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TOPOCLIMATIC MODELING OF THERMOPLUVIOMETRIC VARIABLES FOR THE BÍO BÍO AND LA ARAUCANÍA REGIONS, CHILE

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ABSTRACT

Climatic mapping in the Bío Bío and La Araucanía Regions of Chile is primarily in analog form (paper) and delineation of contours, making it unsuitable for digital handling by geographic information systems (GIS). Therefore, in this study, topoclimatic models were created and spatially represented to explain the spatial and temporal variation of monthly mean temperature and precipitation, as a function of variability and singularity of the physiographic characteristics of the Bío Bío and La Araucanía Regions. The physiographic factors considered were latitude, longitude, altitude, aspect and distance to coastline. To elaborate equations, data from thermopluviometric stations of the study area were compiled and systematized. These stations were standardized to a common reference system in order to locate them in space and obtain the value of physiographic factors for each station. With this information, the equations were calculated using a stepwise (backward) regression procedure, with a statistical significance of 95%. The regression equations obtained for mean monthly and annual temperature and precipitation were all significant ($P \leq 0.05$) and had $R^2 > 0.7$. These equations were applied to the rest of the study area in raster format using a GIS, which yields a spatially continuous cartography. The spatial resolution or pixel size was 90 m, which allows carrying out research at a 1:100 000 scale, commonly used at the regional or provincial level.

Key words: Topoclimatic models, mean temperature, mean precipitation, pluviometric cartographic, GIS.

INTRODUCTION

Climate, defined as the mean state of the atmosphere in a determined place, is a variable that affects, models and conditions biological, physical and chemical processes that occur in nature (Hufty, 1984). The elements influenced by climate are geography, soil characteristics, vegetation, and ultimately the use and occupation of a determined territory. Because of this, the climatic variable is a conditioning factor in the planning of human activities (Romero and Martínez, 2001). If we consider the importance of climate for the processes that occur in nature and the possible variations of climate owing to physiographic factors, it is necessary to have base climatic information to undertake any study about a determined territory.

This is relevant for Chile, where the physiographic factors are highly variable, with a latitudinal range of approximately 38° (Di Castri and Hajek, 1976), altitudes that range from 0 to 6000 m.a.s.l. and a marked maritime influence (Errázuriz *et al*., 1994). The study of climatic variation attributable to physiographic factors has been undertaken using what is termed "topoclimatic analysis", which is defined in general terms as the climatic characteristics of a place that can be described as a combination of topographic parameters (Okolowicz, 1969, cited by Kaminski and Radosz, 2005). The cartographic representation of climatic variables has generally been carried out manually, subject to expert criteria, such as isothermal and isohyet maps, which are isolines that join points with the same temperature and the same level of precipitation, respectively. These isolines are drawn on the basis of an altitudinal gradient, considering the values registered each year from observatories in the zone, the density of which conditions the interval of its plotting (Fernández, 1996). As an alternative to this method of representation, different interpolation algorithms have been developed and automated to estimate and predict the spatial distribution of a variable based on timely data generated by meteorological stations (Hijmans *et*

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al., 2005; Hunter and Meentemeyer, 2005; Attorre *et al*., 2007).

The processes of obtaining climatic cartography, whether through the use of a traditional methods (analogic) or an automated method, is conditioned by the availability and quality of climatic information or data that comes mainly from meteorological stations located in particular points in space (Skirvin *et al*., 2003; Morales *et al*., 2006) that often do not cover the totality of a region, leaving areas without information. Given this, models are developed that allow for spatially representing the monthly distribution of temperature and precipitation on an ongoing basis, using Geographic Information System (GIS) raster, obtaining Digital Terrain Models (DTM), which are spatial representations of continuous variables (Doyle, 1978; cited by Florinsky, 1998; Daly *et al*., 2008). Given the importance of having climatic information to develop studies in a determined area, and considering the physiographic variability of Chile associated with the lack of good coverage by meteorological stations and the continuous character of the distribution of climatic variables, this study aims to generate estimation models of climatic information that allow for continuously characterizing the whole territory, taking into consideration physiographic variables.

MATERIALS AND METHODS

Area of study

The study was carried out in the Bío Bío and La Araucanía Regions, central Chile (36°0' to 39°38' S; 70°49' to 73°57' W) covering an approximate surface area of 68 704 km^2 (Figure 1). The Bío Bío Region marks a transition from the temperate climate that characterizes the central zone of Chile and the rainier climate characteristic of areas south of the Laja River. The characteristics of a temperate Mediterranean climate predominate in this region. Nevertheless, differences are observed within the territory, fundamentally owing to the effect of the latitudinal gradient and the distance from the coast. The La Araucanía Region presents two well-differentiated climatic typologies, the first located in the intermediate zone in the north of the region until around 39° S lat, characterized by precipitation distributed throughout the year and a relatively short dry season of no more than 3 or 4 months during the summer. The second zone is characterized by a temperate rainy climate with Mediterranean influence, while extends until Castro in the Los Lagos Region.

Climatic and topographic data

Data was used for this research from stations with ten or more years history of taking climatic measurements (Table 1) derived from: Climatology in Chile (United Nations Development Program [UNDP] - Government of Chile, 1964), Agroclimatic Map of Chile (INIA, 1989), General Water Directorate (DGA) and yearbooks from the Meteorological Directorate of Chile (DMC). To spatially represent the equations, four Digital Terrain Models were used, with information on latitude, longitude, exposure and distance from the coast, and a Digital Elevation Model obtained from the Shuttle Radar Topography Mission (SRTM), of the United States Geological Survey (USGS, 2004), all of them with a pixel size of 90 m.

