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Soil water surplus and ENSO events during the last humid period in Argentine Pampean flatlands

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Abstract: Daily soil water balances are estimated for the period 1951–2006 in the Pampean flatlands. Daily soil water surplus is the major output with their annual trends, being analysed because of their harmful effects on crop's harvest and floods. Soil water surplus trends were analysed founding positive trends, although only two stations were statistically significant at probability level of 95%. Differing phases of ENSO – using the multivariate ENSO index (MEI) – have differing impacts on rain and soil moisture conditions. The probabilities of occurrence of predetermined soil water surplus and hence flood risk are calculated and mapped.

Keywords: Argentina; Pampean flatlands; soil water balance; soil water surplus; trend; ENSO; El Niño-Southern Oscillation; probabilities of soil water surplus; water table; autumn soil water surplus; agriculture region.

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1 Introduction

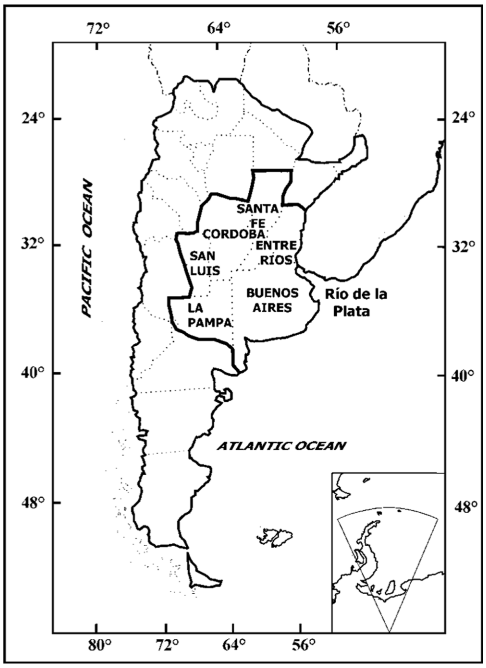
The main Argentine agricultural and cattle raising region has an area of 840,000 km^2 and is located in the Pampean flatlands (Figure 1) of Buenos Aires, Santa Fe, Córdoba, La Pampa, San Luis and Entre Ríos provinces.

The limits of the Pampean flatlands are not clearly defined because they involve phytogeographical, geomorphological, agronomic and economic parameters, which are not always coincident. They comprise a natural plain with natural pasture, now highly modified for human use. Even in the non-irrigated areas there have been many technological improvements, particularly in the central-eastern portion. The agricultural limits are advancing towards the north, west and southwestern areas, so the limits are dynamic. The climate of the area is temperate and humid, with warm summers and cool winters. Mean annual temperatures oscillate between 13°C and 16°C, with the warmest month (January) reaching 20–23°C, and the coldest month (July) varying between 7°C and 9°C. Annual precipitation ranges from 1000 mm in the north-east to 700 mm in the south-west were the climate is sub-humid.

The vertical hydrological fluxes of rainfall and evapo-transpiration are of more concern in regions of limited relief, like the study area, than horizontal surfaces and sub-surface flows. Soil water surplus occurs during periods of precipitation exceeding evapo-transpiration. During such periods, once soil storage capacity is achieved, the soil water table is elevated. Eventually the surplus water is unable to infiltrate because the water table is so close to the surface, a common occurrence in many low-lying areas of the Pampean flatlands. The water table rises to the surface, thereby increasing the flood potential and the area of lakes, ponds and surface impoundments.

Historically, the west of the region is characterised by long periods of water deficit, persistent droughts and high temperatures, interspersed with periods of heavy rainfall culminating in heavy floods. These periodic processes limit livestock and agricultural production in potentially usable areas, and endanger regional urban centres. Such a variable hydrological system also causes uncertainties that hinder investments, such as the adoption of new agricultural technologies and integrated development of the flatlands to realise their full potential.

Figure 1 Studied area



This situation has become increasingly common during the last decades as a result of increased precipitation, mainly in summer and over the western area (Castañeda and Barros, 1994; Minetti and Vargas, 1997; Rusticucci and Penalba, 2000; González and Barros, 1998; Quintela et al., 1989; Forte Lay and Troha, 1992).

