A comparison of temporal variability of observed and model-based pan evaporation over Uruguay (1973-2014)

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Abstract. This study analyzes variability and trends of atmospheric evaporative demand (AED) across Uruguay in the past four decades. Changes were assessed using pan evaporation measurements from 10 meteorological stations and compared to PenPan model calculations, which is a physically based model that employs meteorological data as input. Results demonstrate a high agreement between the observed AED and those estimated from the PenPan model. Both observations and model estimations agree on a high interannual variability in AED, though being statistically insignificant ($p > 0.05$) at seasonal and annual scales. Given that AED shows high sensitivity to changes in relative humidity and sunshine duration, as a surrogate of solar radiation, the lack of significant trends in the AED observations and estimations over Uruguay can be linked to the insignificant trend found for these climate variables for the period from 1973 to 2014. This is the first study that reports Pan evaporation trends for this part of the

world, helping to infill gaps for mid-latitude southern hemisphere areas, which are poorly represented in Pan evaporation trends.

Key-words: Reference Evapotranspiration, Evaporation, Penman-Monteith, Uruguay, South America, Climate Change.

1. Introduction

Atmospheric evaporative demand (AED) is a key meteorological variable, with strong agronomic and hydrological impacts (Wang and Dickinson, 2012). AED is the maximum quantity of water that would evaporate from a surface under unlimited water availability and no-resistance factors from soil and vegetation (Katerji and Rana, 2011; such as pan evaporation and potential evaporation) or when resistance factors are not temporally varying (as is the case for FAO-56 crop reference evaporation). AED can be observed by pan evaporation and can be estimated using fully-physically based formulations of potential evaporation (Roderick et al. 2009; McVicar et al., 2012a and b). Following the seminal ‘combination equation’ work of Penman (1948) fully-physically forms of potential evaporation are those that explicitly include the four main meteorological drivers of AED (i.e., air temperature, radiation, atmospheric humidity and wind speed) in their formulations to fully capture the AED responses of the radiative and aerodynamic components. The use of fully-physically based AED models has been widely advocated (e.g., Donohue et al 2010; McKenney and Rosenberg, 1993; McVicar et al 2012b; Roderick et al 2007). Given there are regional differences in the baseline climatologies and trends of air temperature (e.g., Jones et al., 2012), radiation (see Wild 2009 and the references therein), atmospheric humidity (e.g., Willett et al 2008; Durre et al 2009) and wind speed (see McVicar et al 2012b and the references therein) means some studies report increasing AED trends (e.g., Vicente-Serrano et al.,

2014a; Abtew et al., 2011; Tabari et al., 2012; Yu et al., 2016) while others report decreases AED trends (e.g., Peterson et al., 1995; Roderick and Farquhar, 2004. McVicar et al 2012a). The ‘four-meteorological-variable / regionally-specific’ framework to understand AED dynamics contrasts with the ‘single-meteorological-variable / global’ view that given global warming AED would increase by about 7% per 1°C according to the Clausius-Clapeyron relationship (due to the incremental capacity of air to store water under warming conditions). Implicit in the ‘single-meteorological-variable / global’ approach is the notion that only air temperature trends are large enough to impact AED; clearly not the case everywhere (see McVicar et al 2012b). This means when assessing AED dynamics the ‘four-variable / regionally-specific’ framework is required.

Few studies have compared temporal variability and trends in AED from pan evaporimeters and physically-based models (exceptions are Chattopadhyay and Hulme, 1997; Hobbins et al., 2004; Roderick et al 2007; Johnson and Sharma, 2007; Johnson and Sharma, 2010; Abtew et al., 2011; Azorin-Molina et al., 2015). As pan evaporimeter measurements are infrequent and uncertain in large regions of the world (Abtew et al., 2011), physically-based models can replicate AED observations, providing longer and homogeneous time series for assessing AED trends and variability. Nonetheless, given that the estimation of AED using physical models is based on different meteorological variables, it is possible to assess the role of each of these variables in the evolution and variability of AED.

In regions and countries whose economy depends heavily on agriculture, AED changes may have strong socioeconomic impacts. Positive trends of AED may increase plant

respiration rates, actual evapotranspiration, plant water stress and ultimately xylem embolism, especially when soil water availability is not enough to supply the actual demand (McDowell et al., 2008). These impacts may also include a reduction/loss of crop yields, increase rates of forest drying and trigger forest fires. Even if the water availability is enough to supply the extra water required due to AED increases, it can affect the availability of water for other uses (e.g. the generation of electricity in hydroelectric plants, which is of key importance in Uruguay).

