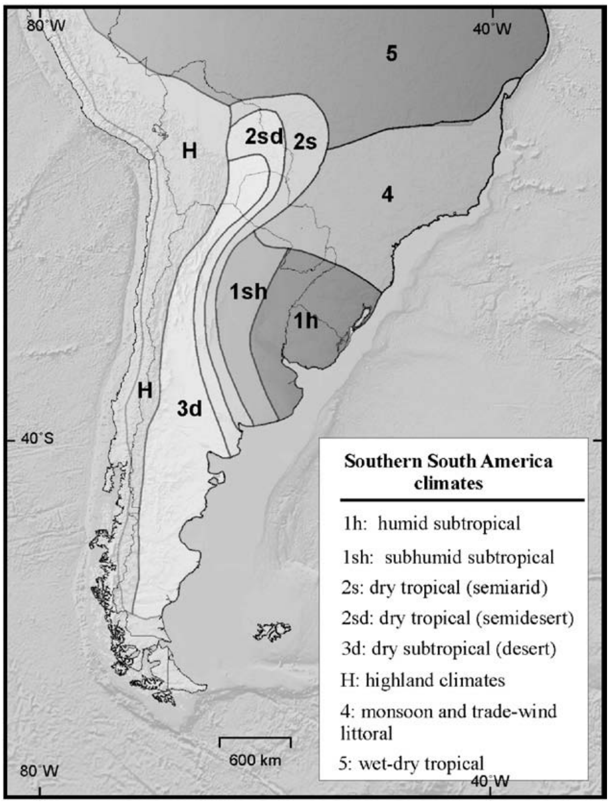

Fig. 1. Climatic provinces of Argentina (modified from Strahler, 1997).

in a relatively narrow region, with strong wind speeds at low levels downstream and to the east of mountain barriers, as documented in earlier studies for various regions of the world (Marengo and Soares, 2004). The circulation anomalies at upper and lower levels suggest that the intensification of the SALLJ would lead to an intensification of the South Atlantic Convergence Zone (SACZ) later on and to the penetration of cold fronts with an area of enhanced convection ahead at the exit region of the SALLJ (Marengo and Soares, 2004).

In southern South America, episodic incursions of mid-latitude air to the east of the subtropical Andes (also referred to as South American cold surges) are a distinctive year-round feature of the synoptic climatology (Garreaud, 1999 and 2000). Statistical analyses by Kousky and Cavalcanti (1997), Compagnucci and Salles (1997) and Garreaud and Wallace (1998) also demonstrate that South American cold surges dominate the synoptic variability of the low-level circulation, air temperature, and rainfall over much of the continent to the east of the Andes. The prevalence of this phenomenon seems at least partially related to the favorable continental-scale topography: the Andes Cordillera. The large-scale environment in which the cold air incursion occurs is characterized by a developing mid-latitude wave in the middle and upper troposphere, with a ridge immediately to the west of the Andes and a downstream trough over eastern South America. At the surface, a migratory cold anticyclone over the southern plains of the continent and a deepening cyclone centered over the southwestern Atlantic grow mainly due to upper-level vorticity advection (Garreaud, 2000). Extreme wintertime episodes produce freezing conditions from central Argentina to southern Brazil, which has motivated observational and numerical case studies (e.g., Hamilton and Tarifa, 1978; Fortune and Kousky, 1983; Marengo et al., 1997; Bosart et al., 1998; Garreaud, 1999; Müller et al., 2003; Müller and Berri, 2007). Summertime episodes produce less dramatic fluctuations in temperature and pressure, but they have been associated with bands of enhanced convection and rainfall (e.g., Ratisbona, 1976; Parmenter, 1976; Kousky, 1979; Garreaud and Wallace, 1998).

Several lines of evidence show that over the past few decades the tropical belt has expanded (Seidel et al., 2008). Most importantly, associated poleward movement of large-scale atmospheric circulation systems, such as jet streams and storm tracks, could have resulted in shifts in precipitation patterns affecting natural ecosystems. Changes in the width of the tropical belt, show an increase since 1979, whose rates vary from 2.0 to 4.8° latitude per 25 years. Estimations of these changes are based on indirect measurements of the width of the Hadley circulation (Seidel et al., 2008). Particularly, the climate of South America is a consequence of its geographical position with respect to latitude and ocean current activity. Thus in Argentina, the presence of the Andes along the occidental coast modifies the climate of the western regions significantly (García, 1994). As a consequence, the annual isohyets in this region run in a north/south direction. During the second half of the twentieth century, there was an important positive trend in annual precipitation in almost the entire South American region between 22° lat. S and 45° lat. S to the east of the Andes which, in some places, represented a rainfall increase of at least 30% (Castañeda and Barros, 1994; 2001). This trend (from 1950/1969 to 1980/1999) favoured the westward extension of the humid region by 200 km. Additionally, summers were longer and major changes occurred in autumn temperatures (Barros et al., 2008).

Several areas in Southern South America (extra-tropical regions) have been reported as presenting strong inter-annual precipitation variability associated with El Niño (EN) and La Niña (LN) events. In general, the precipitation anomalies result from changes of already existing climatic circulation features that influence the precipitation during a given season in specific regions (Grimm et al., 2000).

According to Rusticucci and Barrucand (2004), the extreme temperature events show high correlation with the sea surface temperatures; they are closely related to the warming and cooling of the coastal waters in the South Atlantic and South Pacific (Rusticucci et al., 2003) as well as ENSO variability (Rusticucci and Vargas, 2002).

4. Late Quaternary climatic sequence of Pampas

Numerous studies have been undertaken on paleoclimates in the Pampean region, some of them as far back as the ninetieth century. A modern synthesis can be found in Iriondo and Kröhling (1995) and in Iriondo (1999). Basically, following the warm and humid last interglacial period, the OIS 4 occurred, which appears in the South America literature as the coldest period in the last glacial–interglacial cycle (Clapperton, 1993). During that period, the Pampean Eolian System (PES) was generated (Fig. 2a), formed by a sand sea characterized by longitudinal megadunes oriented in a SSW direction. The following OIS 3 (65 to 36 kyr B.P.) is marked, in the PES and neighboring regions, by a climatic improvement with complex processes, including the generation of two soil levels and a generalized flattening of the relief inherited from OIS 4. Rainfalls during the soil-forming phases were definitely higher than present, estimated between 1000 and 1200 mm/year in central Pampas (Iriondo, 1999).

OIS 2 was shaped by general advances of glaciers in the Andean Cordillera and South Patagonia (Clapperton, 1993) and by a dry climate in the plains, with an important remobilization of sand and generation of a major loess belt in North Pampa (Fig. 2a; Iriondo, 1999). The scenario for OIS 2 is similar to OIS 4, with dominant eolian dynamics, although less strongly manifested. Iriondo and García (1993) estimated a shifting of climatic belts of about 750 km to the northeast of their present positions. Those authors, based on current situation analogy, stated a lowering of the mean annual temperature by 2.5/3 °C, with larger differences occurring in winter (4 °C) than in summer (1 °C) estimated for the area of Santa Fe, located at the northeast of the Pampas (31°40′ lat. S and 60°35′ long. W). Rainfall was considerably lower amounting to about 350–400 mm/yr (today it is around 1100 mm/yr). The main phase of this period ended around 16 kyr B.P.