Kruse et al. (2001) and Forte Lay et al. (2007) have described the relationships between precipitation, evapo-transpiration, soil water storage, soil water surplus, soil water deficit, water table, subsurface and surface runoff under different scenarios in northwest of Buenos Aires province, and have demonstrated that there is a good temporal relationship between water table levels and water surplus.

Several studies show the strong relationship between ENSO and meteorological elements such as temperature and precipitation, in Argentina (e.g., Tanco, 1994, Barros et al., 2000, Barros and Silvestri, 2002; Forte Lay and Aiello, 2001). Heavy rains and, consequently, floods are more possible during El Niño years in the studied area. La Niña is associated with low precipitation rates.

However, a few papers have analysed the relation between ENSO and soil water storage, which, according to Forte Lay and Spescha (2001), Spescha and Forte Lay (2002) and Scarpati et al. (2004, 2007) is very important in the Pampean region.

Soil water content is very important for maize and soybean crops. For maize, the water content during December and January defines the yield, and, for soybean, the soil water moisture during late summer, particularly in February.

2 Objective

The objectives of this paper are, therefore, to analyse the trend of soil water surplus during the last decades and the relationship between autumn soil water surplus and ENSO in Pampean flatlands of Argentina.

3 Materials and method

Figure 1 describes the general setting of the studied area.

Daily precipitation data, for the period 1950–2006, were provided by the National Meteorological Service (63 meteorological stations) and by the National Institute of Agronomic Technology (13 meteorological stations). Normal mean monthly reference evapo-transpiration for the period 1961–1990, was calculated by the Penman-Monteith method (Allen et al., 2004).

The spatial and temporal variability of the soil water storage was examined using the Forte Lay and Aiello (1996) method, which permits the estimation of the soil water content and its anomalies. It is based on Thornthwaite and Mather daily soil water balance method, using measured precipitation and daily mean reference evapo-transpiration.

For the statistical study, the series of water surplus data obtained were adjusted, following Forte Lay and Troha (1992), by means of the theoretical normal cubic-root probability distribution.

El Niño-Southern Oscillation is the most important coupled ocean-atmosphere phenomenon causing global climate variability in inter-annual time scales. In this paper, ENSO events are defined according to the MEI (Wolter, 2007) based on the six main observed variables over the tropical Pacific: sea-level pressure (P), zonal (U) and meridional (V) components of the surface wind, sea surface temperature (S), surface air temperature (A), and fraction of the sky total covered (C). These are published and updated as bimonthly MEI values (in 1/1000 of standard deviations), starting December 1949/January 1950. Fifty-seven bimonthly observations between 1950 and 2006 were used in the study. As all values are normalised for each bimonthly season, values may still change very slightly with each update and the consequent recalculation of the mean and variance.

Wolter (2007) proposes the following scheme for determining different ENSO phases by employing terciles of the ranked MEI values:

$$\textit{La Niña (weak to strong)}: \quad 1 \le \text{ranking} \le 19$$
$$\textit{Near-normal or neutral}: \quad 20 \le \text{ranking} \le 38$$
$$\textit{El Niño (weak to strong)}: \quad 39 \le \text{ranking} \le 57.$$

The divisions were used here and the bimonthly December – January observations were selected as predictors for the ENSO phase of the next autumn.

Eight meteorological stations: Río Cuarto (33° 07′ S 64° 14′ W, 421 m), Marcos Juárez (32° 42′ S 62° 09′ W, 114 m), Rosario (32° 55′ S; 60° 47′ W 25 m), Gualeguaychú (33° 00′ S 58° 37′ W, 21 m), General Pico (35° 39′ S; 63° 56′ W 140 m), Pehuajó (35° 49′ S 61° 54′ W, 86 m), Las Flores (36° 02′ S 59° 08′ W, 36 m), and Dolores (36° 21′ S 57° 44′ W, 9 m), were considered to study the variations of soil water surplus for the 1950–2006 period. These stations represent two rough transects following W–E lines through the central region of the study area.

