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ENSO EFFECTS ON REFERENCE EVAPOTRANSPIRATION (ETo) AT THE MAIPO RIVER BASIN, CHILE.

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Abstract

The efficient operation of water resources is one of the major challenges in modern society. One of the main characteristics of the hydrological cycle corresponds to its temporal variability, expressed as fluctuations in the precipitation regime as well as modifications in the rates of evapotranspiration as a result of changes in atmospheric conditions. A better knowledge of the relationships between the main components of the hydrological cycle and atmospheric and/or oceanic indices that can be monitored and forecasted, represents useful information for management decisions. In Chile, rainfall variability has been studied and associated to the El Niño-Southern Oscillation concluding that abundant precipitation is observed while el Niño phase is present, and relatively low precipitation is expected in La Niña events. Evapotranspiration, on the other hand, has received little attention by researchers even though there is evidence supporting sea surface temperature anomalies (SSTA) are influencing meteorological variables that play an important role in determining rates of evapotranspiration.
The purpose of this work is to describe the main relationships between reference evapotranspiration (ETo), estimated by means of the Penman-Monteith equation, and the phases of el Niño phenomenon. A weather generator conditioned on El Niño phases is used to generate synthetic series of daily meteorological variables and to get estimates of the main statistical characteristics of the variability of ETo and its association to SSTA. Such knowledge can be used in hydrological forecast and operation of water resources since ETo can be translated into agricultural water demands, and there are skillful models that forecast sea surface temperature conditions in the eastern Equatorial Pacific.

1. Introduction

According to Oram (1989) agriculture represents one of the most weather dependent productive sectors. In addition to that it is also the largest consumer of water resources due to the extensive surface that crops utilize during their development. Rosegrant *et al* (2000) identifies climatic variability and the growing competition for water among economic sectors as two key issues that a modern society has to face when designing efficient water allocation policies.

Crops can be seen as biophysical systems that act capturing resources, such as solar radiation, carbon dioxide, water, and nutrients transforming them into organic compounds that result into the final harvest. During this process the total satisfaction of plant water demands is a fundamental issue because there is a strong link between the amount of water transpired and the biomass accumulated (Chang, 1968 ; Norero, 1999).
The magnitude of this phenomenon is dictated by the meteorological conditions that determine the demand of water by the atmosphere, such as solar radiation, vapor pressure deficit, temperature and wind speed. It is modified by the properties of the soil and the pant since both act on the energy balance, and canopy architecture affects the rate of exchange of matter between the plant and the atmosphere (Norero, 1984).
The correct estimation of crop water requirements is therefore an important step towards the development of efficient water management policies. For such studies researchers and engineers usually rely on empirical equations fed by monthly means of atmospheric variables that are assumed as constant for all years (examples can be found in Doorenbos y Pruitt, 1976; Meza, 1999). The latter assumption neglects temporal variability in evapotranspiration as a consequence of climatic fluctuations, missing the opportunity to incorporate recent advances in medium range weather forecasts and climate forecasts.

1.1 Climate Variability in Chile

El Niño-Southern Oscillation (ENSO) phenomenon has been described as a factor that explains an important fraction of climate variability in several parts of the world. Examples of such correlations are found in the original work of Walker (1923) as well as in recent studies developed by Ropelewski and Halper (1996). The climatic regime of central Chile is exposed to important fluctuations that, up to some extent, can be associated with El Niño phenomenon. Rainfall variability has been studied and associated to the El Niño-Southern Oscillation concluding that abundant precipitation is observed while el Niño phase is present, and relatively low precipitation is expected in La Niña events. Even though there have been studies that describe its influence over independent meteorological variables, there is still a need to extend the investigation addressing the relationships between El Niño and more complex processes that require the integration of climate and agricultural systems. Among them, Evapotranspiration is one of the most interesting because it has a strong link with agricultural productivity and it represents one of the components of the hydrological cycle.

Daily meteorological variables have been studied conditioned on El Niño phases. Maximum, Minimum and Dew Point Temperatures as well as Wind Speed were analyzed by Meza et al (2003). These authors concluded that the influence of El Niño phenomenon is not as marked as in the case of precipitation. However, the precipitation regime does affect other meteorological variables because there are differences between days with and without precipitation. In that sense the El Niño phenomenon will affect daily meteorological variables because it produces changes in the relative frequencies of rainy days. This feature suggests that El Niño phases could affect crop development and plant water demands.