To adjust the temperature model, only the stations that had data for more than 10 yr were considered, from the four aforementioned sources. On the other hand, owing to the greater spatial and temporal variability of precipitation, only data from DGA stations with ten or more years of sampling records were used (Table 2). For the development, adjustment and spatial representation of topoclimatic models, it is necessary to homogenize the information, given that the stations that provide

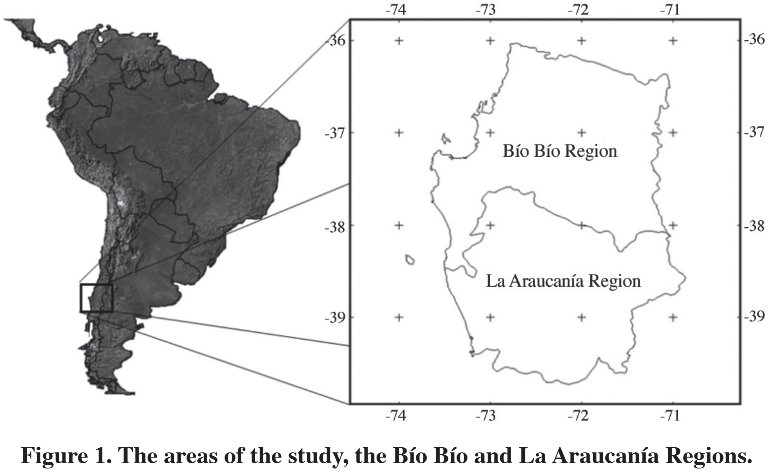


Figure 1. The areas of the study, the Bío Bío and La Araucanía Regions.

Table 1. Meteorological stations used in the temperature models.

Station	Latitude	Longitude	Altitude	Distance to coast	Years	Period
	degrees		m.a.s.l.	km		
Cauquenes	-35.971	-72.336	142	28.05	22	NE
Chillán Viejo	-36.633	-72.126	140	70.78	15	NE
B. O'Higgins Chillán	-36.571	-72.036	124	76.50	16	1982/1997
Punta Tumbes	-36.624	-73.102	120	0.61	30	1916/1945
Caracol	-36.651	-71.389	725	133.90	20	1988/2007
Embalse Coihueco	-36.638	-71.797	330	98.94	31	1977/2007
Talcahuano	-36.721	-73.119	84	0.97	18	NE
Carriel Sur Concepción	-36.771	-73.052	12	3.94	16	1982/1997
Concepción	-36.837	-73.036	10	10.58	20	NE
Diguillín	-36.868	-71.643	710	120.31	38	1970/2007
Quilaco	-37.686	-72.006	225	119.58	38	1970/2007
Angol	-37.804	-72.702	79	71.64	15	NE
Contulmo	-38.012	-73.228	60	20.91	19	1988/2007
Laguna Malleco	-38.213	-71.814	959	143.76	18	1990/2007
Traiguén	-38.256	-72.654	189	70.90	26	1979/2004
Lonquimay	-38.455	-71.365	878	180.19	16	1992/2007
Malalcahuello	-38.471	-71.571	900	162.58	16	1989/2004
Lautaro	-38.534	-72.434	240	89.59	10	1995/2004
Liucura	-38.646	-71.091	1035	196.44	20	1988/2007
Carillanca	-38.687	-72.419	200	84.95	25	NE
Temuco	-38.771	-72.636	114	64.07	26	1920/1945
Maquehue Temuco	-38.754	-72.636	114	64.78	16	1982/1997
Puerto Saavedra	-38.793	-73.396	5	1.26	25	1979/2004
Tricauco	-38.844	-71.554	518	151.67	16	1989/2004
Teodoro Schmidt	-39.003	-73.095	47	18.17	16	1989/2004
Pucón	-39.289	-71.927	200	110.62	19	1986/2004
Loncoche	-39.371	-72.636	31	49.02	14	NE
Puesto (Aduana)	-39.534	-71.557	726	143.11	17	1988/2004
Pichoy Valdivia	-39.621	-73.086	19	17.10	15	1982/1984-1986/1997

NE: not specific (INIA, 1989).

information have different reference systems, so that all the information of a geographic character was worked in the World Geodetic System (WGS84) in spherical coordinates. Subsequently, the database was completed that was used for the generation and spatial representation of the topoclimatic models. The physiographic variables included in this study were altitude, latitude, longitude and distance from the coast. All these variables were represented with a pixel resolution of 90 m, which was used for the spatial representation of topoclimatic models and is responsible for the continuous character of the cartographies of temperature and precipitation that were generated. Once the equations have been estimated, thematic cartographies of a continuous character were developed using the computer program IDRISI® (IDRISI 32, Clark Labs, Clark University, Massachusetts, USA) and the MDTs of latitude, longitude, altitude and distance to the coast.

Topoclimatic modeling

The modeling of different climatic variables was done by applying a mathematical model described by Equation [1]:

$$F(x_1,x_2,....x_n)=\sum_{j,kn,m=0} a_j x_{k_1}^{n_1} x_{k_2}^{n_2}...x_{k_m}^{n_m} \qquad [1]$$

where $F(x_1, x_2 ,.....x_n)$ represents a climatological variable in a given period of time, x is a descriptor variable, which can be latitude, longitude, altitude, distance from the coast or slope, among others, and a_j are coefficients to be determined (Qiyao *et al.*, 1991; Canessa, 2006). With

Table 2. Meteorological stations used in the temperature models.