The distribution and annual trend were calculated for the period 1950–2006 and the significance of trends was calculated using the Mann-Kendall test, and values for several probability levels (50, 20, 10, 5 and 2%) of soil water surplus were calculated for the period 1970–2006.

The different ENSO events between 1962 and 2006 are listed in Table 1.

Table 1 Values of the Multivariate ENSO Index (MEI) corresponding to ENSO events between 1962 and 2006

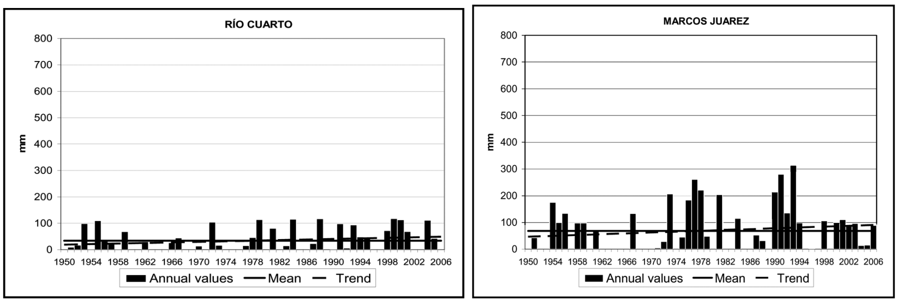
ENSO events	*Years*
La Niña	1962–1963–1965–1968–1971–1972–1974–1976–1985–1989–1996–1999–2000
Neutral	1967–1970–1975–1981–1982–1984–1986–1990–1991–1994–1997–2001–2002–2004–2005–2006
El Niño	1964–1966–1969–1973–1977–1978–1979–1980–1983–1987–1988–1992–1993–1995–1998–2003

Finally, for three stations, a test of hypotheses and significance for small samples (16 cases with El Niño and La Niña with 13 cases) was done where the null hypothesis was tested H_0: $\mu_0 = \mu_a$ (mean surplus of El Niño years μ_0 is not different from mean surplus of La Niña years μ_a) against alternative hypotheses H_1: $\mu_0 > \mu_a$ (mean surplus of El Niño years μ_0 is greater than mean surplus of La Niña years μ_a in a tail test (unilateral).

4 Results

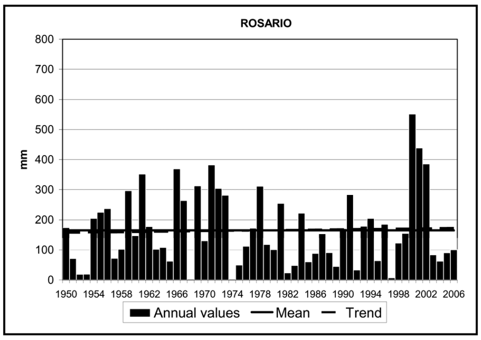
The initial analysis identified that increasing trends in annual soil water surplus are evident at all stations. Figure 2(a)–(d), identify the first used transect: Río Cuarto, Marcos Juárez, Rosario and Gualeguaychú; and Figure 2(e)–(h) the second transect: General Pico, Pehuajó, Las Flores and Dolores.

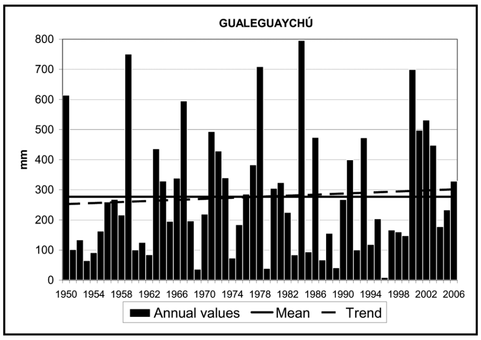
Figure 2 Annual values, and mean and trend of soil water surplus in: (a) Río Cuarto (Córdoba province); (b) Marcos Juárez (Córdoba province); (c) Rosario (Santa Fe province); (d) Gualeguaychú (Entre Ríos province); (e) General Pico (La Pampa province); (f) Pehuajó (Buenos Aires province); (g) Las Flores (Buenos Aires province) and (h) Dolores (Buenos Aires province)