Uruguay is one of the countries with a higher percentage (82.4%) of the territory covered by crops and forages to feed livestock (mainly cattle and sheep; <http://www2.mgap.gub.uy/DieaAnterior/Anuario2015/DIEA-Anuario2015-01web.pdf>; last access on 1st February 2017). Agriculture and livestock represent together more than 10% of the gross domestic product (GDP) of the country, contributing to more than 12% of the workforce and making Uruguay one of the main exporters of primary products (e.g. soybeans, wheat and rice) in the world. In Uruguay, climate variability and drought episodes cause drastic damages to the agricultural sector (Hareau et al., 1999; Grosskopf et al., 2015). A representative example is the severe drought in 2008, which caused an estimated loss of 450 million US dollars, which is equivalent to 1.5% of the Uruguanean GDP. Since high AED may increase drought severity impacts (Vicente-Serrano et al., 2014b; Hunt et al., 2014; Otkin et al., 2014), but also affect the severity of flood events via actual evapotranspiration and soil moisture conditions (Lana-Renault et al., 2014), assessing recent AED variability and changes in Uruguay deserves investigation. Also assessing AED trends is severely limited in mid-latitude southern hemisphere and Pan evaporation trends are rare for South America (see

McVicar et al., 2012b) where 422.5 million people live (2015 estimate; UN, 2015) and is projected to grow to 500 million people in 2050 (UN, 2015).

In this study, we analyzed variability and trends of the AED in Uruguay from 1973 to 2014 using pan evaporation measurements and calculations based on a fully-physically based model that employs meteorological data as input. The objectives of this study are to: (i) quantify and compare the temporal variability of the observed pan evaporation and those derived model estimations; (ii) determine annual and seasonal AED trends; and (iii) to evaluate the contribution of each climatic variable in explaining AED variability in Uruguay.

2. Data and methods

We employed meteorological data from 10 observatories, provided by the *Instituto Nacional de Investigación Agropecuaria* (INIA) and the *Instituto Uruguayo de Meteorología* agrometeorological networks (INUMET) (Table 1). The earliest available agrometeorological station was established in 1973, while the last two stations were installed in 1991. Spatially, the meteorological stations are evenly distributed across the country, whose topography is very homogeneous, with an elevation lower than 300 m (Figure 1). Additionally, the spatial distribution of these stations is representative of the main climatic conditions across Uruguay, which are generally temperate, with rainfall evenly distributed across the whole year (Peel et al., 2007). Daily records of maximum and minimum air temperatures, relative humidity, wind speed, sunshine duration (used to estimate solar radiation following Allen et al., 1998) and Class-A pan evaporation were used. A maximum of 3 missing days per month was allowed to obtain mean monthly values of each meteorological variable. Otherwise, the entire month was set as

missing. Overall, the available time series of the different variables were almost complete, with less than 10% of missing months for all stations over the variable-length study periods (as seen in Table 1).

The monthly series were checked carefully for quality assurance and homogenization. Following Vicente-Serrano et al. (2010), the quality control procedure compared the rank of each data record with the average rank of the monthly observations at the remaining 9 stations. We used a relative homogeneity method (HOMER – HOMogenization software in R), which compares each candidate series with the rest of available series (Mestre et al., 2013). HOMER is a semi-automated methodology that combines a fully automatic joint segmentation with a partly subjective pairwise comparison. HOMER corrected the existing inhomogeneities and inserted missing monthly values using the method of Mestre et al. (2013; specifically their Equation (8)). Among the different existing models that estimate AED from meteorological data (e.g. Penman, 1948; Allen et al., 1998), we selected the PenPan model (Rotstayn et al., 2006), which coupled the radiative component of Linacre (1994) and the aerodynamic component of Thom et al. (1981). PenPan estimates monthly and annual Class-A pan evaporation. Previous studies indicated good agreement between Pan evaporation observations and PenPan calculations over Australia (Roderick et al., 2007; McMahon et al., 2013), China (Liu et al., 2011; Yang and Yang, 2012), US (Hobbins et al., 2012), India (Padmakunari et al., 2013), and Spain (Azorin-Molina et al., 2015).

According to Rotstayn et al. (2006), PenPan is defined as:

$$E_{PenPan} = \frac{\Delta}{\Delta + 2.4\gamma} \frac{R_{NPan}}{\lambda} f_{Pan}(u)(e_s - e_a)$$

$f_{Pan} = 1.202 + 1.62u_2$ where E_{PenPan} is the pan evaporation (mm day^{-1}) calculated by the PenPan model, Δ is the slope of the vapour pressure curve ($\text{kPa } ^\circ\text{C}^{-1}$), γ is psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), λ is the latent heat of vaporization (MJ Kg^{-1}), $e_s - e_a$ is vapour pressure deficit (kPa), u_2 is the average daily wind speed at 2m height (ms^{-1}) and R_{Npan} is the net radiation at the Class-A pan evaporimeters, whose calculation is provided in the Supplementary Material 6 of McMahon et al. (2013). Following this equation, we calculated PenPan evaporation using the meteorological data in each of the ten available stations across Uruguay.