Station	Latitude	Longitude	Altitude	Distance to coast	Years	Period
	degrees		m.a.s.l.	km		
Embalse Tutuven	-35.901	-72.376	400	20.662	28	1977/2004
Embalse Ancoa	-35.922	-71.287	430	116.472	30	1975/2004
Los Huinganes	-35.941	-71.942	132	58.817	11	1994/2004
Liguay	-35.948	-71.690	145	81.068	30	1975/2004
Quella	-36.061	-72.092	130	51.920	30	1975/2004
Mangarral	-36.233	-72.342	150	42.189	13	1992/2004
Millauquen	-36.316	-72.038	130	69.509	13	1992/2004
San Agustín de Puñual	-36.352	-72.393	100	38.349	12	1993/2004
Coelemu	-36.484	-72.698	30	16.995	30	1975/2004
Dichato	-36.546	-72.931	4	0.298	25	1980/2004
San Fabián	-36.561	-71.548	500	117.421	30	1975/2004
Chillán Viejo	-36.633	-72.126	140	70.776	28	1977/2004
Rafael	-36.637	-72.844	198	10.099	12	1993/2004
Embalse Coihueco	-36.638	-71.797	330	98.937	30	1975/2004
Caracol	-36.651	-71.389	725	133.896	18	1987/2004
Nueva Aldea	-36.653	-72.455	60	43.985	30	1975/2004
Caman	-36.674	-71.298	920	142.368	12	1993/2004
Cancha Los Litres	-36.705	-72.578	250	34.888	12	1993/2004
Chillancito	-36.761	-72.421	70	49.872	30	1975/2004
Las Pataguas	-36.790	-72.891	250	11.022	12	1993/2004
Mayulermo	-36.817	-71.893	375	97.221	13	1992/2004
Diguillín	-36.868	-71.643	710	120.308	30	1975/2004
Las Trancas	-36.910	-71.477	1160	135.700	30	1975/2004
Fundo Atacalco	-36.916	-71.579	730	126.850	30	1975/2004
Pemuco	-36.977	-72.096	200	83.993	30	1975/2004
Las Cruces	-37.109	-71.766	650	116.663	12	1993/2004
Cholguán	-37.152	-72.066	225	94.780	30	1975/2004
Laja	-37.271	-72.719	40	42.258	30	1975/2004
Trupán	-37.279	-71.822	460	119.539	30	1975/2004
Tucapel	-37.294	-71.952	330	108.433	30	1975/2004
Fundo Las Achiras	-37.354	-72.386	125	73.155	30	1975/2004
Los Ángeles	-37.502	-72.407	120	78.696	30	1975/2004
Fundo San Lorenzo	-37.509	-71.768	740	130.430	30	1975/2004
San Carlos de Purén	-37.595	-72.277	150	93.836	20	1985/2004
Quillaileo	-37.653	-71.712	500	141.067	12	1993/2004
Quilaco	-37.686	-72.006	225	119.578	30	1975/2004
Mulchen	-37.716	-72.244	130	103.532	30	1975/2004
Angol (La Mona)	-37.779	-72.637	154	78.003	25	1975/1990-1996/2004
Cerro El Padre	-37.780	-71.865	400	135.501	30	1975/2004
Cañete	-37.798	-73.391	25	15.608	30	1975/2004
Pilguen	-37.832	-72.219	300	111.884	12	1993/2004
Poco a Poco	-37.872	-71.993	650	130.592	13	1992/2004
Collipulli	-37.955	-72.442	257	90.200	30	1975/2004
Contulmo	-38.012	-73.228	60	20.915	17	1987/1989-1991/2004
Tranaman	-38.021	-73.009	55	39.732	17	1988/2004

Continuation Table 2.

Station	Latitude	Longitude	Altitude	Distance to coast	Years	Period
	degrees		m.a.s.l.	km		
Encimar Malleco	-38.104	-72.117	420	117.025	16	1989/2004
Lumaco	-38.164	-72.902	127	48.305	30	1975/2004
Laguna Malleco	-38.213	-71.814	959	143.761	30	1975/2004
Las Mercedes, Victoria	-38.243	-72.210	466	109.370	19	1986/2004
Traiguén	-38.256	-72.654	189	70.904	26	1979/2004
Galvarino	-38.410	-72.786	58	62.716	26	1979/2004
Rari-Ruca	-38.425	-72.011	361	128.381	13	1992/2004
Curacautín	-38.437	-71.885	499	138.398	30	1975/2004
Quillén	-38.464	-72.386	275	95.918	30	1975/2004
Malalcahuello	-38.471	-71.571	900	162.582	16	1989/2004
La Cabaña	-38.530	-73.121	709	33.204	16	1989/2004
Lautaro	-38.534	-72.434	240	89.591	30	1975/2004
Chochol	-38.609	-72.845	72	52.739	17	1988/2004
Vilcún	-38.672	-72.218	376	101.976	30	1975/2004
Cherquenco	-38.683	-72.002	528	119.496	17	1988/2004
Carahue	-38.713	-73.148	50	24.200	10	1995/2004
Pueblo Nuevo, Temuco	-38.723	-72.570	115	71.350	30	1975/2004
Almagro	-38.781	-72.952	20	38.231	10	1995/2004
Puerto Saavedra	-38.793	-73.396	5	1.263	26	1979/2004
Tricauco	-38.844	-71.554	518	151.667	16	1989/2004
Cunco	-38.929	-72.016	470	110.422	30	1975/2004
Sendos Freire	-38.950	-72.667	123	43.491	24	1981/2004
Los Laureles	-38.959	-72.188	250	95.151	30	1975/2004
Quecherehua	-38.998	-72.044	420	105.993	30	1975/2004
Teodoro Schmidt	-39.003	-73.095	47	18.172	16	1989/2004
Quitratue	-39.155	-72.658	88	50.106	30	1975/2004
Toltén	-39.181	-73.166	17	7.169	10	1995/2004
Lago Caburga	-39.221	-71.585	480	140.684	24	1977/2000
Villarrica	-39.278	-72.228	187	84.799	30	1975/2004
Pucón	-39.289	-71.927	200	110.619	21	1984/2004
Curarrehue	-39.363	-71.581	580	140.096	28	1977/2004
Loncoche	-39.371	-72.636	31	49.024	11	1994/2004
Chanlelfúl	-39.465	-72.375	166	72.279	17	1988/2004
Puesto (Aduana)	-39.534	-71.557	726	143.112	17	1988/2004
Lago Calafquén	-39.552	-72.152	375	92.485	18	1987/2004
Liquiñe	-39.731	-71.853	230	121.527	11	1994/2004
Lago Riñihue	-39.774	-72.453	120	73.540	20	1985/2004