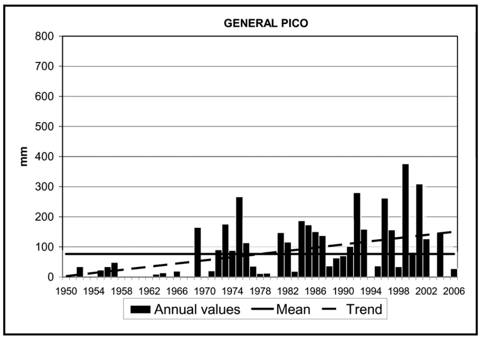
(a) (b)

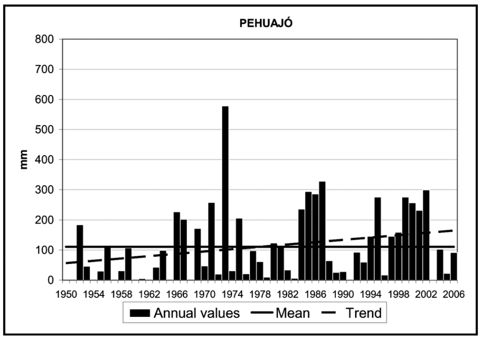
Figure 2 Annual values, and mean and trend of soil water surplus in: (a) Río Cuarto (Córdoba province); (b) Marcos Juárez (Córdoba province); (c) Rosario (Santa Fe province); (d) Gualeguaychú (Entre Ríos province); (e) General Pico (La Pampa province); (f) Pehuajó (Buenos Aires province); (g) Las Flores (Buenos Aires province) and (h) Dolores (Buenos Aires province) (continued)



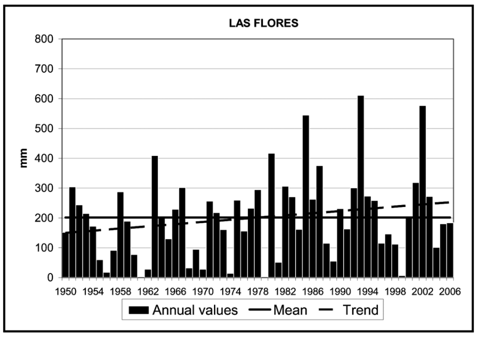


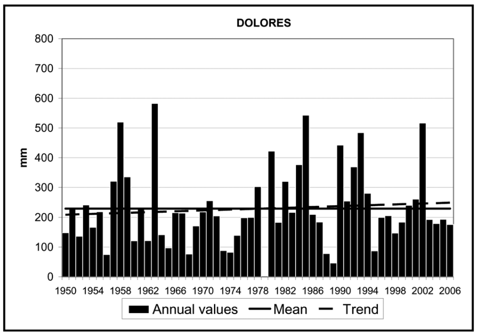
(c) (d)





(e) (f)





(g) (h)

Despite the fact that growing trends were found in all the analysed stations, with values from 26.3 mm every ten years at General Pico, up to just 2.8 mm every ten years in Rosario, the Mann-Kendall test found statistically significant trends at 95% likely only in two of them in the western part of the second transect: General Pico and Pehuajó (Table 2).

Table 2 Results of Mann-Kendall test for soil water surplus trends

Station	*Mann-Kendall test for the trend*						
	n cases	mm/*10 years*	*P value*	*Confidence levels p = 95%*		τ (Tau)	*Significance*
Río Cuarto	57	5.4	867.0	+0.178	–0.178	0.086	No
Marcos Juárez	57	7.8	899.0	+0.178	–0.178	0.127	No
Rosario	57	2.8	786.5	+0.178	–0.178	–0.014	No
Gualeguaychú	57	8.7	854.0	+0.178	–0.178	0.070	No
Gral. Pico	57	26.3	1079.5	+0.178	–0.178	0.353	Yes
Pehuajó	57	19.3	992.0	+0.178	–0.178	0.243	Yes
Las Flores	57	18.4	896.5	+0.178	–0.178	0.123	No
Dolores	57	7.2	837.0	+0.178	–0.178	0.049	No

This is the consequence of the increase in the amount of precipitation during the last decades and it is more remarkable in the second transect. This area experienced a different land use for this event.

