ESTIMATION OF THE MONTHLY REFERENCE EVAPOTRANSPIRATION IN THE ARAUCANÍA REGION, CHILE, FROM MODIS/TERRA SATELLITE DATA

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ABSTRACT

We propose a multiple regression model is to estimate the monthly reference evapotranspiration (ET_o), on a regional scale, from data provided by the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on board the TERRA satellite platform. The input data assumed by the model are the Normalized Difference Infrared Index (NDII) and the earth's surface temperature, described by the equation

$$ET_o = A \times NDII + B \times T_s + C \ (mm/month)$$

The model was applied in twelve meteorological stations located at different points in the Araucanía Region, Chile, and resulted in the satisfactory measurement of ET_o, obtaining $R^2 = 0.87$, $RMSE = 24.84$, $MAE = 19.42$ between the observed and estimated data. The model was validated with the Curacautín and Freire stations, obtaining $R^2 = 0.82\ yR^2 = 0.78$ respectively.

KEYWORDS: Monthly reference evapotranspiration, MODIS sensor, Normalized Difference Infrared Index, Earth's surface temperature.

INTRODUCTION

The impact of climate change in Chile has generated a series of effects, including temperature increases, significant reductions in precipitations in the country's central zone and increased precipitations in the extreme south. The average annual precipitation has fallen seriously in the last 70 years, with decreases ranging from 20% in La Serena (Coquimbo Region) to 15% in Concepción (Biobío Region). At the same time,increases have been observed in the minimum daily temperatures in the central zone, as well as a water deficit [1]. All these effects have had major implications for the water cycle, principally the availability of water resources, the seasonality and intensity of river flows, and hence the evapotranspiration (ET) of ecosystems. In practice, the ability to measure this variable will enable us to detect hydric stress in vegetation at an early stage, predict crop yields, calculate the hydric balance and characterize the climate of different zones [2]; it is also a fundamental component of the hydrological cycle [3].

Interest in measuring the various manifestations of ET (potential evapotranspiration, ETP; reference evapotranspiration, ET_o; real evapotranspiration, ETR) has led to the implementation of a range of methods. Following Sánchez [4], these can be divided into two major groups: the classic or conventional, consisting of models based on information obtained from various sources, basically meteorological or climatic; and those, which use data derived from Satellite Remote Detection. In the latter case, a number of algorithms exist based on: (a) the surface energy balance; (b) surface temperature; (c) vegetation indices; and (d) vegetation/surface temperature indices.

The possibility offered by satellites of providing large amounts of data about the earth's surface has led to particular interest in the method based on the vegetation/surface temperature index. Various studies have shown a clear linear ratio between the surface temperature and vegetation indices, especially NDVI [5].

In recognition of the fact that methods based on satellite remote detection are not sufficiently known in Chile, much less used, the object of the present article is to estimate ET$_o$, at a regional scale, based on data provided by the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on board the TERRA satellite platform. MODIS is an electro-optical sensor which works in three spatial resolutions (250m, 500m and 1000m) and has **36 spectral bands between the visible and thermal infrared range.**

MATERIALS AND METHODS

STUDY AREA

The study area is the Araucanía Region, Chile, which has an area of 31,842 km^2. It lies between 37º35’ and 39º37’S, and from 70º50’W to the Pacific Ocean. The average altitude above sea level in the Central Valley and intermediate plateaux is 200 (m); the average minimum and maximum temperatures are from 0-23(°C); the average minimum and maximum precipitation are from 1500-2500 (mm). The main economic activities are forestry and farming, particularly the production of crops like oats, barley, oilseed rape and rye, as well as lupines and potatoes. The region has the largest areas in the country of all these crops except potatoes.