Given the close location of the different meteorological stations and the low elevation differences between them, we created two series representing the observed Pan and modelled PenPan evaporation across Uruguay. Given the varying length of the series, we obtained the monthly series of the standardized anomalies for each series, with respect to a 1992-2014 reference period. The series of anomalies were averaged and transformed into evaporation units (in mm months^{-1}) using the mean and the standard deviation for the 1992-2014 common period. Regional series for the input meteorological variables were then obtained according to the same approach implemented for Pan and PenPan evaporation.

To assess changes in seasonal and annual Pan and PenPan evaporation, as well as the input meteorological variables (e.g. relative humidity, air temperature, wind speed and sunshine duration), we used the nonparametric Mann-Kendall statistic. Autocorrelation was considered in the trend analysis applied to the different series and climatic variables. The modified Mann-Kendall trend test was used, which returns the corrected p-values after accounting for temporal pseudor replication (Hamed and Rao, 1998; Ye

and Wang, 2004). To quantify the magnitude of change in Pan and PenPan, we used linear regression analysis between the series of time (independent variable) and the evaporation series (dependent variable). The slope of the regression measures the change per year. Finally, to account for the possible contribution of different climatic variables (i.e. relative humidity, mean air temperature, wind speed and sunshine duration) to the evolution of AED, we assessed the links between the seasonal and annual time series of observed Pan and modelled PenPan evaporation and those of the climatic variables using correlation analysis.

3. Results

3.1. Spatial consistency of evaporation across Uruguay

Figure 2 shows two density plots that illustrate the Pearson correlation coefficients between the annual and seasonal time series of Pan evaporation (Figure 2a) and PenPan evaporation (Figure 2b) recorded between all the different pairs of meteorological stations. As depicted, the correlations are generally positive and high among the stations, either for Pan observations or PenPan estimations. The only exception was found for the austral winter season (Jun-Jul-Aug), particularly for Pan evaporation. Similarly, the regional series calculated for the whole country show high agreement with the individual stations for both Pan observations and PenPan estimations (Figure 3). These results reinforce the robust utility of the regional series in the analysis.

3.2. Temporal variability of evaporation in Uruguay

Figure 4 reveals a strong agreement between the monthly regional Pan observations and PenPan estimations, calculated for the whole of Uruguay. The series show a similar interannual variability, with almost identical magnitudes. The agreement at the annual timescale is also revealed at the seasonal scale, where there is a high agreement between

the regional Pan observations and PenPan estimations series for all seasons between 1973 and 2014 (Figure 5). Although PenPan generally shows higher values than Pan observations, both indicate close interannual variability. The correlation between Pan observations and PenPan estimations is high (> 0.86) at the seasonal and annual timescales. The only exception is the austral winter, where the correlation did not exceed 0.78, though being statistically significant at the 95% confidence level. Note: due to the low contribution of winter to the total annual evaporation, the lower winter correlation did not adversely impact the annual timescale correlation ($r=0.89$). The strong relationship found with the regional series is also recorded at the individual stations (Table 2). Although our analysis covers different periods as a function of the availability of meteorological data at each station, the correlations were strong and statistically significant ($p<0.05$), particularly during the austral summer (Dec-Jan-Feb).

Overall, the nationwide regional series did not show statistically significant trends over the whole period (1973-2014) either for Pan observations or PenPan estimations; however, PenPan significantly increased during summer and annually when considering the 1992-2014 reference period (Table 3). In contrast, this significant increase was not observed for the Pan observations regional series. Trends in individual stations did not reveal any clear pattern, with the exception of two INUMET stations (Treinta y tres and Tacuarembó), which exhibited dominant negative and positive trends for Pan observations and PenPan estimations, respectively. The statistically insignificant ($p>0.05$) trends dominated in the remaining stations across Uruguay.

3.3. Relationship with driving meteorological variables

Similar to Pan observations and PenPan estimations, seasonal and annual evolution of the meteorological variables did not show any noticeable trends between 1973 and 2014 (Figure 6 and Table 4). Results reveal a moderate increase in minimum air temperature, which is statistically significant ($p < 0.05$) during spring and annually. Annual relative humidity showed a dominant insignificant decrease, which was statistically significant only in summer. There were no noticeable changes in the annual and seasonal series of wind speed and sunshine duration.