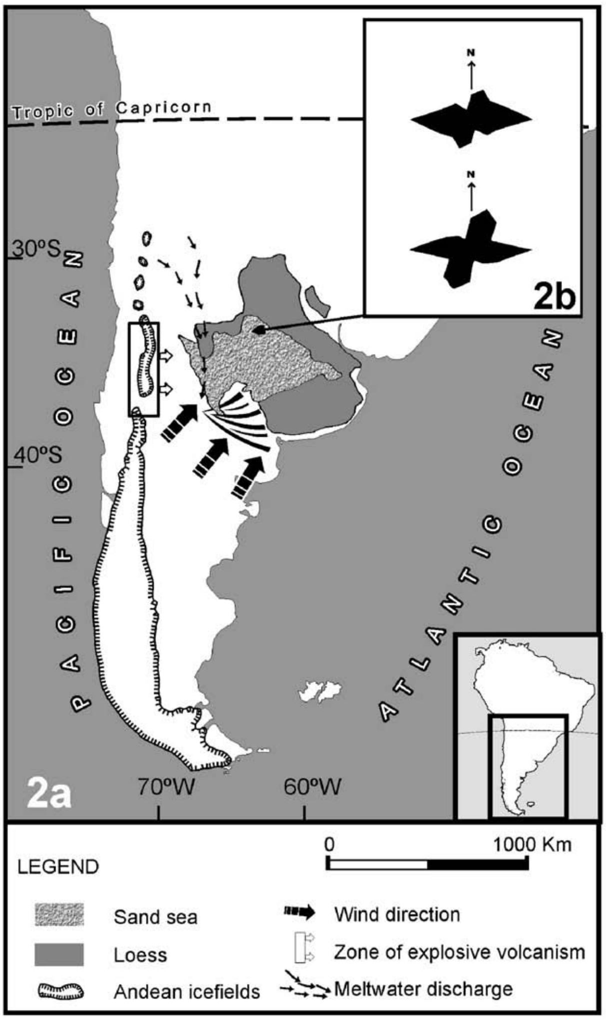

Fig. 2. a) Pampean Eolian System (PES) at OIS 2 (from Iriondo, 1990b). b) Late Pleistocene–Lower Holocene paleowind directions in South Santa Fe and Córdoba provinces — 34° lat. S and 62° long. W (from Iriondo and Kröhling, 1995).

A short improvement of the climate marked by pedogenic $CaCO_3$ leaching in the northeast of the PES occurred around 15–16 kyr B.P. (Iriondo, 1999). After that the Late Pleistocene–Early Holocene phase began, characterized by environmental conditions milder than those of LGM (Last Glacial Maximum), strong Westerly winds in Central Pampas (Fig. 2b), shifting of the climatic belts some 6–7 °C north of the present climatic belts, and accumulation of loess up to 3.5 m thick in peripheral areas to the north. According to several TL dates (Iriondo and Kröhling, 1995; Iriondo, 1999; Kröhling and Iriondo, 1999), this phase ended about 8.5 kyr B.P.

4.1. The Climatic Optimum of the Holocene

The Holocene Climatic Optimum was a ca. 5000 year-long period, characterized by a humid climate in the Pampean region, produced by a shift to the south in the zonal circulation of the Westerlies and an intensification of the anti-clockwise circulation around the South Atlantic Anticylone.

A strong indicator of that condition is a moderately to well-developed soil, that represents a distinct pedostratigraphic marker identified in the main geomorphological units of the PES, and even outside of that system (Kröhling and Iriondo; 2005).

Paleosols respond very slowly to climate variations, reflecting average conditions at very low resolution and thus recording low-frequency climate variability (Grosjean et al., 2003). It is accepted among specialists that a well-developed soil profile takes several thousand years to be formed (see Paleopedology Manual of INQUA; Catt, 1990), as is the case here also according to other stratigraphic and absolute dating information.

The buried soil of Pampas (mainly Alfisol) is represented by a moderately to well-developed Bt-horizon. The soil was truncated and later covered by an eolian formation, Late Holocene in age. In fluvial valleys, that soil forms an accretionary pedocomplex formed by argillic horizons separated by strata of Andean volcanic ash concentrated there by alluvial processes. Typical pedogenic processes of the period were: argillan/ferriargillan illuviation, horizon differentiation, pedoturbation and hydromorphism (Kröhling and Iriondo, 2005).

This soil has also been identified in different provinces inside the Pampas by several authors (Fig. 3): in Buenos Aires (Puesto Callejón Viejo Soil, Fidalgo et al., 1973; 9 radiocarbon dates of the soil in the type profile permitted to Figini et al. (2003) to locate this pedogenic event for the area between 5.9 and 1.8 kyr B.P.), in southern Córdoba (Las Tapias Soil, Cantú and Degiovanni, 1984), eastern Córdoba and Santa Fe (Hypsithermal Soil of North Pampa; Iriondo, 1990a; Kröhling and Iriondo, 1999; Kröhling, 1999a), and in the eastern fringe of Pampas — Entre Ríos province — (buried Alfisol; Iriondo and Kröhling, 2004a). It is even more important that similar degrees of pedogenesis have been described in the West and Central climatic provinces of Argentina, where at Present aridic and ustic regimes make pedogenesis poorly recognized. In San Luis province, Ramonell and Latrubesse (1991) described the Los Toldos Soil, buried by an eolian deposit of Late Holocene age. Also in that province (western part of North Pampa), mid-Holocene lake levels above the modern playa floor in Laguna del Bebedero support an increase in precipitation at 5 kyr B.P., indicated also by the pollen data (González et al., 1981). In La Pampa province, the soil was described in early times by Guiñazú (1940) as a “buried black fossil earth”, reaching 37° lat. S and 65° long. W (Fig. 3).

Bonadonna et al. (1999) reported the results of a stable isotope study on biogenic carbonate of fossil terrestrial molluscs in the southern of Buenos Aires province, indicating an isotopic shift starting around 8.5 kyr B.P. The authors explain such an isotopic record as a

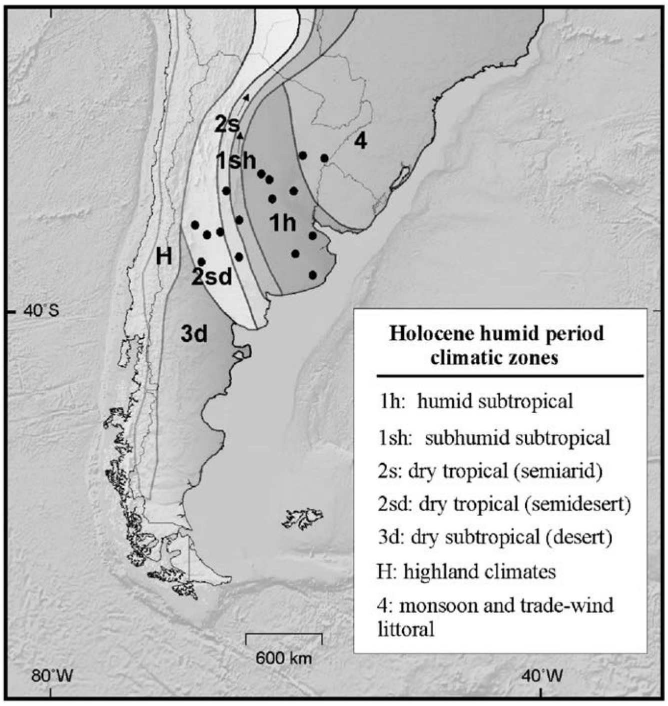

Fig. 3. Inferred Holocene Climatic Optimum climates. Dots indicate field data referred in the text. Geological evidence marks a displacement of the climate zones southwestward with respect to Present (compare to Fig. 1).

rise in atmospheric moisture and increasing rainfall linked to an increase in temperature.