FAO PENMAN-MONTEITH MODEL (PM)

The FAO Penman-Monteith model, derived from Penman-Monteith's original equation and the aerodynamic resistance and crop equations, is currently the method most widely accepted by the scientific community for estimating reference evapotranspiration [6]. The FAO Penman-Monteith equation is expressed by the equation:

$$ET_o = \frac{0{,}408\times\Delta(R_n-G)+\gamma\left(\frac{900}{T+273}\right)\times u_2(e_s-e_a)}{\Delta+\gamma(1+0{,}34u_2)} \quad (1)$$

ET_o, reference evapotranspiration (mm day^{-1}); R_n, net radiation at the crop surface (MJ m^{-2} day^{-1}); R_a, extra-terrestrial radiation (MJ m^{-2} day^{-1}); G, soil heat flow (MJ m^{-2} day^{-1}); T, average air temperature (ºC); u_2, wind velocity (m s^{-1}); e_s, saturation steam pressure (kPa); e_a, real steam pressure (kPa); e_s - e_a, steam pressure deficit (kPa); Δ, steam pressure curve gradient (kPa ºC^{-1}); γ, psychrometric constant (kPa ºC^{-1}).

The FAO Penman-Monteith equation determines the evapotranspiration of the reference hypothetical area and provides a standard value with which the evapotranspiration in different periods of the year or other regions can be compared; it can also be related with the evapotranspiration of other crops.

To estimate ET$_o$, each variable of equation (1) was calculated using the equations described in the “Guidelines for computing crop water requirements – FAO56” [7], while the meteorological data required were extracted from fourteen meteorological stations located across the Araucanía Region, as shown in Figure 1.Table 1 shows the geographical coordinates, elevation and observation period for each meteorological station.

SURFACE VEGETATION AND TEMPERATURE INDICES FROM MODIS DATA

The satellite data used, extracted from the MODIS sensor, are the product of reflectance (MOD09GA) and temperature/emissivity (MOD11A1), each of which has been subjected to radiometric and atmospheric correction.

The reflectance data allow the vegetation indices to be estimated; these are the result of combinations of two or more spectral bands in which the vegetation presents a different reflective response. Thus while in the visible region of the spectrum vegetation pigments absorb the majority of the energy received, they scarcely affect the near infrared, producing a marked contrast between the reflectivity of the visible and near infrared bands. The greater the contrast observed between these bands, the more vigorous is the vegetation; on the other hand, low contrasts indicate sick or ageing vegetation, and areas free of plant cover present very small contrasts [8]. Table 2 shows the different vegetation indices used: *Normalized Difference Vegetation Index [9]; Normalized Difference Infrared Index*[10]; Global Environmental Monitoring Index [11].

RESULTS AND DISCUSSION

We looked for a linear model to relate ET_o with the vegetation index (IV) and temperature of the earth's surface (T_s), in a ratio of the type:

$$ET_o = A \times IV + B \times T_s + C[mm/month] \quad (2)$$

Twelve meteorological stations were used to train the model: Carahue, Carilafque, Carillanca, Collipulli, Cunco, Dollinco, Gorbea, Llancahue, Maquehue, Pto. Saavedra, Tranapuente and Vilcún.

The Curacautín and Freire stations were used to validate the model, where the goodness of fit was expressed in terms of the coefficient of determination (R^2), as follows:

$$R^2 = \frac{[\sum(E_i-\bar{E})(O_i-\bar{O})]^2}{\sum(E_i-\bar{E})^2 \sum(O_i-\bar{O})^2} \quad (3)$$

O_i is the observed value,E_i is the estimated or modelled value, while $\bar{O}$ and $\bar{E}$ respectively are the observed and estimated mean values.

The root mean squared error (RMSE) and the mean absolute error (MAE) were used as additional statistical tools to assess the model's accuracy. These statistics are expressed as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i-E_i)^2}{n}} \quad (4)$$

$$MAE = \frac{\sum_{i=1}^{n}(O_i-E_i)}{n} \quad (5)$$

n is the number of observations, O_i is the observed value, E_i is the estimated or modelled value.

Table 3 shows the results of the multiple regression model, indicating the A, B and C coefficients which result when ET_o is correlated with the vegetation/surface temperature index for a total of twelve meteorological stations; it also shows the statigraphs for R^2, RMSE and MAE.