these relationships, the data matrices are calculated for each climatological variable in binary format (raster) for the months of January and July. The binary metrical format was used because it corresponds to the format of the IDRISI Program®, which is used for the spatial characterization of continuous variables. The proposed topoclimatic model (Equation [1]) to estimate mean monthly temperature and precipitation considered that spatial variation of the aforementioned variables is determined by factors of position on the surface of the earth, this being latitude (*LAT,* degrees) and longitude (*LON,* degrees), as well as physiographic factors like altitude *(ALT,* m.a.s.l.) and distance to the coast (*DL,* km), as shown in Equation [2].

$$Y = a_0 + a_1LAT + a_2LON + a_3ALT + a_4DL \qquad [2]$$

where Y represents mean monthly temperature and precipitation estimated for each month, while the values a_0, $a_1 \ldots a_4$ are coefficients of the corresponding equation. All the models represented by Equation [2] were submitted to a stepwise regression procedure in its backward form, with the aim of finding the reduced models of greater statistical significance. The goodness of fit of all the topoclimatic regressions previously described was calculated with a statistical significance of 95% ($P \leq 0.05$), both for the complete model and for each one of its coefficients. To validate the models, four stations were used for the case of temperature (Table 3) and eight for precipitation (Table 4). The spatial coverage of the available stations was analyzed to choose the stations for validation, selecting those that were distributed all along the zone under study, avoiding stations that were isolated from other stations. As well, to minimize errors in the administrative boundaries of the two regions, stations outside the area of study were considered.

RESULTS AND DISCUSSION

To calculate the models, 25 stations with temperature information and 74 stations with precipitation information were used, which meet the requirement of ten or more years of records. The spatial location of the selected stations is presented in Figures 2a and 2b.

The distribution of stations with temperature data has a low density and representativeness in the Bío Bío Region (Figure 2). As well, it can be observed that the stations with pluviometric data are mainly concentrated in the intermediate valley of the area of study, without information from the coastal Nahuelbuta mountain range or areas above 1200 m.a.s.l. in the Andean Range. Given this, the authors recommend not including aforementioned zones for the estimation of the models.

Estimation of mean monthly temperature ($TMMest_{(i)}$, ºC)

To estimate $TMMest_{(i)}$ (where *i* corresponds to the months of the year), the general model of Equation [1] was used and the values corresponding to coefficients a_n were obtained with the backward stepwise analysis (Table 5). The models generated for the different months were significant to a level of confidence of 95% ($P \leq 0.05$), explaining over 60% of the variation of the data and the standard error was less than 1.5 ºC. The descriptor variable used resulted significant with 95% of confidence.

With these values, the mean monthly temperatures of the stations selected for validation of the models (Table 6).

The statistical difference between what was measured and what was estimated for the four seasons indicate that the regressions are all significant to 95% of confidence

Table 3. Selected stations for the validation of the models of mean monthly temperature.

Season	Latitude	Longitude	Altitude	Distance to coast
	degrees		m.a.s.l.	km
Chillán	-36.633	-72.126	140	70.78
Carriel Sur Concepción	-36.771	-73.052	12	3.94
Lonquimay	-38.455	-71.365	878	180.19
Lautaro	-38.534	-72.434	240	89.59

Table 4. Selected stations for the validation of the models of mean monthly precipitation.

Season	Latitude	Longitude	Altitude	Distance to coast
	degrees		m.a.s.l.	km
San Agustín de Puñual	-36.352	-72.393	100	38.349
Caman	-36.674	-71.298	920	142.368
Cancha Los Litres	-36.705	-72.578	250	34.888
San Carlos de Purén	-37.595	-72.277	150	93.836
Rari-Ruca	-38.425	-72.011	361	128.381
Lautaro	-38.534	-72.434	240	89.59
Quecherehua	-38.998	-72.044	420	105.993
Curarrehue	-39.363	-71.581	580	140.096