Outside the Pampas, Carignano (1999) identified the El Ranchito Geosol in "bolsones", broad valleys located to the northwest behind the Pampean ranges. Polanski (1963) identified a grey soil in the middle section of the El Zampal Formation, a silty eolian unit located in the Andean piedmont (34° lat. S and 69° long. W), today under a desertic climate. El Zampal Fm was dated by radiocarbon into 9.9 ± 0.2 kyr B.P. at the base and covers most of the Holocene.

To the northeast of the Pampas, in the neighboring subtropical province of Corrientes, Lena (1975) described a buried lateritic B-horizon in several localities, which lies in the same stratigraphic position. Iriondo and Kröhling (2004) identified a buried Plinthosol in the upper part of the Tapebicuá Formation (eastern Corrientes). Both references confirm the shifting of the Brazilian tropical climate to the southwest up to 30° lat. S. during that period (Fig. 3).

Sedimentological, geomorphological, magnetic and biogeographic data also reinforce a humid climate that characterized the Climatic Optimum of the Holocene in the region (Fernández and Romero, 1984; Tonni, 1985; Aguirre and Whatley, 1995; Orgeira et al., 2003; Iriondo, 2004; Iriondo and Kröhling, 2004, 2008).

4.2. The Late Holocene

A dry, basically semiarid climate occurred in the Argentine plains and adjacent regions during the Late Holocene (Iriondo, 1990a). Absolute datings suggest that it extended from 3.5 to 1.4 kyr B.P., and possibly up to 1 kyr B.P. (Iriondo, 1990a; Tonni et al., 2001; González, et al., 2008; Iriondo and Kröhling, 2008). The dominant eolian activity provoked deflation of surface sediments, particularly of the A-horizon of the soil developed during the Holocene Climatic Optimum period. Consequently, an extensive sheet of eolian silt was generated in the surface of the Pampas and in the Chaco Plain of Bolivia, Paraguay and Argentina, as well as surrounding regions of Brazil and Uruguay (Fig. 4). This deposit (20–80 cm thick) was formally named San Guillermo Formation in the North Pampa (Iriondo, 1990a). The unit lies on the truncated soil and underwent an incipient pedogenesis since the deposition under the present humid climate. A recent OSL dating of this unit provided an age of 1.0 ± 0.1 kyr B.P. (Kemp et al., 2004). A cineritic stratum on top of the sequences developed inside the main fluvial valleys of North Pampa, was TL dated by Kröhling (1999a) into 1.3 ± 0.1 kyr B.P.

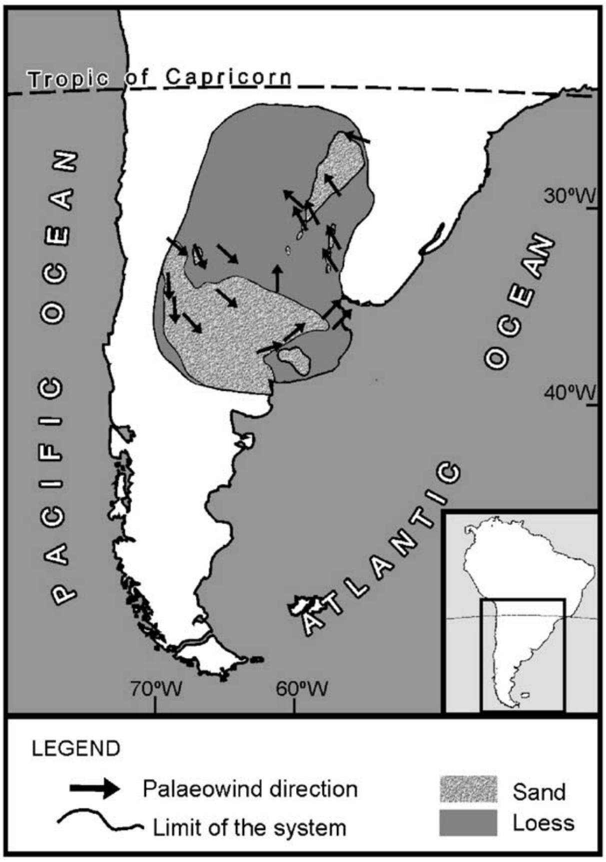

Fig. 4. Late Holocene scenario (from Iriondo, 1990a). Arrows mark palaeowind-direction measured in the field.

Application of grain size analysis to samples distributed in the North Pampa allowed the construction of isoplethic maps (based on the silt content) of the PES. The SSW–NNE transport path of sediments of the system is registered in the textural trend across the region: from eolian sand through sandy loess to typical loess. Eolian landforms of the region indicate the same wind directions. The equivalence in the general distribution of the isoplethic curves between the maps of the San Guillermo loessic unit and infralying loess formation confirms the scenario deduced for the Late Holocene (Kröhling, 1999b).

The eolian activity during this period is also represented in the South Pampa by dune development and characterized by parabolic dune fields; lunettes, sand sheets and deflation hollows have also been recognized (Iriondo and Kröhling, 1995). A TL age of a lunette in southern Santa Fe province gave an age of 2.0 ± 0.1 kyr B.P. (Kröhling, 1999a). According to measurements of paleowind directions on the basis of the orientation of parabolic dunes which, together with the