The table above shows values of $R^2 > 0.8$, from which it may be inferred that there is a high degree of associativity between ET_o and the vegetation/surface temperature index. This result agrees with the findings reported by other authors [12-13]. It should be noted in these results that the highest value for R^2 was obtained with the NDII vegetation index. Figures 2, 3, 4 and 5 show the fit of the $ET_{o\ \mathrm{observed}}$ and the $ET_{o\ \mathrm{estimated}}$ and the evolution over time of the observed and estimated values of ET_o, all obtained using this index, for the Curacautín and Freire stations, representing respectively the Pre-Cordillera and the Central Valley of the Araucanía Region.

The results obtained show that R^2 is greater than 0.7 for the validation stations. This value is considered acceptable if the diversity of the geography, pixel spatial resolution and vegetation in the study area are taken into account.

Based on Table 3, the following equation is proposedto obtain the ET_o from data provided by the TERRA/MODIS sensor.

$$ET_o = 169.9 \times NDII + 9.68 \times T_s - 97.88\ [mm/month] \qquad (6)$$

Figure 6 shows the observed and estimated monthly reference evapotranspiration values for all the stations used for model training in the study. The regression coefficient obtained is greater than 0.8, which confirms the high functional dependence of the ET_o on the NDII vegetation index and the surface temperature.

CONCLUSIONS

We propose an operating model which allows the monthly ET_o to be estimated based on the NDII vegetation index and the surface temperature. The validity of the model in two meteorological stations in the study area gave regression coefficients greater than 0.7. This indicates the feasibility of using data from satellite-mounted remote sensors, particularly the TERRA/MODIS sensor, for estimating ET_o, as well as for calculating the regional value for this variable, since it can be estimated from the image with known spatial ranges.

Figure 1. Spatial distribution of meteorological stations in the Araucanía Region.

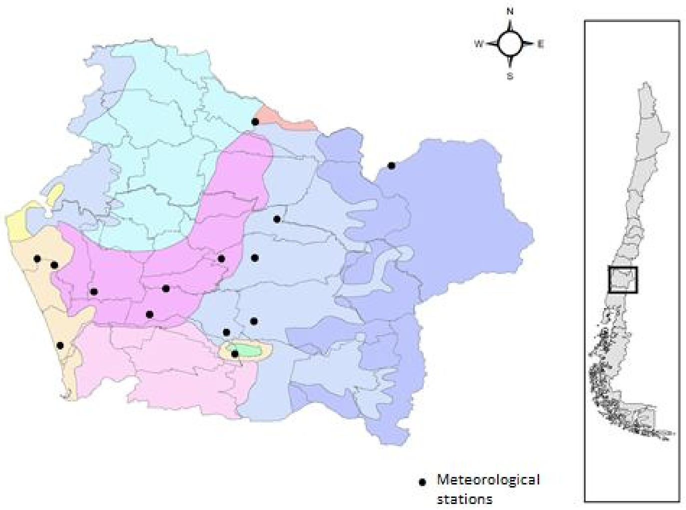


Table 1. Meteorological stations in the IX (Araucanía) Region. (*) Stations used in model validation

No.	Sampling point	**Latitude**	**Longitude**	**Elevation [m]**	**Observation Period**
1	Carahue	38.7237	73.2681	92.58	July/2010 – July/2012
2	Carilafquen	39.1708	72.3495	138.8	July/2009 – July/2011
3	Carillanca	38.6913	72.4172	84.78	September/2010 – July/2012
4	Collipulli	38.0010	72.2456	124.39	July/2009 – July/2012
5	Cunco	39.0068	72.2516	167.05	July/2009 – July/2012
6	Curacautín*	38.2205	71.5530	97.87	September/2010 – July/2012
7	Dollinco	38.4913	72.1341	149.56	July/2009 – October/2011
8	Freire*	38.9715	72.7842	94.96	July/2009 – July/2012
9	Gorbea	39.0615	72.3916	138.8	July/2010 – July/2012
10	Llancahue	38.8573	73.0661	124.98	July/2009 – December/2010
11	Maquehue	38.8412	72.7010	94.96	July/2009 – September/2011
12	Pto.Saavedra	39.1297	73.2377	124.98	July/2010 – July/2012
13	Tranapuente	38.6909	73.3548	82.65	July/2010 – July/2012
14	Vilcún	38.6861	72.2480	148.75	July/2009 – September/2011

Table 2. Vegetation indices obtained from MOD09GA. ρ_v, ρ_{nir}, ρ_{swir} indicate the reflectivities in the spectral channels of the visible, near infrared and medium infrared respectively.