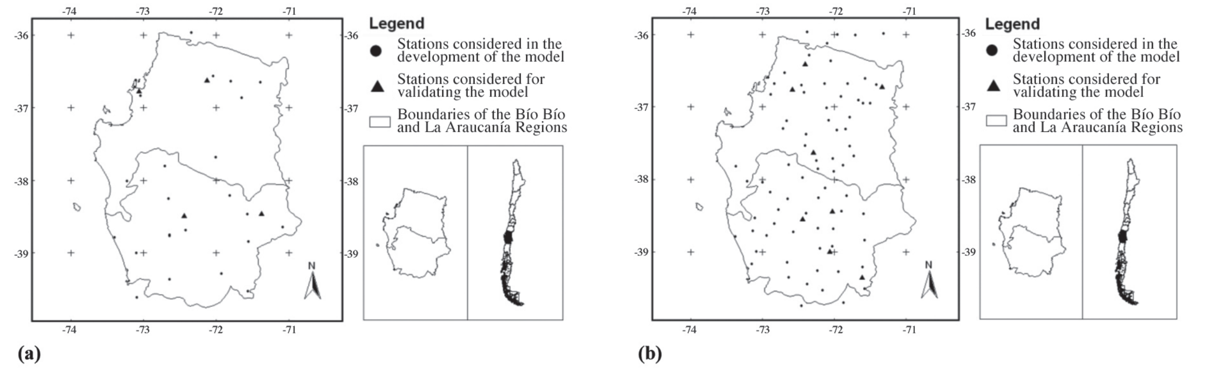


Figure 2. Spatial distribution of the stations used to develop and validate the models for (a) mean temperature and (b) mean precipitation.

Table 5. Values of the regression coefficient that notes the dependence of mean monthly temperature (TMMest) on physiographic variables according to Equation [2].

	a_0	a_1	a_2	a_3	R_2 (%)	Standard error	P value
$TMest_{jan}$	235.598	1.10635	2.41645	-6.61815×10^{-3}	62.21	1.48	0.0001
$TMest_{feb}$	199.049	1.14058	1.90388	-5.14687×10^{-3}	61.31	1.39	0.0001
$TMest_{mar}$	167.758	1.00095	1.56891	-4.90345×10^{-3}	68.58	1.08	0.0000
$TMest_{apr}$	46.7321	0.89483	0	-3.2538×10^{-3}	75.52	0.88	0.0000
$TMest_{may}$	37.6259	0.710772	0	-3.6215×10^{-3}	79.46	0.77	0.0000
$TMest_{jun}$	37.4814	0.74865	0	-4.245×10^{-3}	82.32	0.81	0.0000
$TMest_{jul}$	35.781	0.713728	0	-4.86937×10^{-3}	85.39	0.79	0.0000
$TMest_{aug}$	35.1862	0.68114	0	-4.19248×10^{-3}	80.14	0.83	0.0000
$TMest_{sep}$	37.5339	0.711895	0	-3.48239×10^{-3}	78.44	0.78	0.0000
$TMest_{oct}$	40.7885	0.7532	0	-3.01246×10^{-3}	66.50	0.98	0.0000
$TMest_{nov}$	159.176	0.774336	1.58728	-5.59061×10^{-3}	67.54	1.07	0.0000
$TMest_{dec}$	210.495	1.09226	2.10016	-6.13975×10^{-3}	68.99	1.24	0.0000

Table 6. Statistical summary of the stations with mean monthly temperature considered for the validation.

Stations	R^2 (%)	Standard error	P value
Chillán	98.82	0.45	0.0000
Carriel Sur	98.77	0.37	0.0000
Lonquimay	99.20	0.36	0.0000
Lautaro	98.37	0.45	0.0000

($P \leq 0.05$, Table 6). The determination coefficients indicate that the models explain over 98% of the variation observed in the data and the standard error was lower than 0.5 ºC. These results are presented graphically in Figure 3.

An overestimation of the model can be observed in Figure 3b. This could be explained by the proximity of the Carriel Sur station to the Concepción station, the latter being within the city, while the former is located some 8 km from Concepción. Concepción has higher mean temperatures owing to the "caloric island" effect associated with populated centers (Rivero, 1988 cited by Navarrete *et al*., 2001).

Estimation of mean monthly precipitation (*$PPMest_{(i)}$*, mm)

As was done for the mean temperature models, the general model of Equation [2] was used, and the values corresponding to coefficients a_n were obtained with backward stepwise analysis. The models generated for different months were significant to a level of confidence of 95% ($P \leq 0.05$, Table 7), explaining over 60% of the variation in the data and the standard error was less than 70 mm. The descriptor variables used resulted significant with 95% of confidence.

Mean monthly precipitation was estimated with these values from the stations selected for validation of