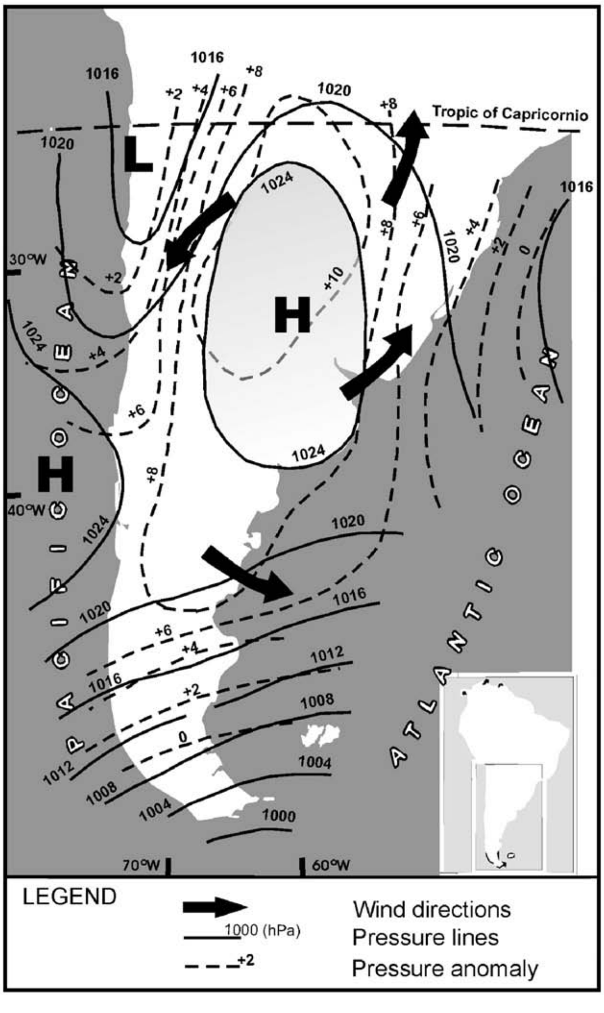

Fig. 5. Anticyclone pattern for one of the driest registered period (year 1962). Data were obtained from Servicio Meteorológico Nacional (SMN). Pressure data are referenced to sea level. Anomalies are outlined as dashed lines. Cold surges and dry conditions are associated with positive anomalies over the continent.

orientation of elliptical deflation hollows in the loess area, provide robust indicators of paleowind directions. The geographic pattern of the paleowinds reveals an anticyclonic circulation 600–800 km in radius, which is typical for anticyclones of the Southern Hemisphere. Such a condition would have been frequent in Pampas during the Late Holocene (Fig. 4; Iriondo, 1999).

Some extra-Pampean areas have correlative evidence of sand mobilization. For example, sediments of a parabolic dune field associated with the fluvial belt of the Uruguay River (eastern Entre Ríos province) were dated by TL into 1.2 ± 0.2 kyr B.P. (Iriondo and Kröhling, 2008). OSL ages of ca. 2.5 and 0.9 kyr B.P. of the Médanos Negros dune field (La Rioja province) indicate repeated Late Holocene dune reactivation events (Tripaldi and Forman, 2007). An eolian sand covering alluvial fan gravels of Médanos Grandes dune field (San Juan province) was OSL dated by those authors into 2.7 ± 0.1 kyr B.P.

Iriondo and García (1993) estimated for the Late Holocene a relatively homogeneous semiarid climate over the entire plain, with precipitation of about 300–400 mm/yr and larger temperature range than today, low water-tables and an absence of the Chaco forest and wetlands in Corrientes and southern Paraguay. The discharge of the Paraná River decreased significantly, indicated by a migration upstream of the estuarine conditions (Iriondo, 2004). Fernández and Romero (1984) cited evidence of dry steppe vegetation during this period. Tonni (1985) concludes arid or semiarid conditions on the basis of mammal faunas in Buenos Aires province. Also Salemme and Miotti (1987) deduced for that province that the Late Holocene fauna was typical of the Central and Patagonian Dominio indicating arid conditions extended to 1 kyr B.P.

It is known that frosts are connected with cold anticyclones moving towards tropical regions over Pampas (Müller et al., 2003, 2005; Müller and Berri, 2007). Cold surges are associated with surface anticyclogenesis east of the Andes (Lupo et al., 2001). Otherwise, dry conditions over Argentina are associated with positive anomalies over the continent (principally at low levels), high circulation index and an enhancement of Westerlies during the warm season. Patterns related to the cold season reflect high pressure at the surface and the enhancement of the Pacific and weakening of the Atlantic Anticyclones (Alessandro and Lichtenstein, 1996; Barrucand et al., 2007). An important subsidence is assumed due to the intense positive anomaly centered over the area affected by droughts (Labraga et al., 2002; Barrucand et al., 2007). The months with rainfall deficit were concurrent with the strengthening of the south-tropical anticyclone in the eastern Pacific, abnormally high pressure in central and northern Argentina and the development of a cyclonic anomaly in the southwest Atlantic (Labraga et al., 2002). Many studies, conducted all over the world, have considered the ENSO phases to explain wet and dry periods, but this is not necessarily the dominant forcing factor in Argentina. The analysis of the dry cases in relation to ENSO phases revealed that the great majority of dry months in the Pampas have occurred under neutral conditions (Barrucand et al., 2007).

The geological evidence correlates with the present patterns shown above and could be interpreted as generated by the intensification of the passage of migratory anticyclones moving from southeast Pacific over the Pampas (Müller et al., 2005) and provoking advection of cold air and blocking the circulation of South Atlantic humid air masses (Fig. 5), during the Late Holocene.

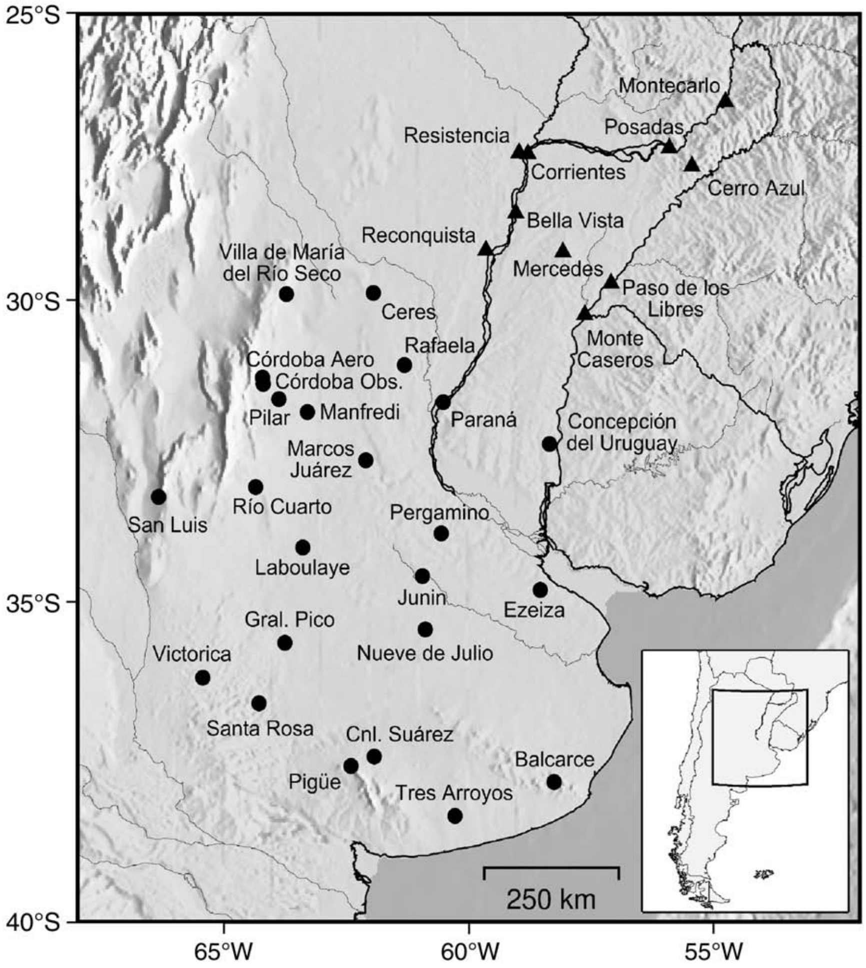

Fig. 6. Distribution of meteorological stations considered in this contribution. Data were obtained from the Servicio Meteorológico Nacional (SMN) and the Instituto Nacional de Tecnología Agropecuaria (INTA). Full circles correspond to stations selected for analyzing extreme dry periods. Full triangles represent stations with anomalous rainfall data (above 2000 mm/yr).

