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Topoclimatic zoning of continental Chile

Donna Cortez[a,b], Sebastián Herrera[a], Daniela Araya-Osses[a], Carolina Caroca[a], Rodrigo Padilla[c], Juan Manuel Uribe[b] and Manuel Paneque [b]

[a]Bionostra Chile Research Foundation, San Miguel Santiago, Chile; [b]Department of Environmental Sciences and Natural Resources, Faculty of Agricultural Sciences, University of Chile, La Pintana Santiago, Chile; [c]Climate Services Office, Climatology Section, Climatology and Applied Meteorology Subdepartment, Estación Central, Chile

ABSTRACT

In this study, the topoclimates of continental Chile are mapped. The mapping involves the identification of homogeneous zones based on the relationships between the climatic variables that characterize a location and the topography that influences the spatial behavior of these variables. The climatic and topographical zoning of the study area is conducted using a statistical methodology based on a combination of principal component analysis and cluster analysis. The climate, topography, and topoclimatic zoning yield 20, 8, and 96 clusters, respectively. Maximum topoclimatic variability is identified in sectors with mountain ranges and intermediate depression (especially in valley areas), and minimum variability is detected in the coastal sector. Furthermore, only one of the topoclimatic units has an area larger than 50,000 km^2, whereas 46.8% of the units have surface areas below 2,000 km^2.

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KEYWORDS
Topoclimatic zoning; automatic weather stations; principal component analysis; cluster analysis

1. Introduction

The climatic conditions of a location must be known for the development of various functions and applications, especially in areas such as agriculture, forestry, ecosystems, energy, and management of water resources (OMM, 2011). These conditions are influenced by atmospheric patterns and the topographic characteristics of a given location (Garreaud, 2011; Giorgi et al., 2003; Leung et al., 2003).

Chile has a wide variety of climates due to the effects of ocean–atmospheric and topographic factors such as the Humboldt Current, Andes, Cordillera de la Costa, Pacific Anticyclone, and Western Wind System. Globally, the country has an arid climate from its northern border at 17° S to 32°30′ S, a temperate climate from 32°30′ S to 43° S, and a cold climate extending from 43° S to the southern tip of the country at 56° S (Sarricolea et al., 2017).

Locally, the climate distribution varies depending on the landforms (Gil & Olcina, 2017; Romero & Vinagre, 1985), which form a barrier to oceanic influences in the west and to precipitation from the Amazon in the east, modify the temperature depending on the altitude, and cast shadows on the valleys, changing the daily and annual temperature regimes (Antonioletti et al., 1972; Juliá et al., 2008). Only 20% of Chile's surface is flat (Gaete et al., 2006), with an altitude ranging 0–6,800 m (Errázuriz et al., 1998). Topographically, four macroforms are distributed in continental Chile, which from the east to the west are: Andes Mountain Range, which is the main orographic unit of the country, Intermediate Depression, Coast Range, and Coastal Plains.

Climate studies require the provision of accurate and extensive meteorological information that is available on demand (OMM, 2011; UNGRD, 2014). Chile's National Agroclimatic Network (RAN), consisting of public and private entities, includes 322 meteorological stations (Automatic Weather Stations, AWS; Caroca et al., 2015). However, the homogeneity of parameters and spatial representativeness were not considered during the installations, making it difficult to conduct climate studies more precisely than in the past (Garreaud, 2011; Meza, 2014; Uribe et al., 2012).

While researchers have recently established distinct climate zones for Chile, the methodologies differed in their degree of detail and classification strategy. Such studies include the edaphoclimatic zoning of Coquimbo (Morales et al., 2006), bioclimatic zoning of Chile (Uribe et al., 2012), agroclimatic zoning of Chile (Santibáñez et al., 2017), and an update of the Köppen–Geiger climate classification for continental Chile (Sarricolea et al., 2017). In this study, a geographical information system (GIS) technology was integrated with statistical methods.

We developed homogenous zone maps for defining areas with relationships between the climatic variables and topography (Romero & Vinagre, 1985) based on

CONTACT Manuel Paneque mpaneque@uchile.cl Department of Environmental Sciences and Natural Resources, Faculty of Agricultural Sciences, University of Chile, Santa Rosa 11,315, La Pintana, 8820808 Santiago, Chile
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independent climate and topographic classifications (Juliá et al., 2008). The methodology of this study can be applied to other countries using climate information layers that have already been developed; therefore, it is less time-consuming and less computationally intensive than other climate studies. Based on this method, quality national climatic information maps can be generated, which can be used by researchers working on related topics and decision-makers involved in territorial planning (Canu et al., 2015; Canu et al., 2006) and the preparation of public policies aimed at the economic and social development of the country.