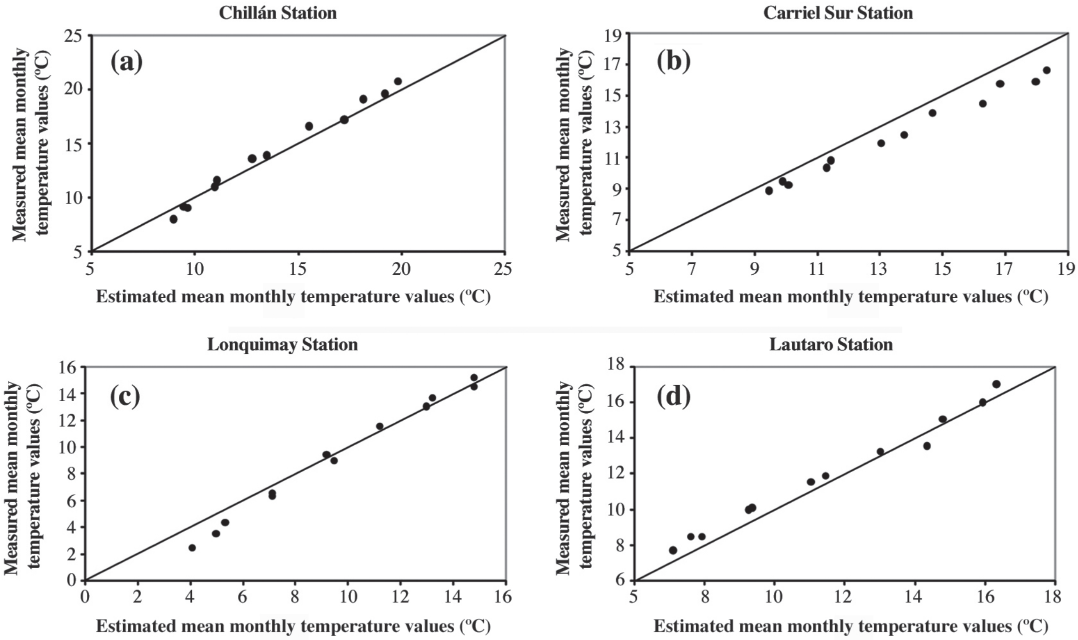


Figure 3. Graphic representation of the measured and estimated values of mean monthly temperature for the stations at (a) Chillán, (b) Carriel Sur, (c) Lonquimay; and (d) Lautaro.

the models. The regression statistics for the validation stations are presented in Table 8.

The statistical difference between what was measured and what was estimated for the eight stations of validation indicate that the regressions are all significant to 95% of confidence ($P \leq 0.05$). The determination coefficients indicate that the models explain over 92% of the variation observed in the data and the standard error was less than 32 mm (Table 8). The graphic representation of the models for the eight seasons is presented in Figure 4.

The calculated models show significant statistical values ($P \leq 0.05$), and the values of R^2 in the majority of the estimations are higher than 70%. These values are within the range of those obtained in other studies of a topoclimatic character undertaken in Europe by Ninyerola *et al*. (2000), who reports values of R^2 higher than 70% for the estimation of precipitation and higher than 86% temperature. In turn, the studies of Goodale *et al*. (1998) indicate values higher than 69% for the estimation of mean precipitation. Nevertheless, these studies have a high

Table 7. Values of the regression coefficient that notes the dependence of mean monthly precipitation (PPMest) on physiographic variables according to Equation [2].

	a_0	a_1	a_2	a_3	a_4	R^2 (%)	Standard error	P value
$PPMest_{jan}$	1087.32	-17.683	23.734	0.013808	-0.163251	79.24	9.25	0.0000
$PPMest_{feb}$	1253.4	-13.1457	23.6611	0.0297537	-0.162335	76.22	9.13	0.0000
$PPMest_{mar}$	2040.91	-26.7829	41.24	0.0395461	-0.382452	85.69	11.07	0.0000
$PPMest_{apr}$	1369.52	-27.4925	32.0169	0.0894716	0	75.56	25.72	0.0000
$PPMest_{may}$	3327.51	-22.0545	54.9394	0.163666	0	63.46	51.94	0.0000
$PPMest_{jun}$	11012.3	-70.4274	184.006	0.270749	-1.6294	68.90	69.46	0.0000
$PPMest_{jul}$	3581.95	-28.1637	61.5454	0.185075	0	64.30	58.18	0.0000
$PPMest_{aug}$	1548.44	-31.8821	36.0421	0.135594	0	64.45	43.62	0.0000
$PPMest_{sep}$	4589.99	-30.1919	77.2407	0.114014	-0.537785	77.01	26.68	0.0000
$PPMest_{oct}$	4020.95	-40.1851	74.9192	0.100963	-0.532335	82.89	23.34	0.0000
$PPMest_{nov}$	2993.47	-31.9756	56.8982	0.0577807	-0.428223	85.74	14.74	0.0000
$PPMest_{dec}$	2017.42	-30.8262	43.1771	0.0499619	-0.331919	82.36	15.57	0.0000

Table 8. Statistical summary of the stations, with monthly mean precipitation data considered for the validation.

Stations	R^2 (%)	Standard error	P value
San Agustín de Puñual	99.06	7.41	0.0000
Caman	96.03	31.85	0.0000
Cancha Los Litres	98.28	11.28	0.0000
San Carlos de Purén	98.46	10.69	0.0000
Rari-Ruca	92.42	30.97	0.0000
Lautaro	98.74	10.93	0.0000
Quecherehua	96.43	23.73	0.0000
Curarrehue	96.83	26.86	0.0000

density of stations, greater than those used in this work. As well, the regions where the models are developed tend to present less geographic complexity than is found in the zone under study.

Spatial analysis with thermopluviometric data is problematic because meteorological stations that operate under different institutions provide information using distinct cartographic reference systems that rarely have detailed databases. As well, the stations lack strict spatial location, considering only a level of exactitude of degrees and minutes of longitude and latitude. To resolve this problem there should be a homogenization and documentation criterion of the location of meteorological stations in space in a unique reference system and