Table 1
Precipitation and temperature data for the Feb./86–Jan.87 period corresponding to the stations located in the northeastern region of Argentina (with precipitation above 2000 mm/yr).

SMN-INTA stations	Annual precipitation (mm/yr)	Mean temperature (°C)	Normal value (°C)	Mean temp. deviation (°C)	Maximum temperature (°C)	Normal value (°C)	Max. temp deviation (°C)	Minimum temperature (°C)	Normal value (°C)	Min. temp deviation (°C)
Mercedes	2249.7	20.8	19.9	0.9	26.0	25.3	0.7	15.5	14.3	1.2
Bella Vista	2140.2	21.2	20.8	0.4	25.9	26.0	−0.1	17.0	15.7	1.3
Reconquista	2128.0	20.6	19.9	0.7	25.8	25.5	0.3	15.9	14.6	1.3
Cerro Azul	2666.5	21.9	21.3	0.6	27.0	26.4	0.6	16.8	16.2	0.6
Montecarlo	1986.8	21.6	21.6	0.0	27.5	27.5	0.0	15.7	15.2	0.5
Monte Caseros	1969.3	20.02	19.3	0.7	25.8	25.3	0.5	15.5	14.3	1.2
Resistencia	2220.0	21.8	20.9	0.9	27.6	27.1	0.5	16.8	15.5	1.3
Paso de los Libres	nd	20.2	19.8	0.4	25.8	25.6	0.2	15.5	14.4	1.1
Posadas	nd	22.0	21.3	0.7	27.9	27.5	0.4	17.4	16.2	1.2
Corrientes	2105.0	21.9	21.2	0.7	27.2	27.0	0.2	17.3	15.7	1.6
Average	2183.2	21.2	20.6	0.6	26.7	26.3	0.3	16.3	15.2	1.1
Standard deviation	218.7	0.7	0.8	0.3	0.9	0.9	0.3	0.8	0.8	0.3

Previously, the pattern of wind directions over Pampas had been related to the minor analogue seasonal anticyclone structure, which appears during the summer in the high troposphere of the Bolivian Altiplano (Bolivian High) (Iriondo and García, 1993).

5. Identification of extreme periods in the twentieth century

Meteorological data from 50 stations in Argentina (SMN — Sevicio Meteorológico Nacional and INTA — Instituto Nacional de Tecnología Agropecuaria) were processed in order to identify modern analogues (with instrumental register) of the Holocene Climatic Optimum and the Late Holocene climates (Fig. 6). The amount of precipitation was considered the main indicator, assuming here that the mobilization of eolian sand occurs below the threshold of 400 mm/yr (Late Holocene environment). Large ergs are located in zones with less than 250 mm of precipitation (with a great variability in inter-annual precipitation), although for southern Africa the margin of the active dunes oscillates between 100 and 150 mm (Lancaster, 1981; Wilson, 1973; Mainguet et al., 1980). From numerous data, Goudie (1992) estimates that, when the mean precipitation exceeds 100–300 mm, the vegetation is sufficiently effective in limiting the dunes' movement. Likewise, a threshold of 2000 mm/yr and mean temperatures higher than 20 °C were considered in this contribution for the general mobilization of iron oxides in superficial sediments (Holocene Climatic Optimum environment). Kemp (1985) and Barron and Torrent (1986) relate soil rubefication in well-drained soil (not derived from red parent materials) to an increase in hematite. In Brazil hematite forms in place of goethite where the mean annual temperature exceeds 17 °C, mean annual precipitation exceeds mean annual evapotranspiration by 900 mm or more, and the soil organic matter is less than 3% (Kämpf and Schwertmann, 1983).

The instrumental record series begins in the year 1900 for precipitations and in 1961 for temperatures and other parameters. Therefore, we considered the 1961–1993 series for defining mean conditions. On that basis, gauging data beyond the thresholds of 2000 and 400 mm/yr were selected.

A statistical study undertaken produced by García and Ghietto (1996) defined extreme hydrological years for 50 meteorological stations located to the north of 40° lat. S. A more systematic approach was adopted by Larese and Kröhling (2005), who identified extreme events based on processing of monthly precipitation data in a grid-point format. Those antecedents together with raw data permitted us to register and analyze other significant meteorological parameters for construction of typical scenarios of both periods.

5.1. Results

5.1.1. Holocene Climatic Optimum analogue

Representative extreme humid periods are: 12 months between February of 1986 and January of 1987 and 12 months between October of 1997 and September of 1998.

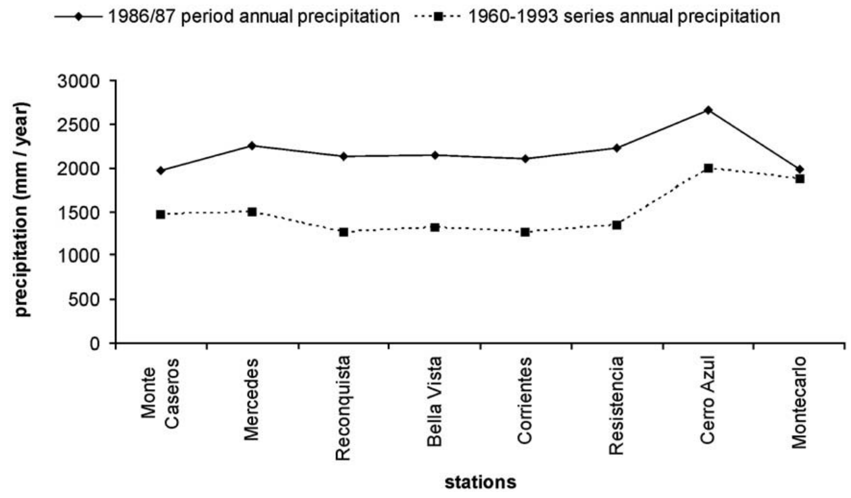

Fig. 7. Annual precipitation of the Feb./86–Jan./87 humid period in selected gauging stations. Ca 500 mm/yr precipitation above normal values can be observed for meteorological stations located in the northeastern area (see Fig. 6).

Table 2
Absolute temperatures, frost frequencies and relative humidity data of five stations included in Table 1 (Feb./86–Jan.87 period).