1.2 Background

Vapor flux from a crop can be described as a mass exchange process and approximated by Ohm´s Law. Because water is absorbed by the root system in its liquid phase there is a link between mass and energy fluxes.. Therefore we can express the evaporation rate as:

$$\lambda E = \lambda(\rho_{vs} - \rho_{va})/r_v \tag{1}$$

Where E is the amount of water evaporated (mm day^{-1}), ρ_{vs} is the absolute humidity (kg m^{-3}) in the evaporating surface, ρ_{va} is the concentration of water vapor in the air (kg m^{-3}), and r_v represents the resistance to the water transfer (day m^{-1}).

Potential evapotranspiration is a term that has been coined to indicate the evaporating capacity of an environment. As a way to standardize measurements the term “reference evapotranspiration” (ETo) has been proposed. This concept corresponds to the evapotranspitration of an active dense crop with a height of roughly 10 cm. As in the previous case, it is assumed that the crop does not experience water stress.

Combining energy balance equations, boundary layer theory, and aerodynamic properties of such crop, it is possible to develop an expression to calculate reference evapotranspiration, known as the Penman-Monteith equation (Monteith, 1965, Monteith y Unsworth, 1990).

$$\lambda E = \frac{\Delta\left((R_N - G) + \rho c_p \dfrac{(e_s - e)}{r_h} \right)}{\left(\Delta + \gamma\left(1 + \dfrac{r_c}{r_h}\right)\right)} \tag{2}$$

Here, Δ is the slope of the vapor pressure with respect to temperature between the evaporating surface and the surrounding air (Pa K^{-1}). R_N is the net radiation (J m^{-2} day^{-1}), G represents the soil heat flux (J m^{-2} day^{-1}). ρ is the density of the air (kg m^{-3}). c_p is the specific heat at constant pressure (J kg^{-1} K^{-1}). e_s and e are the saturation vapor pressure and the actual vapor pressure, respectively (Pa). r_h is the aerodynamic resistance (day m^{-1}). γ psicrometric constant (Pa K^{-1}). r_c is the canopy resistance (day m^{-1}).

A detailed analysis of Penman-Monteith equation used to estimate ETo reveals that most of its components are directly related to meteorological variables, and consequently are affected by climatic variability.

1.2.1 Net Radiation

Net radiation is the balance between incoming and outgoing electromagnetic energies at the crop surface. Its value can be calculated using the radiation budget equation.

During cloudy days (and especially days with precipitation) solar global radiation is reduced, in the extreme case only diffuse radiation reaches the surface. For central Chile, the presence of warm sea surface temperature anomalies implies higher frequency of rainy days; consequently one would expect to see a reduction in RG.

In addition to that, the long wave radiation emitted by the atmosphere depends on air temperature , cloud cover and relative humidity.The higher the temperature the larger the amount of radiation emitted. For seasons (years) that show warmer temperature regimes, long wave radiation from the atmosphere could be intensified. The greater the vapor pressure in the atmosphere, the larger the fraction radiation that is emitted by the atmosphere. A similar situation is observed with clouds. Cloudy days have larger emissivities than clear sky days. As in the case of solar radiation, changes in the precipitation regime (especially frequency of rainy days) could affect the value of emissivity, being different among years.

1.2.2 Air density

According to the equation of state (Ideal Gas Law), air density has a dependence on pressure and air temperature. However, its variation is not important for the purposes of estimating ETo.

1.2.3 Saturation vapor pressure

It is the partial pressure of water vapor at the equilibrium state between condensation and evaporation. It is found by integrating Clasius-Clapeyron equation. being a function of temperature

1.2.4 Actual vapor pressure

It is a measure of the partial pressure that is exerted by the actual water content of the air. If this value is lower than the saturation vapor pressure the demand of water by the atmosphere will be higher.

1.2.5 Aerodynamic resistance

This is a parameter that depends on the morphology of the crop but it is modified by wind speed. If wind is blowing with higher intensity, evaporation rate will be greater because it weakens the boundary layer and mass transport is more efficient. As in the case of actual vapor pressure, wind speed was found to vary among El Niño phases (Meza et al., 2003).

It can be concluded that there are several mechanisms by which ETo could be affected by different climatic conditions. It would be theoretically possible to assess the impact of individual changes in these variables only by looking at the Penman-Monteith following a sensitivity analysis approach. However, that kind of analysis does not provide with a useful tool for water or agricultural management operations because says nothing about the likelihood of such changes, especially in relation to observed climatic variability.
It is necessary to identify the proper correlation structure of the meteorological variables involved in the evaporation process, to perform studies of the association of El Niño phenomenon with ETo.