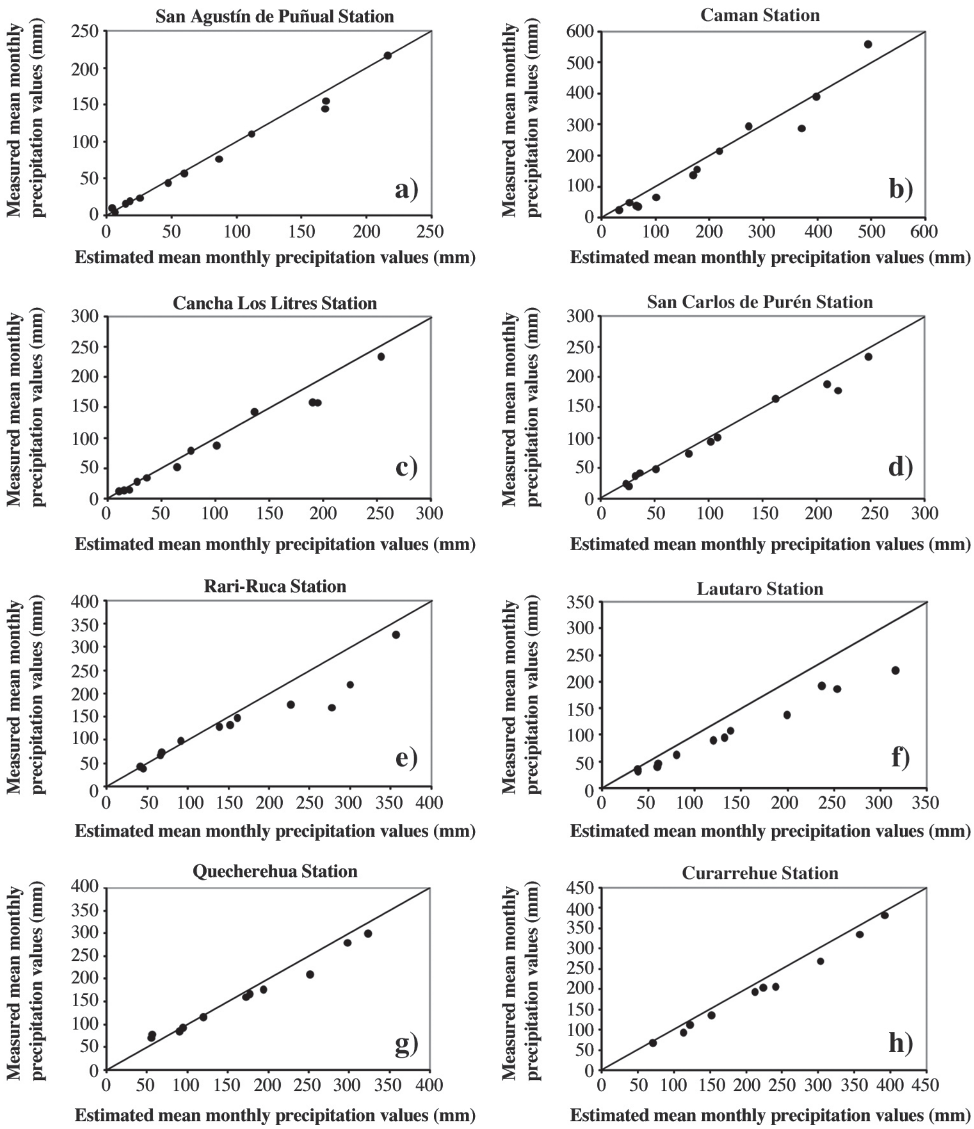
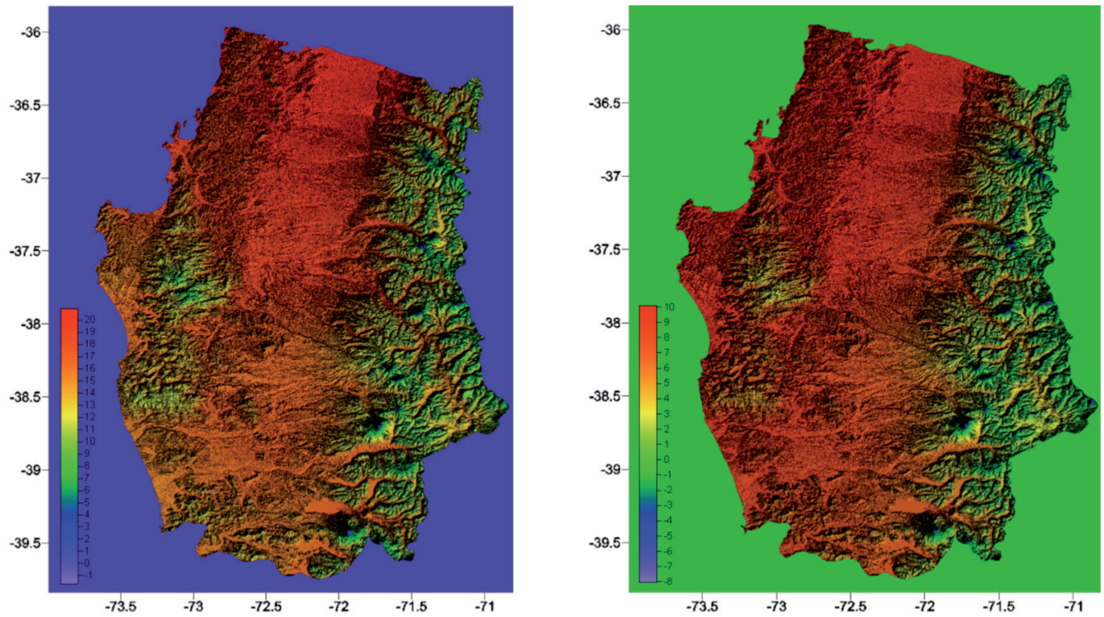
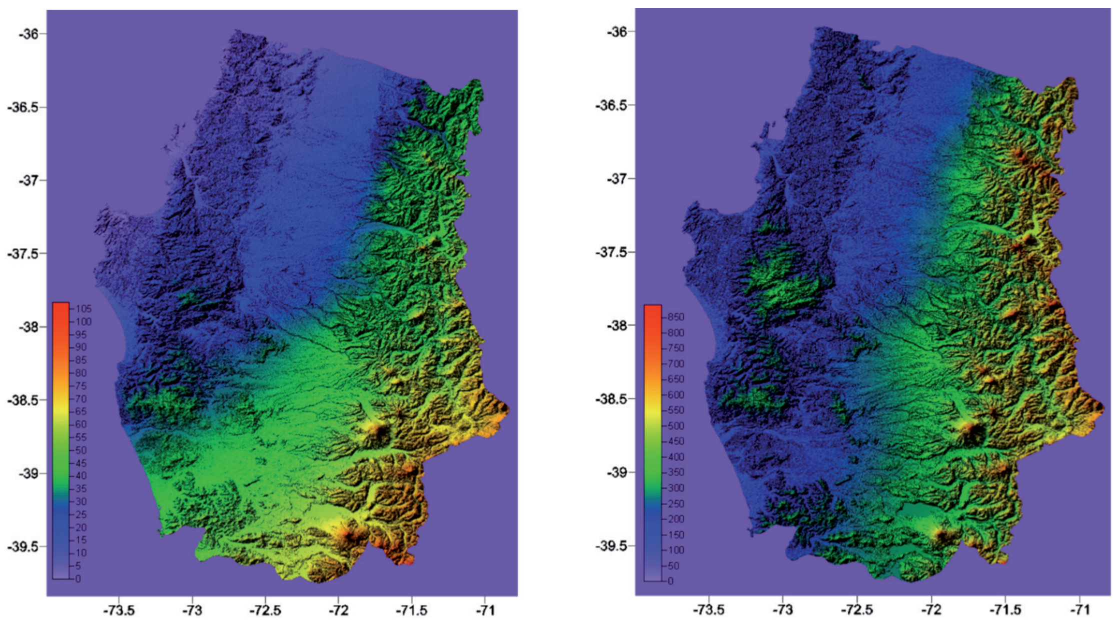