The lack of significant trends in the analyzed meteorological variables is consistent with the observed changes in Pan observations and PenPan estimations, confirming that these four variables strongly determine the interannual variability of both observed and estimated AED. Figures 7 and 8 illustrate the relationship between annual and seasonal regional series of Pan observations and PenPan estimations and the different regional meteorological variables. The relationships are quite similar considering both the observed Pan and modelled PenPan evaporation series. As depicted, maximum air temperature was positively correlated with Pan and PenPan evaporation at seasonal and annual scales. In contrast, minimum air temperature showed negative correlations with all variables, albeit with statistically insignificant levels. In comparison to other analyzed variables, relative humidity exhibited the strongest correlations with Pan and PenPan evaporation series at the annual and seasonal scales, mainly with statistically significant ($p < 0.05$) negative correlations. Results also indicate small differences in the magnitude of correlations between Pan and PenPan evaporation. Wind speed showed a positive correlation with Pan and PenPan evaporation, though being statistically significant only in summer and annually. Sunshine duration also exhibited positive and statistically significant associations with both Pan and PenPan evaporation; the

strongest correlations were found annually and seasonally. As expected, we found very few differences when analyzing the series for the individual stations (Tables 5 and 6), stressing a similar behavior for both Pan observations and PenPan estimations. The relative humidity, sunshine duration and maximum air temperature (in this rank) are the variables that better explain the interannual variability of AED across Uruguay over the past four decades.

4. Discussion and conclusion

We present the first analysis of AED variability and trends based on Pan evaporation observations in Uruguay, southern South America. This study has analyzed recent variability and trends in AED over Uruguay using Class-A pan evaporation measurements and estimations by means of a physical model that uses meteorological variables as input. The high agreement found between AED observations and estimations over Uruguay agrees well with the results reported earlier for other regions of the world (e.g. Cohen et al., 2002; Xu et al., 2006; Zhang et al., 2007; Roderick et al 2007; Azorin-Molina et al., 2015). This agreement stresses the capacity of using physical methods for estimating long-term variability and trends in AED. In this context, although some input variables in these physical models are scarce and usually inhomogeneous (e.g. relative humidity, wind speed, and sunshine duration), they are measured much more frequently than Pan evaporation.

For the series analysed here, AED shows a high interannual variability, albeit with statistically insignificant trends at seasonal and annual scales. This result was also obtained using AED rates estimated using the PenPan model. The general results obtained based on the nationwide regional series of Uruguay concur with those found

for the individual 10 meteorological stations employed in this work, suggesting non-noticeable changes in the AED during 1973-2014.

It is difficult to establish regional comparisons with the observed trends in AED found for Uruguay, given that very few studies have analyzed this issue in southern South America. De la Casa and Avando (2016) analyzed crop reference evapotranspiration (ET_o) variability and trends in central Argentina between 1941 and 2010 using Allen et al. (1998). Although covering a longer period, the Argentinian results of De la Casa and Avando (2016) resemble those of Uruguay, with no significant changes in ET_o evolution. They attributed this pattern to the notion that climate variables that determine AED observed in central Argentina have shown insignificant changes. Thus, they indicated that, over the second half of the 20th century, only 10%, 18% and 6% of the central Argentina region exhibited significant changes ($p < 0.05$) in air temperature, relative humidity and wind speed, respectively.

Similar to Argentina, the lack of significant trends in AED observations and estimations over Uruguay can be linked to the insignificant trends found for surface climate variables for 1973-2014. In particular, significant trends ($p < 0.05$) are only found for spring maximum air temperature, annual and spring minimum air temperature (positive) and summer relative humidity (negative). Thus, the temperature series in Uruguay do not show the dominant pattern found at the global scale, characterised by accelerated warming from 1970s to 2000s and hiatus periods from 2000s (e.g., Cahil et al., 2015; Trenberth, 2015).

The studies on trends in surface climate variables in La Plata basin, albeit with longer periods than our study, demonstrate dominant insignificant trends. For example, Ricardo Barros et al. (2015) suggested a warming trend in Argentina of $+0.04\text{ }^{\circ}\text{C decade}^{-1}$, which is lower than the global terrestrial average of $+0.065\text{ }^{\circ}\text{C decade}^{-1}$ during the 20th century (Hartmann et al., 2013). Other studies suggest an opposite trend over the same region. Nuñez et al. (2008) revealed no significant trends in the mean air temperature across Argentina for 1961–2008. Maximum air temperature exhibited a dominant decrease in La Plata basin during the past decades, while a significant increase was only recorded for minimum air temperature (Rusticucci and Barrucand, 2004; Rusticucci and Renom, 2008; Rusticucci, 2012; Tencer and Rusticucci, 2012; Skansi et al., 2013; Marengo and Camargo, 2008). The higher warming trends for minimum than maximum air temperature agree with our results obtained for Uruguay during 1973–2014. Nevertheless, AED variability is not a consequence of the variability of minimum air temperature alone, as correlations were dominantly insignificant in the majority of meteorological stations and seasons of the year. Although AED showed more sensitivity to maximum air temperature in Uruguay, it exhibited no significant changes during the analyzed period. Similar to maximum air temperature, AED showed high response to interannual variability in relative humidity and sunshine duration; these variables also did not show any significant trends over Uruguay. Likewise, sunshine duration almost showed a steady evolution in southern South America during the past four decades (Raichijk, 2012) also in opposition to the dominant dimming and brightening periods recorded in the last decades globally (Wild, 2012).