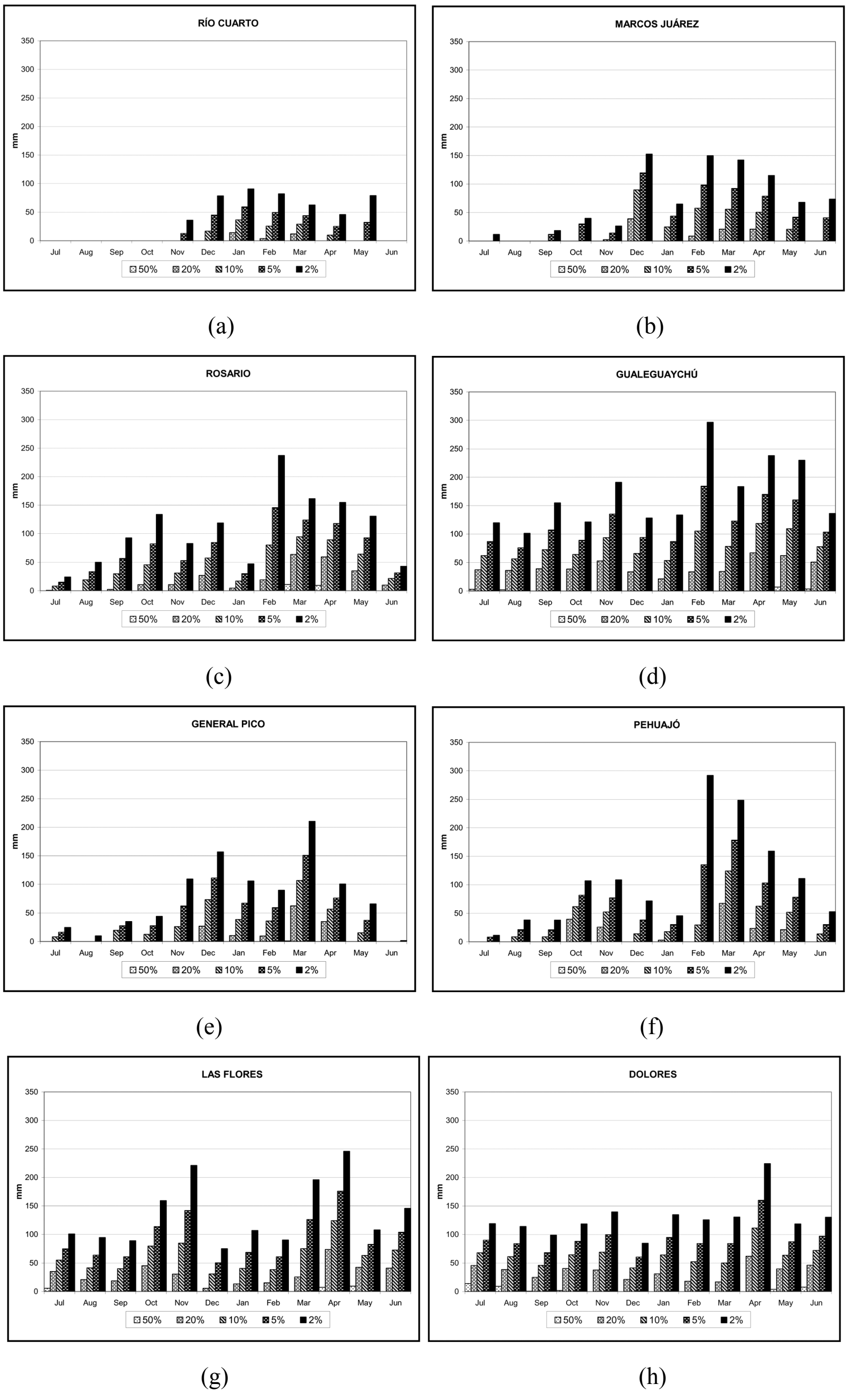
Figure 3(a)–(h) present the soil water surplus corresponding to various probabilities of occurrence for all the selected stations. The comparison emphasised the different characteristic of each station. The probability of 50% represents the median situation.