Figure 4. Graphic representation of mean and estimated values of mean monthly precipitation at the stations (a) San Agustín de Puñual, (b) Caman, (c) Cancha Los Litres, (d) San Carlos de Purén, (e) Rari-Ruca, (f) Lautaro, (g) Quecherehua, and (h) Curarrehue.



(a) (b)

Figure 5. Cartographic representation of the mean temperature (ºC) model for (a) January and (b) July, applying the topoclimatic models.



(a) (b)

Figure 6. Cartographic representation of the mean precipitation model (mm) for the months of (a) January and (b) July, applying topoclimatic models.

incorporate exactitude to the level of latitudinal/longitudinal seconds.

A continuous model of climatic variables facilitates carrying out environmental studies of a local character, allowing for deriving a range of models that have the thermopluviometric characteristics of a determined place as independent variables.

This work is a starting point to improve models of a topoclimatic character, whether by the quality and quantity of stations with thermopluviometric data or by the incorporation of new factors that modify the space-time variability of precipitation and temperature. Among the factors that could be included to improve the models is the use of satellite images, specifically spectral indices, reflectivity and surface temperature (Pesquer *et al*., 2007). For other meteorological variables, such as extreme mean monthly temperatures, we believe that it is possible to apply the same method.

Spatial representation of the models

Figures 5 and 6 show the cartographic results of the application of temperature and precipitation models.

CONCLUSIONS

It was possible to estimate the spatial distribution of the mean values of precipitation and temperature with statistical reliability of 95%, through the generation of topoclimatic models based on multiple linear regressions with descriptor variables, such as position (latitude, longitude, altitude and distance to the coast).

Despite the extreme physiographic variability of the territory under study and the low density of meteorological stations, the topoclimatic models satisfactorily estimated mean monthly and annual temperature and precipitation in vast areas lacking stations, such as the Nahuelbuta Range.

The method developed allows for storing the results in binary matrices compatible with geographic information systems, which in turn allows for calculating other derived variables, such degree-days and chilling hours, which are very useful for studies of agricultural adaptability.

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RESUMEN

Elaboración de modelos topoclimáticos de variables termopluviométricas para las Regiones del Bío Bío y La Araucanía, Chile. La cartografía climática existente en las Regiones del Bío Bío y La Araucanía está fundamentalmente en formato analógico (papel) y con trazado de isolíneas, lo que la hace inadecuada para el manejo digital mediante sistemas de información geográficas (SIG). Por ello, en este estudio se elaboraron y representaron espacialmente modelos topoclimáticos que explicaron la variación espacio-temporal de la temperatura y precipitación en su distribución media mensual, en función de la variabilidad y particularidad de la fisiografía de las Regiones del Bío Bío y de La Araucanía. Los factores fisiográficos considerados fueron latitud, longitud, altitud, exposición y distancia a la línea de costa. Para la construcción de las ecuaciones se recopilaron y sistematizaron los datos provenientes de estaciones termopluviométricas de la zona en estudio. Estas estaciones fueron estandarizadas a un mismo sistema de referencia, con la finalidad de localizarlas en el espacio y obtener los valores de sus factores fisiográficos. Con esta información se calcularon las ecuaciones mediante un procedimiento de regresión “stepwise” en su forma “backward”, con una significancia estadística del 95%. Las ecuaciones de regresión obtenidas para las temperaturas y precipitaciones medias mensuales estudiadas fueron significativas ($P \leq 0,05$) y con coeficientes de determinación que superaron 0,7. Estas ecuaciones fueron representadas espacialmente utilizando SIG de tipo raster. La resolución espacial o tamaño de píxel empleado fue de 90 m, la que permite realizar estudios a una escala aproximada de 1:100000, que es comúnmente utilizada en análisis de carácter regional y/o provincial.

Palabras clave: modelos topoclimáticos, temperaturas medias, precipitaciones medias, cartografía termopluviométrica, SIG.

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