SMN station	Max. annual record (°C)	Max. annual deviation (°C)	Min. annual record (°C)	Min. annual deviation (°C)	Frost frequency (n°/yr)	Frost frequency deviation (n°/yr)	Relative humidity (%)	Deviation (%)
Mercedes	40.0	−2.1	0.0	3.6	nd	nd	nd	
Bella Vista	39.3	−2.7	4.4	6.4	0	−7	79.3	4.5
Reconquista	38.6	−3.9	2	6.7	15	−7	89.2	12.2
Cerro Azul	36.6	−4.8	2.1	6.0	3	−5	75.0	
Montecarlo	37.2	−4.2	−0.4	5.2	1	−3	80.0	
Average	38.3	−3.5	1.6	5.6	5	−5	80.9	8.4
Standard deviation	1.4	1.1	1.9	1.2	7	2	6.0	5.4

In the Feb./1986–Jan./1987 period, ten gauging stations were found with precipitation above 2000 mm/yr (Table 1 and Fig. 7). Such stations are located outside but near the Pampas (Fig. 6). For the Oct./1997–Sep./1998 period, four stations show precipitation values above that threshold.

According to Berri (1998), the 1997/98 period experienced a strong influence of ENSO-El Niño phenomenon. As a consequence, the 1986/87 humid extreme is a better analogue for synoptic conditions linked to the influence of the South Atlantic Anticyclone (neutral conditions).

The Feb./1986–Jan./1987 period (Table 1) shows that mean temperature was 21.2 ± 0.7 °C, 0.6 ± 0.3 °C above mean values, considering the 1961–1993 series. The maximum annual temperature was 26.7 ± 0.9 °C and the deviation oscillates 0.3 ± 0.3 °C with respect to average values. Minimum annual temperature is 16.3 ± 0.8 °C, 1.1 ± 0.3 °C above mean values. Otherwise in a lesser quantity of stations (5), maximum absolute temperature is 38.3 ± 1.4 °C, 3.5 ± 1.1 °C lower than normal values (Table 2). The absolute minimum record is 1.6 ± 1.9 °C, 5.6 ± 1.2 °C higher than mean values (Table 2). Thermal amplitude is smaller than normal years, because minimum annual temperature increases more than maximum ones (Fig. 8). Larger differences in monthly temperatures occur in winter (Fig. 9). Frost frequency is lower than the average record of the series (Table 2) and relative humidity is above mean values. Only one datum of mean wind velocity was found in Reconquista station (7.3 km/h, 0.3 km/h less than average).

At Concordia station (Oct./97–Jun/98 period) evaporation reached 798.9 mm (123 mm below the average for the 1961–1993 series). For the same period, mean wind velocity of 6.1 km/h was registered in Bella Vista, Reconquista and Concordia stations.

In conclusion, a typical scenario for the Holocene Climatic Optimum period in the Pampean region is characterized as follows:

1. Mean annual precipitation ca. 2200 mm
2. Mean temperatures around of 21 °C, less than 1 °C higher than today
3. Mean maximum annual temperatures around 27 °C
4. Mean minimum annual temperatures around 16 °C, close to 1 °C higher than today
5. Thermal amplitude smaller than today, virtually without frosts.

5.1.2. Late Holocene analogue

The period from January to December, 1962, was the most extreme dry period of the instrumental record. Table 3 shows precipitation data between 300 and 400 mm/yr in four stations located in Southern Pampas; unfortunately other significant parameters were not registered. In consequence, such parameters were analysed in the Apr.–Nov./1988 period that is another characteristic extreme dry period, with large spatial influence. The results obtained for the dry periods are in accordance with those reached by Malaka and Nuñez (1980) (1962 drought) and Minetti et al. (2007) (1975–76 and 1988–89 droughts), by using monthly, three-month period and annual drought indices.

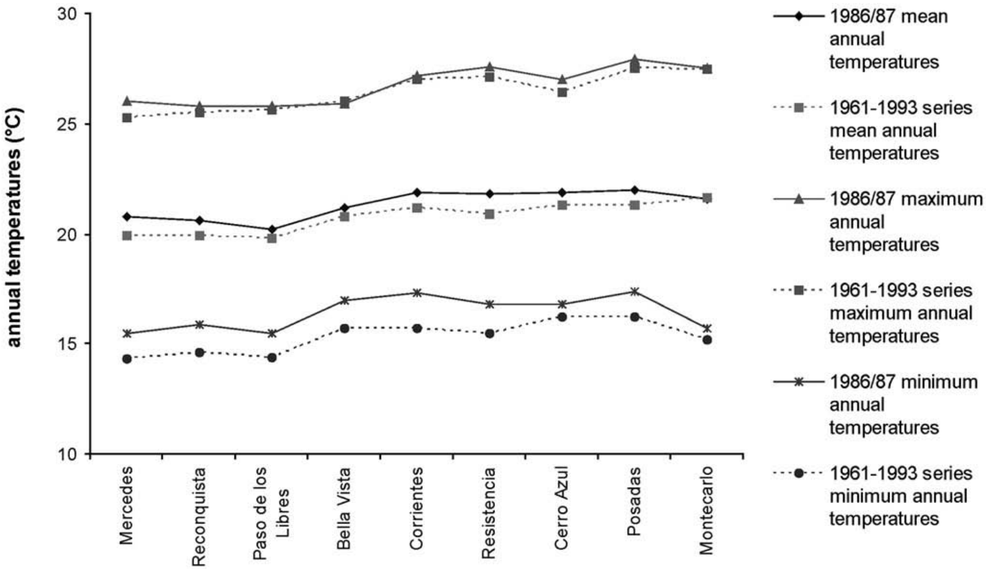

Fig. 8. Spatial variations of mean temperatures in a humid period (Feb./86–Jan./87). Observe that minimum annual temperatures increase faster than maximum ones.

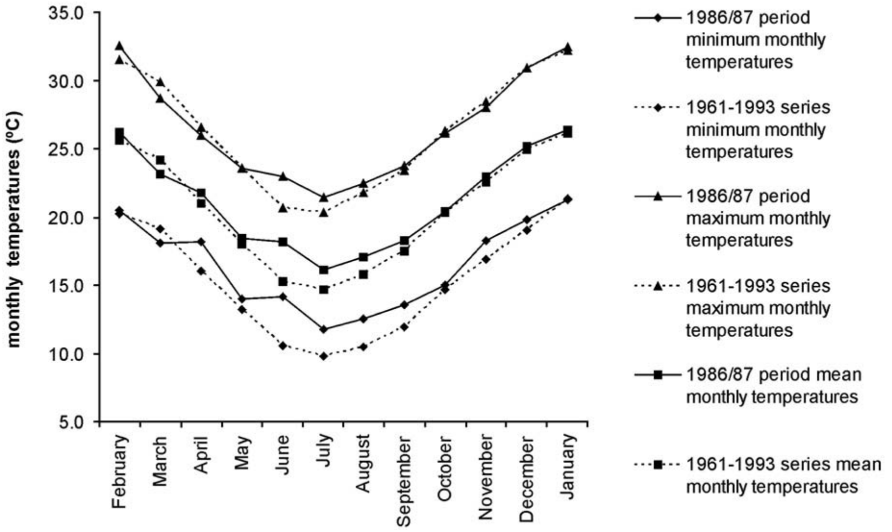

Fig. 9. Seasonal variations of monthly temperatures in a humid period (Feb./86–Jan./87), based on data from 10 stations with precipitation above 2000 mm/yr. Higher departures respect to mean values (1961–1993 series) are observed in cold season (JJAS), particularly for minimum temperatures.