Río Cuarto (Figure 3(a)), the most north westerly station, presents the lowest surplus for the selected probabilities. The major periods of soil water surplus occur at mid summer and early autumn (January, February, March), and only for low probabilities in other months (November, December, April and May). This distribution is representative of the west and northwest areas of the Pampean flatlands, with a peak precipitation in summer (Canziani et al., 1992) and the highest seasonal evapo-transpiration at that time.

Pehuajó (Figure 3(f)) represents the central area of the Pampean flatlands, and has higher values of soil water surplus at the various probability levels in autumn, particularly in March. However, February has high values for low probabilities and there is a secondary peak in spring months. The area located around this station (northwest of Buenos Aires province and surroundings) is a great plain, in an environment with vertical water movements, a minimum slope (~0.1 m/km^{-1}), and is furrowed by minor topographic sandy forms in a prevailing north-south direction that limits the displacement of the surface waters. It is, therefore, a very sensitive area to floods in periods with water surplus, especially when the water table is near to the surface as happened during the year 2001, a neutral year.

Dolores (Figure 3(h)) represents an area with a fairly uniform precipitation regime. The values of soil water surplus are higher than the other two mentioned stations above, and of the greatest impact due to the low regional gradient leads to the detention of rainwater. The surplus is biggest in autumn, especially in April. It represents too, the depleted area of the Salado River basin (Scarpati et al., 2002).

Figure 3 Soil water surplus values that are exceeded for certain probabilities (%) of occurrence in: (a) Río Cuarto (Córdoba province); (b) Marcos Juárez (Córdoba province); (c) Rosario (Santa Fe province); (d) Gualeguaychú (Entre Ríos province); (e) General Pico (La Pampa province); (f) Pehuajó (Buenos Aires province); (g) Las Flores (Buenos Aires province) and (h) Dolores (Buenos Aires province)



Over the same period, mainly for economic reasons, the area under soybean cultivation has been increasing, replacing other summer crops (maize and sunflower), throughout the Pampean flatlands. This crop exacerbates the hydrologic situation, increasing soil water storage and water surplus because of the smaller volume of its roots as compared to maize, sunflower and prairie (Basualdo and Forte Lay, 2004).

For the Pampean area as a whole, a clear trend is apparent in the spatial distribution of autumn soil water surplus (Figure 4). In this figure the median value for the period 1962–2003, using all the 76 meteorological stations, can be seen. One of the results is that the surplus values of 150 mm in the north east diminished to the west and south in central east Córdoba province and southern of Buenos Aires province where the water surplus is 0 mm. The depressed area, close to Dolores, has an autumnal soil water surplus close to 50–75 mm, which is very important for its impact on the flood regime of this area (Scarpati et al., 2002). Entre Ríos province has a rolling pampas topography and good drainage, so the autumnal soil water surplus is not so important in producing local floods but can make the harvesting of summer crops more difficult. The north eastern area of Santa Fe and south western area of Entre Ríos have watersheds that are affected by periodic flooding. When the period used to determine median surplus values is separated into El Niño (Figure 5) and La Niña (Figure 6) phases, distinct differences appear. During years having the El Niño phase, median soil moisture surplus values reached over 150 mm in the extreme northeast of Entre Ríos province.