2. Methodological Approach

Trenberth El Niño classification (Trenberth, 1997) was used in this study to assign months in the series 1976-2000 to their correspondent category.
Daily meteorological variables such as precipitation amount, maximum and minimum temperature, dew point temperature, and wind speed were collected and classified according to the ENSO phases (El Niño, La Niña and Normal). It is assumed in this work that stationary condition is satisfied within each month. Meteorological data for the period 1976 to 1999 at the location of Pudahuel provided by the Dirección Meteorológica de Chile was used to fit a weather generator (Richardson, 1981 ; Wilks and Wilby, 1999). Before performing exploratory data analysis and time series analysis, the data set was checked for consistency and outliers were removed. The main characteristics of the weather generator algorithm are presented here:

- **Precipitation occurrence**

The occurrence of rainfall was simulated by a two state first order Markov Chain.

- **Non precipitation variables**

Maximum, minimum and mean daily dew point temperature, as well as mean daily wind speed are represented by a multivariate first–order autoregressive process. The equation that represents the multivariate process can be written as:

$$Z(t) = [A]Z(t-1) + [B]\varepsilon(t) \qquad (3)$$

Where Z(t) is a K-dimensional vector of standard Gaussian variables for today's variables, [A] and [B] are K x K matrices of parameters (here, K = 4). Finally ε(t) is a vector of independent standard normal values.

In the parameter fitting procedure wind speed was sometimes transformed into an approximately Gaussian variable by taking logarithms of its value, this transformation generally results in better parameter estimates (Stedinger, 1980). The means and variances for each month and El Niño classification were calculated. It is convenient to keep the distinction between wet and dry days, and to model the time series process with different parameters representing the precipitation status, because cloud cover associated with precipitation can influence solar radiation as well as the thermal amplitude (Liu and Scott, 2001).

- **Solar radiation**

Solar radiation data is not available in the region under study. Its value has been estimated with empirical equations developed by Bristow and Campbell (1984) and validated for regions of Chile by Meza and Varas (2000). The procedure uses thermal amplitude as independent variable and calculates solar global radiation as a fraction of its Angot value.

Simulation

The weather generator conditioned on El Niño phases was used on a Monte-Carlo mode to generate synthetic series of daily meteorological variables. 500 years of daily meteorological variables are generated for each ENSO phase. To ensure that series are statistically independent, the weather generator was run for 100 times (representing 100 days) before each yearly synthetic series is generated. This procedure allows for different initial precipitation status (wet or dry at day zero) and different initial Gaussian deviates.

The generated series were used to calculate daily values ETo using Penman-Monteith approach (equation 2). The values were added within each month to get estimates of monthly reference evapotranspiration.

3. Results

Table 1 shows the results of an analysis of variance (ANOVA) performed to assess whether ENSO phases have an influence on monthly reference evapotranspiration.

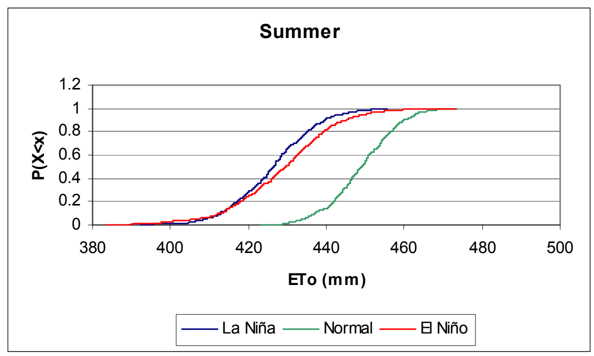
Because of the large sample size (n = 500) all mean values are significantly different.

Table 1. Mean values of monthly reference evapotranspiration (mm), and F value from ANOVA. Critical value (p = 0.05) = 3.00

Month	La Niña	Normal	El Niño	F
Jan	149.93	158.84	158.06	307.54
Feb	125.95	130.50	122.68	301.88
Mar	103.57	105.87	103.98	21.91
Apr	61.00	60.13	53.18	249.56
May	30.76	27.79	26.22	108.34
Jun	16.36	16.19	12.88	205.73
Jul	19.73	19.23	17.15	71.68
Aug	35.00	33.89	32.57	25.88
Sep	52.46	54.71	52.71	17.00
Oct	94.86	98.32	89.98	81.60
Nov	126.21	133.52	122.81	190.87
Dec	150.38	159.66	148.13	383.49

Summer differences in relative terms are less important than the others reflecting that climate does not vary among ENSO phases. Winter differences are more important being in the order of 30% more evapotranspiration during La Niña events mainly because drought conditions are associated with clear sky, higher thermal amplitude, and lower relative humidity. These factors enhance the rate of evapotranspiration or water demand from the atmosphere.