Vegetation Index	Algorithm
Normalized Difference Vegetation Index	$NDVI = \frac{\rho_{nir} - \rho_r}{\rho_{nir} + \rho_r}$
Normalized Difference Infrared Index	$NDII = \frac{\rho_{nir} - \rho_{swir}}{\rho_{nir} + \rho_{swir}}$
Global Environmental Monitoring Index	$GEMI = \frac{\eta(1 - 0.25\eta) - (\rho_{nir} - 0.125)}{1 - \rho_r}$

Table 3. A, B and C coefficients which result from correlating ET_o with the vegetation/surface temperature index for a total of twelve meteorological stations. The statigraphs for R^2, RMSE and MAE are also shown.

Index	A	B	C	R^2	RMSE	MAE
NDVI - TS	109.40	10.05	-136.78	0.85	27.46	20.86
NDII - TS	169.93	9.68	-97.88	0.87	24.84	19.42
GEMI - TS	486.30	9.10	-272.42	0.84	26.90	20.89

Figure 2. Curacautín station fit of observed versus estimated values. The broken line indicates the straight line 1:1

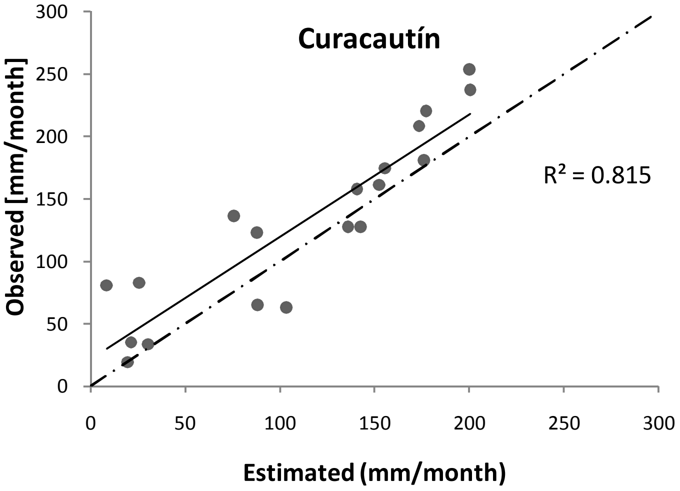


Figure 3. Evolution over time, Curacautín station.

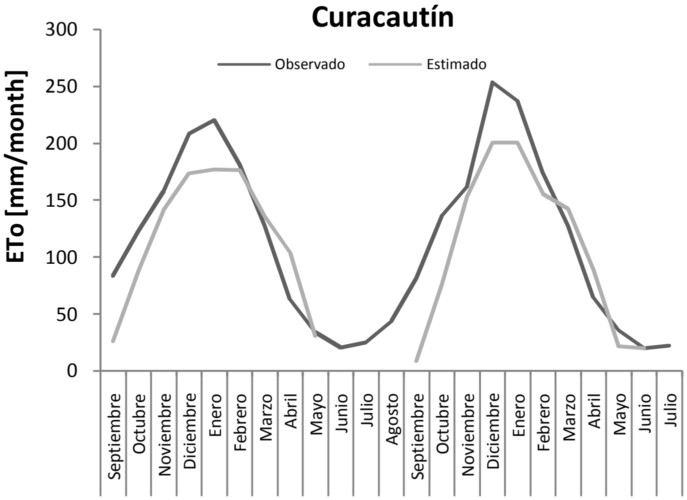


Figure 4. Freire station fit of observed versus estimated values. The broken line indicates the straight line 1:1