Figure 4 Spatial distribution of mean autumn soil water surplus (mm)

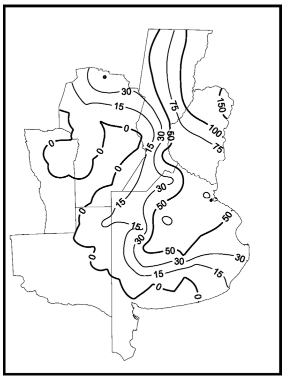


Figure 5 Spatial distribution of autumn soil water surplus (mm) during El Niño phase

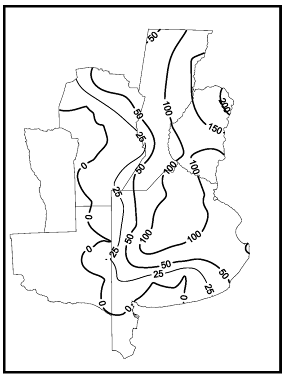
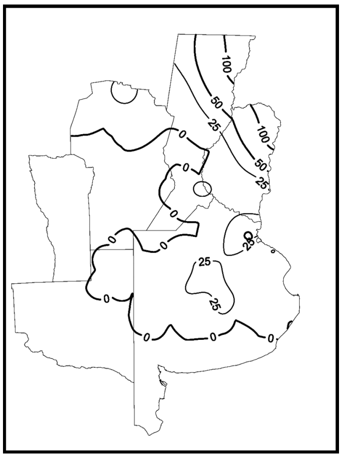


Figure 6 Spatial distribution of autumn soil water surplus (mm) during La Niña phase



The expected differences in median surplus values between the two phases (Figure 7) reveal generally larger soil water surpluses during El Niño.

Figure 7 Spatial distribution of the difference (mm) between the two typical ENSO phases

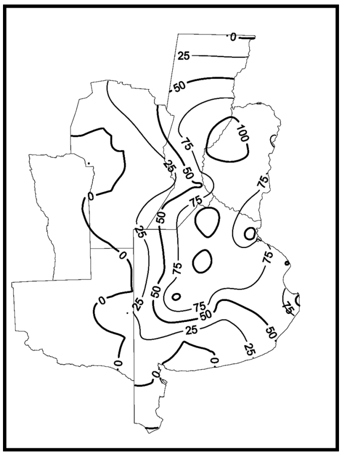
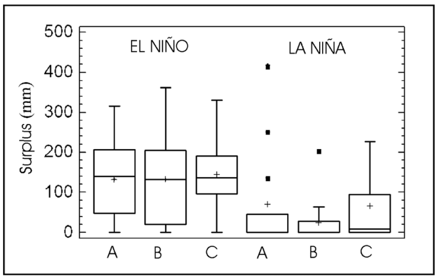


Figure 8 shows the Box Plot analysis for three meteorological stations Paraná (31°44′ S, 60°32′ W), Pergamino (33°54′ S, 60°35′ W) and Nueve de Julio (35°27′ S, 60°53′ W). The median soil water surplus is represented by the smallest box in the plot. In Pergamino and Nueve de Julio cases it is verified that years under El Niño have higher probability of soil water surplus than years under La Niña, and El Niño phase has the highest variability. To test the hypothesis and significance of mean differences: H_0: $\mu_0 = \mu_a$ against H_1: $\mu_0 > \mu_a$, Parana not had a significant result for $p = 95\%$; instead, on Pergamino and Nueve de Julio, the null hypothesis H_0 was rejected to the same level of significance.

Figure 8 Empiric distribution of autumn soil water surpluses for three selected meteorological stations Paraná (A), Pergamino (B) Nueve de Julio and (C), using Box Plots



5 Conclusions

Seasonal soil water surpluses are more important during the autumn in the Pampean flatlands. Values of the surplus amount increase towards the north east of the region, but their impacts are most noticeable in areas with depleted levels and/or those without good surface runoff. Annual and autumn soil water surpluses have displayed positive trends during the last 57 years, corresponding to increased precipitation, although statistically significant trends appeared only in the western part of the second transect appeared statistically significant trends Water surpluses occur in almost all years, but they are particularly marked during the El Niño phase of ENSO, and least during La Niña. Differences between the two phases are most evident in northern of Buenos Aires and west of the Entre Ríos provinces, reaching values of 100 mm. ENSO phase control the magnitude and spatial extent of soil water surplus, but it is a hazard which occurs regardless of the ENSO event.

The south and south western areas are generally free of risk during all ENSO events, while the north eastern area (Santa Fe, Entre Ríos and north eastern of Buenos Aires) reveal high risks of saturated soils and floods during autumn, especially during El Niño years.

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