Although no significant trends were recorded for the AED series of Uruguay, a strong interannual variability was recorded both at seasonal and annual scales. This strong

interannual variability can probably be linked to the influence of different atmospheric circulation patterns like the ENSO, which strongly controls air temperature, precipitation and cloudiness in the region (e.g. Rosenbluth et al., 1997; Rusticucci and Vargas, 2002; Marengo and Camargo, 2008; Rusticucci et al., 2016). In Uruguay, Rusticucci and Renom (2008) demonstrated that air temperature extremes have strong correlation with the Pacific Sea Surface Temperature (SST). Nonetheless, other mechanisms may also affect climate variability in the region, including the frequency of blocking high pressure systems (Alessandro, 2014), changes in the mean regional Hadley circulation (Freitas and Ambrizzi, 2015), the existence of barotropic anticyclonic anomalies in the Southern Atlantic and low pressure centers over South America and the Southern Annular mode (Renom et al., 2011; Rusticucci et al., 2003). Accordingly, further research to define the atmospheric mechanisms responsible for the variability and changes of AED in the region should be conducted.

Although our study has shown no generalized significant trends in the climate conditions over Uruguay for 1973-2014, which explain the lack of significant trends of AED, the most recent climate change models predict a strong air temperature increase in the region at the end of the 21st century. Over La Plata basin, Barros et al. (2015) indicated that average air temperature may increase by 3.5°C at the end of this century. If all other meteorological variables remained constant through time, this warming trend could increase future regional AED, which would reinforce the severity of climate droughts associated with decreased and more temporally variable precipitation (Reboita et al., 2014; Cabré et al., 2016). However, to fully understand AED dynamics from a process perspective and recalling the previously introduced ‘four-meteorological-variable / regionally-specific’ framework (compared to the ‘single-meteorological-

variable / global' view) we strongly recommend that future climate change models need to assess changes in all variables governing the AED process. Recalling the general vulnerability of the primary sector and the overall economy of Uruguay to climate variability (Hareau et al., 1999; Wagner et al., 2013; Bucaram et al., 2016), it is highly probable that increased AED would reinforce negative impacts of climatic change in the region.

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Table 1: Main characteristics of the ten meteorological stations.

(Network – Station)	Elevation (meter)	Longitude	Latitude	Period
INIA - TREINTA Y TRES	46	-54.43	-33.26	1973 -2014
INIA - TACUAREMBO	134	-55.98	-31.74	1987 -2014
INIA - SALTO GRANDE	46	-57.89	-31.27	1984 - 2014
INIA - LA ESTANZUELA	20	-57.69	-34.34	1977 -2014
INIA - LAS BRUJAS	41	-56.34	-34.67	1974 - 2004
INUMET- ROCHA	20	-54.31	-34.49	1985 - 2014
INUMET- TREINTA Y TRES	46	-54.39	-33.22	1988 -2014
INUMET - MERCEDES	62	-58.07	-33.25	1991 - 2014
INUMET - TACUAREMBO	134	-55.99	-31.71	1991 -2014
INUMET- SALTO	56	-57.98	-31.44	1985 - 2014

Table 2: Seasonal and annual Pearson's r correlations between Pan and PenPan evaporation series for each meteorological station. Significant correlations at $p < 0.05$ are bolded.

	Annual	Summer (DJF)	Autumn (MAM)	Winter (JJA)	Spring (SON)
INIA-TREINTA Y TRES	0.82	0.91	0.79	0.60	0.71
INIA-TACUAREMBO	0.80	0.84	0.87	0.71	0.74
INIA-SALTO GRANDE	0.89	0.91	0.91	0.77	0.81
INIA-LA ESTANZUELA	0.77	0.89	0.79	0.61	0.72
INIA-LAS BRUJAS	0.78	0.84	0.73	0.61	0.75
INUMET-ROCHA	0.70	0.86	0.62	0.30	0.60
INUMET-TREINTA Y TRES	0.63	0.73	0.70	0.50	0.56
INUMET-MERCEDES	0.67	0.81	0.93	0.14	0.55
INUMET-TACUAREMBO	0.61	0.81	0.75	0.31	0.59
INUMET-SALTO	0.85	0.90	0.82	0.73	0.73

Table 3: Seasonal and annual trends in Pan observations and PenPan estimations corresponding to each meteorological station for the available period of data and for the common period (1992–2014). Only significant correlations at $p < 0.05$ are shown in bold. Annual trends have units of mm/year/available period, and seasonal trends have units of mm/season/available period.