The Jan.–Dec./1962 dry period shows (Table 3) that the mean temperature is 15.2 ± 1.2 °C, 0.7 ± 0.1 °C above the average for the 1961–1993 series, maximum annual temperature is 22.1 ± 1.6 °C, 0.7 ± 0.1 °C above the mean value and minimum annual temperature is 7.9 ± 0.6 °C (−0.1 ± 0.3 °C below the average).

The Apr.–Nov./1988 dry period (Table 4) indicates for 21 stations from the Pampas: a) mean temperature is 0.6 °C lower than the mean values of the Present climate; b) maximum temperature is near normal conditions; c) minimum temperature is markedly lower (1.2 °C lower than mean values); d) thermal amplitude is higher than

Table 3
Main meteorological parameters of the driest period registered (year 1962).

SMN-INTA stations	Annual precipitation (mm/yr)	Mean annual temperature (°C)	Mean temp. deviation (°C)	Max. annual temperature (°C)	Max. temp deviation (°C)	Min. annual temperature (°C)	Min. temp deviation (°C)
Santa Rosa aero	357.0	16.2	0.7	23.8	0.9	8.1	−0.5
Victorica — LP aero	335.9	16.3	0.6	–	–	8.7	0.1
Pigüe aero	352.0	14.0	0.6	20.6	0.5	7.5	0.1
Coronel Suárez aero	333.0	14.4	0.9	22.0	1.7	7.4	0.1
Average	344.5	15.2	0.7	22.1	1.0	7.9	−0.1
Standard deviation	11.8	1.2	0.1	1.6	0.6	0.6	0.3

Table 4
Precipitation and temperature data for the Apr.–Nov.1988 period taken from stations in the Pampas region.

SMN-INTA stations	Annual precipitation (mm/yr)	Mean temperature (°C)	Normal value (°C)	Mean temp. deviation (°C)	Maximum temperature (°C)	Normal value (°C)	Max. temp deviation (°C)	Minimum temperature (°C)	Normal value (°C)	Min. temp deviation (°C)
Pigüe aero	633.3	9.8	10.4	−0.6	17	16.6	0.4	3.6	4.9	−1.3
Tres Arroyos	552.3	10.5	11.1	−0.6	17.2	17.1	0.1	5.1	6.1	−1.0
Balcarce	759	10.2	11	−0.8	16.2	16.5	−0.3	4.4	5.7	−1.3
Coronel Suárez aero	607.7	9.8	10.5	−0.7	17.1	16.9	0.2	2.5	4.8	−2.3
Victorica — LP aero	552.5	12.4	12.6	−0.2	20.4	20.1	0.3	4.7	5.8	−1.1
Santa Rosa aero	611.0	11.4	12.2	−0.8	19.3	19.6	−0.3	4.9	5.8	−0.9
Gral. Pico aero	779.0	12.5	13	−0.5	19.7	19.9	−0.2	5.7	6.7	−1.0
Nueve de julio	830	12.6	13.3	−0.7	19	19.5	−0.5	6.4	7.6	−1.2
Ezeiza aero	874	12.8	13.5	−0.7	19.1	19.3	−0.2	6.9	8.1	−1.2
Junin aero	721.3	12	12.9	−0.9	19.1	19.5	−0.4	6.2	7.5	−1.3
Laboulaye	729.7	12.4	13.3	−0.9	20.2	20.8	−0.6	5.7	7.1	−1.4
Pergamino INTA	881.3	13	13.6	−0.6	19.8	19.9	−0.1	6.5	7.7	−1.2
San Luis aero	498.2	14	14.3	−0.3	21.4	21.5	−0.1	7.7	8.1	−0.4
Río Cuarto	825.0	13.2	12.7	0.5	22	20.3	1.7	7.1	8.4	−1.3
Marcos Juárez	698.3	13.1	14.2	−1.1	20.9	21.3	−0.4	6.3	8.2	−1.9
Pilar	571.6	14.1	14.5	−0.4	21.9	21.7	0.2	7	7.8	−0.8
Paraná	949.0	14.4	15.3	−0.9	20.4	21.2	−0.8	9.6	10	−0.4
Córdoba aero	721.7	14.1	14.8	−0.7	nd	nd	nd	7.1	8.5	−1.4
Córdoba observ	675.1	15	15.6	−0.6	22.6	22.8	−0.2	8.8	9.6	−0.8
Va. María del R. Seco	603.4	14.7	15.8	−1.1	23.6	23.2	0.4	7	8.3	−1.3
Ceres	649	15.6	16.5	−0.9	23.4	23.3	0.1	9.2	10.6	−1.4
Average	701.1	12.7	13.4	−0.6	20.0	20.1	0.0	6.3	7.5	−1.2
Standard deviation	123.2	1.7	1.7	0.4	2.1	2.1	0.5	1.8	1.6	0.4

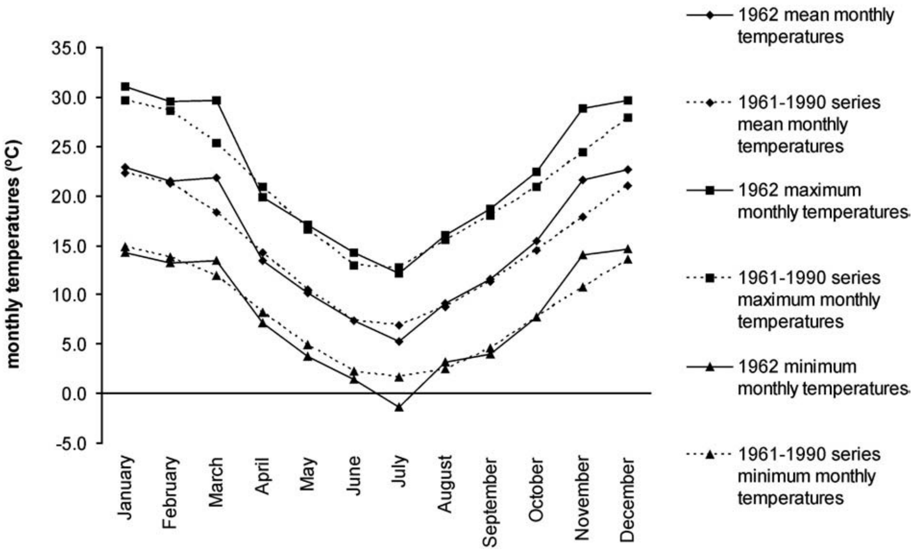

Fig. 10. Seasonal variations of monthly temperatures in the driest period (year 1962), based on data from 4 stations with precipitation below 400 mm/yr. Positive departures with respect to mean values (1961–1990 series) are observed in warm season (ONDJFM) and negative departures in cold season (AMJJAS), in the last case, particularly for minimum temperatures.