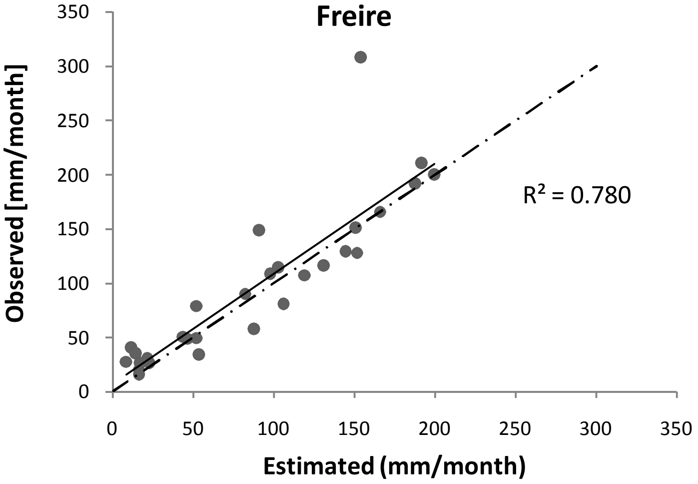


Figure 5. Evolution over time, Freire station.

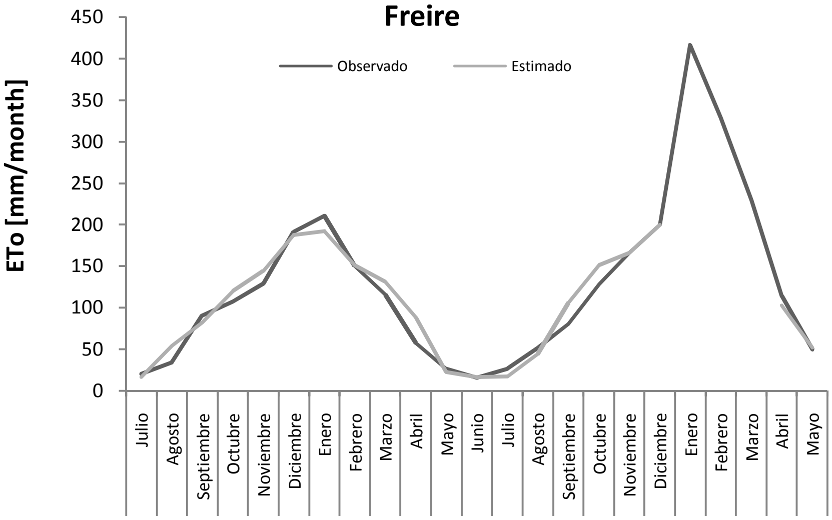
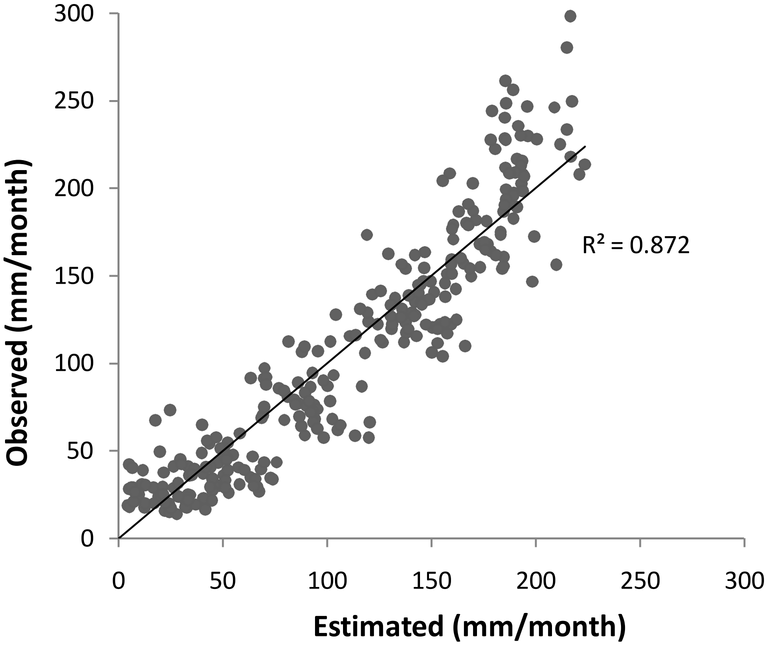


Figure 6. Observed and estimated monthly reference evapotranspiration values for all the stations.



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