	Pan observations									
	Available period (see Table 1)					1992–2014				
	Annual	Summer (DJF)	Autumn (MAM)	Winter (JJA)	Spring (SON)	Annual	Summer (DJF)	Autumn (MAM)	Winter (JJA)	Spring (SON)
REGIONAL	9.67	1.81	1.92	4.12	-0.70	4.91	15.77	-2.14	-1.81	-6.91
INIA-TREINTA Y TRES	1.12	2.34	0.51	-1.36	-0.37	-13.04	-2.47	-1.16	0.59	-9.99
INIA-TACUAREMBO	-60.94	-12.49	-13.98	-14.65	-17.62	-24.54	6.61	-4.37	-11.68	-15.10
INIA-SALTO GRANDE	-11.14	-18.79	0.63	5.94	3.66	18.11	5.31	7.57	9.15	-3.92
INIA-LA ESTANZUELA	7.79	4.36	1.65	0.01	0.34	26.78	49.94	-7.48	-8.62	-7.05
INIA-LAS BRUJAS	3.38	-0.99	-0.31	3.05	-1.57	41.81	24.75	14.09	6.48	-3.51
INUMET-ROCHA	-12.56	12.69	-7.15	-7.33	-3.86	-8.87	19.32	-9.73	-12.24	-6.21
INUMET-TREINTA Y TRES	-76.17	-39.09	-17.94	-1.46	-20.59	-64.81	-27.99	-17.05	1.25	-21.02
INUMET-MERCEDES	31.52	30.92	0.98	4.63	-2.15	31.52	30.92	1.76	4.03	-5.20
INUMET-TACUAREMBO	-34.93	5.02	-14.89	-18.80	-3.43	-34.93	5.02	-11.15	-21.74	-7.06
INUMET-SALTO	20.88	4.54	-5.19	14.00	9.43	77.05	46.26	6.12	14.66	10.01
PenPan estimations										
	Available period (see Table 1)					1992–2014				
	Annual	Summer (DJF)	Autumn (MAM)	Winter (JJA)	Spring (SON)	Annual	Summer (DJF)	Autumn (MAM)	Winter (JJA)	Spring (SON)

REGIONAL	14.38	7.99	0.46	3.05	5.23	41.90	24.70	3.17	2.86	11.16
INIA-TREINTA Y TRES	12.66	7.01	0.40	1.55	5.39	20.91	11.08	0.23	1.69	7.92
INIA-TACUAREMBO	8.58	14.75	0.21	-2.02	-3.94	39.28	32.42	6.36	0.45	0.05
INIA-SALTO GRANDE	-4.98	-3.01	-1.34	-1.94	1.66	25.39	21.28	2.84	-2.38	3.65
INIA-LA ESTANZUELA	6.52	0.16	-1.53	2.34	3.48	67.95	30.97	8.85	9.31	18.81
INIA-LAS BRUJAS	7.37	1.36	-0.84	3.26	3.60	41.13	16.93	2.84	7.88	13.48
INUMET-ROCHA	12.79	5.69	-0.03	3.56	8.41	14.00	9.04	-2.52	0.80	6.68
INUMET-TREINTA Y TRES	8.31	9.38	-4.02	-4.48	4.98	23.77	23.03	-3.01	-3.67	7.42
INUMET-MERCEDES	42.12	26.36	-2.98	0.81	19.23	42.12	26.36	-2.11	-0.36	18.23
INUMET-TACUAREMBO	74.98	38.91	9.43	8.25	18.41	74.98	38.91	11.34	7.46	17.26
INUMET-SALTO	10.91	2.96	0.53	2.60	5.66	69.48	37.04	6.83	7.47	18.14

Table 4: Magnitude of change (per decade) of regional climate series for Uruguay from 1973 to 2014. Significant trends at $p < 0.05$ are bolded.

	Annual	Summer (DJF)	Autumn (MAM)	Winter (JJA)	Spring (SON)
Max. Temp. (°C)	0.06	0.09	-0.06	0.06	0.15
Min. Temp. (°C)	0.15	0.16	0.10	0.01	0.33
Wind speed (ms^{-1})	0.00	0.01	-0.01	-0.02	0.01
Relative Humidity (%)	-0.10	-0.38	0.00	-0.17	0.19
Sunshine duration (hours)	-0.01	0.04	-0.03	0.01	-0.09

Table 5. Correlations between seasonal and annual regional series of Pan observations and the series of the different meteorological variables. Significant correlations at $p < 0.05$ are bolded.