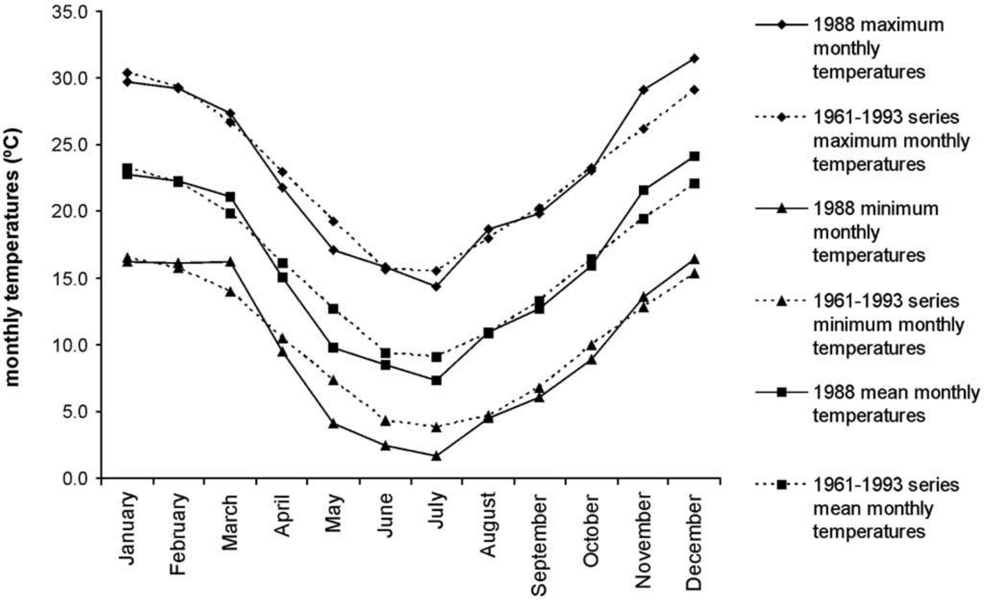

Fig. 11. Seasonal variations of monthly temperatures in a dry period (Apr.–Nov./1988), based on data from 21 stations with precipitation below mean values (1961–1993 series). Positive departures are observed in warm season (ONDJFM) and negative departures in cold season (AMJJAS), in the last case, particularly for minimum temperatures.

normal years; e) frost frequency is the highest in most stations within the 1961–1993 series records.

Figs. 10 and 11 display the seasonal variation of the data for both dry extremes studied. In the dry/cold season (winter), temperatures (particularly the minimum values) tend to decrease; on the contrary, temperatures rise in the humid/warm season (summer). When precipitation is lower than 400 mm/yr (year 1962) the tendency of summer dominates with respect to the dry season one (Fig. 10). In that period, maximum and mean annual temperatures were higher than in normal years.

Table 5
Main meteorological parameters of six stations in the central-eastern region (Apr.–Nov.1988 period).

INTA stations	Precipitation annual (mm/yr)	Evaporation (mm/yr)	Mean annual temp (°C)	Deviation (°C)	Max. annual temp (°C)	Deviation (°C)	Min. annual temp (°C)	Deviation (°C)
Manfredi	563.5	nd	13.8	−0.4	29	3	2	−4.2
Rafaela	636.3	876.2	15.9	−0.6	nd	nd	nd	nd
Paraná	844.4	nd	14.4	−1.2	20.7	−0.3	8.6	−1.9
Conc.del Uruguay	1016	nd	13.6	−1.5	20.2	−0.7	7.2	−2.4
Bella Vista	725.1	nd	20.7	2.1	23.4	−0.2	11.5	−2.2
Reconquista	904.6	nd	16.1	−1.4	22.6	−0.5	10	−2.1
Average	781.7		15.8	−0.5	23.2	0.3	7.9	−2.6
Standard deviation	170.8		2.6	1.3	3.5	1.5	3.6	0.9

Table 6
Complementary meteorological parameters of the stations included in Table 5 (Apr.–Nov.1988 period).

INTA stations	Max. record (C°)	Deviation (C°)	Min. record (C°)	Deviation (C°)	Relative humidity (%)	Deviation (%)	Frost frequency	Deviation (%)	Wind velocitiy at 2 m (km/h)	Deviation (km/h)
Manfredi	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Rafaela	39	nd	−9.0	nd	64.3	−9.9	56	27	nd	nd
Paraná	nd	nd	−5.5	0	68.8	−4.2	10	6.3	8.7	−0.2
Conc.del Uruguay	33.8	−3.8	−3.5	0.9	nd	nd	66	23	8	−0.2
Bella Vista	40.4	−0.1	−0.9	1.1	70.5	−4.9	17	10.5	nd	nd
Reconquista	42.2	0	−8.5	2.5	77.1	−0.4	45	23	8.4	0.8
Average	38.9	−1.3	−5.5	1.1	70.2	−4.9	38.8	18.0	8.4	0.1
Standard deviation	3.6	2.2	3.4	1.0	5.3	3.9	24.4	9.0	0.4	0.6

Despite exceeding 400 mm rainfall (Table 5), the central-eastern region presents during such a period, higher frost frequency with minimum absolute temperatures and lower relative air humidity. Additional mean wind velocity data (Reconquista station) suggest more intense winds during dry periods (Table 6).

Finally, a typical scenario for the Late Holocene was:

1. Mean annual precipitation ca. 350 mm/yr
2. Mean temperatures values of 15 °C
3. Maximum annual temperatures of 22 °C
4. Minimum annual temperatures of 8 °C
5. Important shifts in minimum temperatures in the dry season (lower than normal)
6. Monthly maximum and mean temperatures higher than today
7. Thermal amplitude larger than today
8. Probably, higher quantity of frost per year, stronger winds, lesser relative air humidity and major evaporation rates if compared with humid climate extreme.

6. Conclusions

The following conclusions can be drawn:

- Classical geological proxies have global validity and can be advantageously applied in climatic reconstructions of the Late Quaternary.
- Both indicators chosen here (dune fields and red soils) are simple products of external forcing factors, free of biological and ecological complexities.
- Climatic extremes during the twentieth century represent normal meteorological structures of the Holocene Climatic Optimum period (warm/humid) and the Late Holocene period (dry/cold).
- Both past climates involved major differences in the precipitation/potential evapotranspiration ratio, while temperatures changes were relatively modest.
- The typical Holocene Climatic Optimum scenario for the Pampas was: mean temperatures slightly higher than during the Present climate (1961–1993 series), mainly produced by a clear increase in minimum (larger differences in winter); smaller thermal amplitude; low occurrence of frosts; dominantly convective rains (mean annual precipitation ca. 2200 mm.); frequent intense storms; highly positive hydrological balance.
- Characteristic parameters of the Late Holocene were: mean temperatures of the dry season lower than those of the instrumental record, minimal values markedly lower (larger differences in the dry season), with frequent frosts, thermal amplitude higher than normal, scarce rains (mean annual precipitation ca. 350 mm) with negative hydrological balance.

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