Another important feature of reference evapotranspiration corresponds to the distribution function of the events. The effect of ENSO is reflected not only by producing different mean values but also showing stochastic dominance of one phase over the others. Figure 1 shows the cumulative distribution function assessed using Weibull plotting positions (an empirical way to determine CDF).



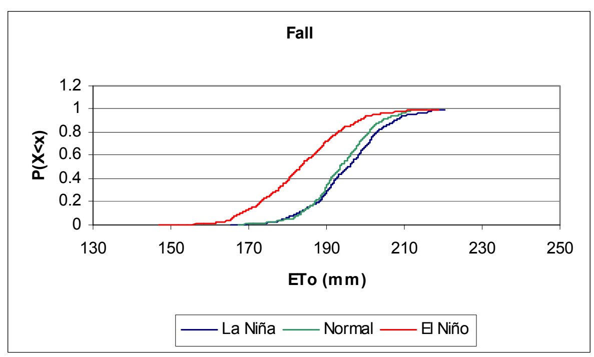
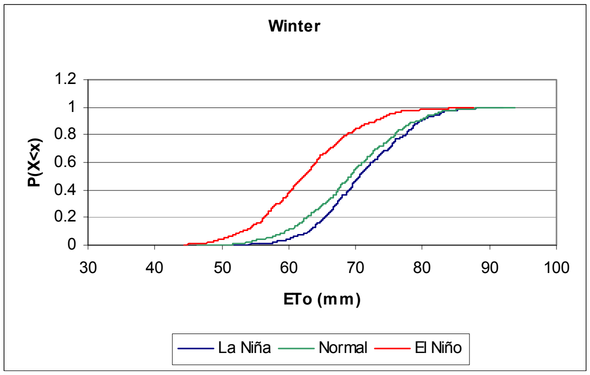


Figure 1. Cummulative distribution functions of seasonal reference evapotranspiration conditioned en ENSO phases for Summer and Fall seasons.



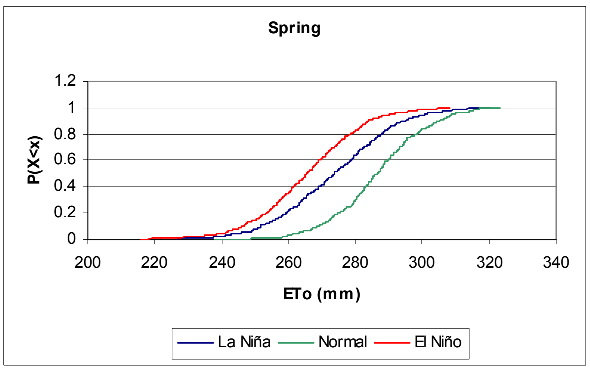


Figure 1 (cont.) Cummulative distribution functions of seasonal reference evapotranspiration conditioned en ENSO phases for Winter and Spring seasons.

Values have been aggregated to show seasonal differences among phases with December, January, February regarded as summer season; March to May as fall season; June to August as winter and September to November as spring.
During summer, Normal years show stochastic dominance over the remaining ENSO phases (i.e. ETo is higher at any cumulative probability) being up to 25 millimeters higher. Since CDF for El Niño years and La Niña years cross each other there is no evidence that one event dominates the other. During the other seasons seasonal ETo is always smaller during El Niño years as a result of the higher frequency of wet days. During fall there are no differences between Normal and La Niña years (curves overlap almost entirely). In winter season, La Niña years tend to dominate all other events, whereas the situation is inverted for spring season.

4. Discussion

Even though it has been shown that there is an effect of ENSO phenomenon that affects the climatic conditions of the region, and that this signal can be propagated to the process of reference evapotranspiration, the real assessment of the potential benefits derived from this information for water resources management purposes requires the translation of these effects into crop yields.
In this way, an economic valuation of the effects of climate variability on the agricultural hydrological cycle can be obtained. Further research should be focused on assessing monetary consequences and exploring suitable water allocation policies considering ENSO forecasts. The aim of the project addresses this issue combining soil information, crop simulation models and commonly used water production functions.

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