	INIA - TREINTA Y TRES	INIA - TACUAREMBO	INIA - SALTO GRANDE	INIA - LA ESTANZUELA	INIA - LAS BRUJAS	INUMET-ROCHA	INIMET-TREINTA Y TRES	INUMET - MERCEDES	INUMET - TACUAREMBO	INUMET- SALTO
Maximum air temperature										
Annual	0.48	0.50	0.68	0.48	0.40	0.39	0.39	0.72	0.49	0.73
Summer (DJF)	0.67	0.70	0.83	0.69	0.69	0.69	0.67	0.73	0.69	0.89
Autumn (MAM)	0.59	0.69	0.79	0.40	0.41	0.53	0.61	0.84	0.68	0.70
Winter (JJA)	0.47	0.38	0.33	0.19	0.11	-0.17	0.16	0.29	0.42	0.55
Spring (SON)	0.30	0.16	0.55	0.49	0.25	0.00	-0.08	0.62	0.20	0.52
Minimum air temperature										
Annual	-0.41	-0.37	-0.23	-0.10	-0.32	-0.20	-0.28	-0.19	-0.34	-0.13
Summer (DJF)	-0.47	-0.18	0.08	0.26	0.10	-0.08	-0.37	0.07	-0.20	0.11
Autumn (MAM)	-0.32	-0.27	-0.46	-0.10	-0.23	-0.26	-0.26	-0.30	-0.35	-0.38
Winter (JJA)	-0.02	-0.01	-0.27	-0.23	-0.27	-0.27	0.05	-0.11	0.19	0.09
Spring (SON)	-0.54	-0.59	-0.42	-0.14	-0.44	-0.67	-0.59	-0.17	-0.74	-0.44
Wind speed										
Annual	0.40	0.17	0.26	-0.02	0.42	0.20	0.32	-0.59	0.07	0.38
Summer (DJF)	0.55	0.27	0.30	0.60	0.54	0.33	0.24	0.24	0.25	0.20
Autumn (MAM)	0.15	0.07	-0.37	0.01	0.52	0.24	0.23	-0.32	-0.09	-0.06
Winter (JJA)	0.19	0.15	-0.02	-0.03	0.19	0.15	0.12	-0.40	-0.30	0.10
Spring (SON)	0.04	-0.02	-0.09	-0.06	0.26	-0.07	-0.05	-0.61	-0.02	0.07
Relative Humidity										
Annual	-0.64	-0.85	-0.76	-0.67	-0.57	-0.35	-0.40	-0.60	-0.67	-0.73
Summer (DJF)	-0.83	-0.88	-0.86	-0.80	-0.62	-0.70	-0.57	-0.75	-0.81	-0.92
Autumn (MAM)	-0.42	-0.80	-0.86	-0.67	-0.30	-0.24	-0.53	-0.71	-0.72	-0.79
Winter (JJA)	-0.40	-0.71	-0.68	-0.65	-0.64	-0.28	-0.18	-0.11	-0.20	-0.47
Spring (SON)	-0.70	-0.72	-0.62	-0.62	-0.62	-0.40	-0.52	-0.68	-0.62	-0.71
Sunshine Duration										
Annual	0.63	0.75	0.84	0.65	0.68	0.66	0.40	0.76	0.69	0.82
Summer (DJF)	0.71	0.62	0.71	0.58	0.59	0.62	0.63	0.50	0.60	0.76
Autumn (MAM)	0.63	0.69	0.85	0.61	0.60	0.53	0.41	0.85	0.62	0.78
Winter (JJA)	0.33	0.37	0.64	0.51	0.41	0.38	0.31	0.38	0.27	0.52
Spring (SON)	0.77	0.79	0.77	0.71	0.75	0.90	0.76	0.50	0.79	0.72

Table 6. Correlations between seasonal and annual regional series of PenPan estimations and the series of the different meteorological variables. Significant correlations at $p < 0.05$ are bolded.

	INIA - TREINTA Y TRES	INIA - TACUAREMBO	INIA - SALTO GRANDE	INIA - LA ESTANZUELA	INIA - LAS BRUJAS	INUMET-ROCHA	INIMET-TREINTA Y TRES	INUMET - MERCEDES	INUMET - TACUAREMBO	INUMET-SALTO
Maximum air temperature										
Annual	0.52	0.65	0.75	0.64	0.38	0.67	0.67	0.76	0.73	0.63
Summer (DJF)	0.70	0.86	0.89	0.80	0.73	0.80	0.80	0.91	0.87	0.93
Autumn (MAM)	0.60	0.72	0.85	0.59	0.48	0.67	0.82	0.87	0.75	0.61
Winter (JJA)	0.59	0.54	0.47	0.50	0.50	0.43	0.56	0.67	0.49	0.30
Spring (SON)	0.51	0.50	0.66	0.61	0.62	0.53	0.41	0.80	0.64	0.50
Minimum air temperature										
Annual	-0.34	-0.31	-0.12	0.06	-0.21	0.06	-0.26	0.13	-0.22	-0.17
Summer (DJF)	-0.32	-0.02	0.18	0.31	0.18	0.04	-0.20	0.27	0.01	0.32
Autumn (MAM)	-0.24	-0.46	-0.41	0.03	-0.10	-0.01	-0.20	-0.19	-0.59	-0.45
Winter (JJA)	0.14	0.14	0.06	0.08	0.12	-0.06	0.32	0.42	0.08	-0.06
Spring (SON)	-0.28	-0.44	-0.24	-0.08	-0.14	-0.18	-0.22	0.04	-0.29	-0.33
Wind speed										
Annual	0.58	0.41	0.38	0.17	0.50	0.24	0.05	-0.25	0.63	0.68
Summer (DJF)	0.62	0.42	0.37	0.58	0.58	0.46	0.22	0.45	0.51	0.51
Autumn (MAM)	0.19	0.24	-0.24	0.03	0.43	0.09	0.26	-0.18	0.12	0.19
Winter (JJA)	0.31	0.35	0.32	0.25	0.38	0.13	0.27	0.36	0.55	0.51
Spring (SON)	0.46	0.22	0.07	0.21	0.43	0.35	-0.14	-0.14	0.40	0.51
Relative Humidity										
Annual	-0.75	-0.85	-0.85	-0.89	-0.84	-0.69	-0.78	-0.82	-0.91	-0.83
Summer (DJF)	-0.87	-0.91	-0.93	-0.89	-0.84	-0.71	-0.89	-0.87	-0.89	-0.89
Autumn (MAM)	-0.66	-0.85	-0.91	-0.82	-0.70	-0.70	-0.69	-0.76	-0.93	-0.94
Winter (JJA)	-0.70	-0.83	-0.71	-0.77	-0.67	-0.70	-0.39	-0.55	-0.70	-0.63
Spring (SON)	-0.68	-0.83	-0.82	-0.88	-0.76	-0.72	-0.89	-0.88	-0.81	-0.79
Sunshine Duration										
Annual	0.66	0.86	0.85	0.74	0.76	0.53	0.80	0.64	0.77	0.86
Summer (DJF)	0.74	0.76	0.71	0.69	0.71	0.72	0.84	0.49	0.66	0.63
Autumn (MAM)	0.64	0.85	0.90	0.76	0.73	0.72	0.70	0.80	0.86	0.90
Winter (JJA)	0.44	0.56	0.55	0.62	0.55	0.64	0.20	0.04	0.51	0.62
Spring (SON)	0.72	0.84	0.71	0.78	0.72	0.62	0.76	0.79	0.75	0.80

Figure 1: Topography and the spatial distribution of the meteorological stations (using a ‘Network – Station’ naming convention) used in this study.

Figure 2: Density plots with the Pearson's r correlation coefficients calculated between
a) Pan observations and b) PenPan estimations for all the different pairs of
meteorological stations.

Figure 3: Box-whisker plot with the Pearson's r correlations between the time series of the individual stations and the regional series for the whole Uruguay. The central horizontal line shows the median, the shaded box is defined by the 25th and 75th percentiles, and the whiskers represent the 10th and 90th percentiles.

Figure 4: a) Temporal evolution of monthly values of Pan (Blue) observations and PenPan (Red) estimations calculated for the whole of Uruguay. b) Scatter plot showing the relationship between monthly values of Pan observations and PenPan estimations for the regional series. The dashed line in the right panel indicates the fitted regression line between Pan and PenPan and the black line is the 1:1 line.

Figure 5: Seasonal and annual evolution of regional Pan (Blue) observations and PenPan (Red) estimations calculated for the whole of Uruguay. The Pearson's r value is between the Pan observations and PenPan estimations. The dotted lines correspond to the fitted regression of the series against time as the independent variable and the equations for each provided in the relevant colour.

Figure 6: Seasonal and annual evolution of maximum and minimum air temperatures, wind speed at 2-m, relative humidity and sunshine duration for the nationwide regional series of Uruguay. Dashed lines correspond to the fitted regression of the series, and are defined by the equations shown on each subpart.

Figure 7: Relationship between seasonal and annual regional series of Pan observations and the series of the different meteorological variables. Solid lines correspond to the fitted regression of the series, and are defined by the equations shown on each subpart.

Figure 8: Relationship between seasonal and annual regional series of PenPan estimations and the series of the different meteorological variables. Solid lines correspond to the fitted regression of the series, and are defined by the equations shown on each subpart.