2. Methodology

2.1. Study area

The study area corresponds to continental Chile, which extends from 17°S (northern border with Peru) to 56° S (Diego Ramírez Islands), and between 66° and 75° W (Riedemann et al., 2010; Figure 1). It has an area of ~753.135 km^2 (SUBDERE, 2017).

2.2. Data

The 26 bioclimatic layers elaborated in the Bioclimatic Atlas of Chile (Uribe et al., 2012, Supplementary Material 1) were used in raster format at a scale of 1:250,000 with a 90-m spatial resolution. These variables correspond to water deficit (WD), growing degree days (GDD), annual degree days (ADD), potential evapotranspiration in January and July (ETP_jan and ETP_jul), water surplus (WS), relative humidity in January and July (RH_jan and RH_jul), chilling hours (CH), aridity index (AI), humidity index for January and July (HI_jan and HI_jul), wet period (WP), dry period (DP), frost-free period (FFP), mean annual precipitation (MAP), solar radiation in January and July (SR_jan and SR_jul), summer severity (sum_SEV), winter severity (win_SEV), average temperature in January and July (TM_jan and TM_jul), maximum temperature in January and July (TX_jan and TX_jul), and minimum temperature in January and July (TN_jan and TN_jul).

In addition, four topographic variables were obtained from a digital elevation model (DEM) of the Shuttle Radar Topography Mission System (SRTM; https://explorer.earthengine.google.com) with a spatial resolution of 90-m: altitude, convexity, slope, and roughness. Based on these variables, which are applicable as direct or indirect topoclimatic estimators (Böhner & Antonić, 2009; Juliá et al., 2008; Novoa et al., 2008), abrupt changes in the topography can be identified (Juliá et al., 2008; Novoa et al., 2008).

A 1-km geographic grid was used for statistical analysis (Bell et al., 2007; Caroca et al., 2015; Vicente-Serrano et al., 2016). In the case of climatic variables, the average value of the data contained in each quadrant was obtained. The mean altitude and maximum slope of the topographic variables were calculated to capture the maximum changes in the topography (Felicísimo, 1994). The standard deviations of the convexity and roughness were calculated to assess the topographic heterogeneity (Beguería & Lorente, 1999).

2.3. Climatic and topographic zoning

Based on the data and the study reported by Cortez et al. (2020), climatic and topographic zoning was independently conducted using principal component analysis (PCA) and cluster analysis (CA).

2.3.1. Principal component analysis

PCA was used to reduce the dimensionality of highly correlated (>0.6) data. During PCA, linear combinations of original variables are generated, and components that explain less of the data are eliminated (Pino & Mulsow, 1983). Thus, the repetition of information can be avoided, and the processing can be simplified (Demey et al., 1994; Vyas & Kumaranayake, 2006). PCA creates new variables or components that contain the most important information from the original data sample in terms of variation (Morales et al., 2008; Peña, 2002).

2.3.2. Cluster analysis

CA was used to form groups with the same characteristics based on similarities or dissimilarities between the data resulting from the PCA (Núñez-Colín & Escobedo, 2011; Rueda et al., 2016), yielding maximum homogeneity within each group and maximum heterogeneity between them (De la Fuente, 2011; Vilá et al., 2014). A non-hierarchical grouping method with a K-means algorithm (Hartigan & Wong, 1979) and Euclidean distance (Castro et al., 2012; Moraleset al., 2006; Rodríguez & Menzonet, 2004; Wagstaff et al., 2001) was used because it is more appropriate for large data matrices. One hundred iterations of this process were performed to achieve greater consistency in the formation of clusters. The data clusters were then spatialized to generate topographic and climatic zoning maps.

2.4. Topoclimatic zoning

The topoclimates were identified by combining the climatic and topographic cartographies to assign a specific value to each unique crossing of zones. In addition, areas accounting for less than 0.2% of the national surface area were eliminated because they were considered negligible within the scale of this study.

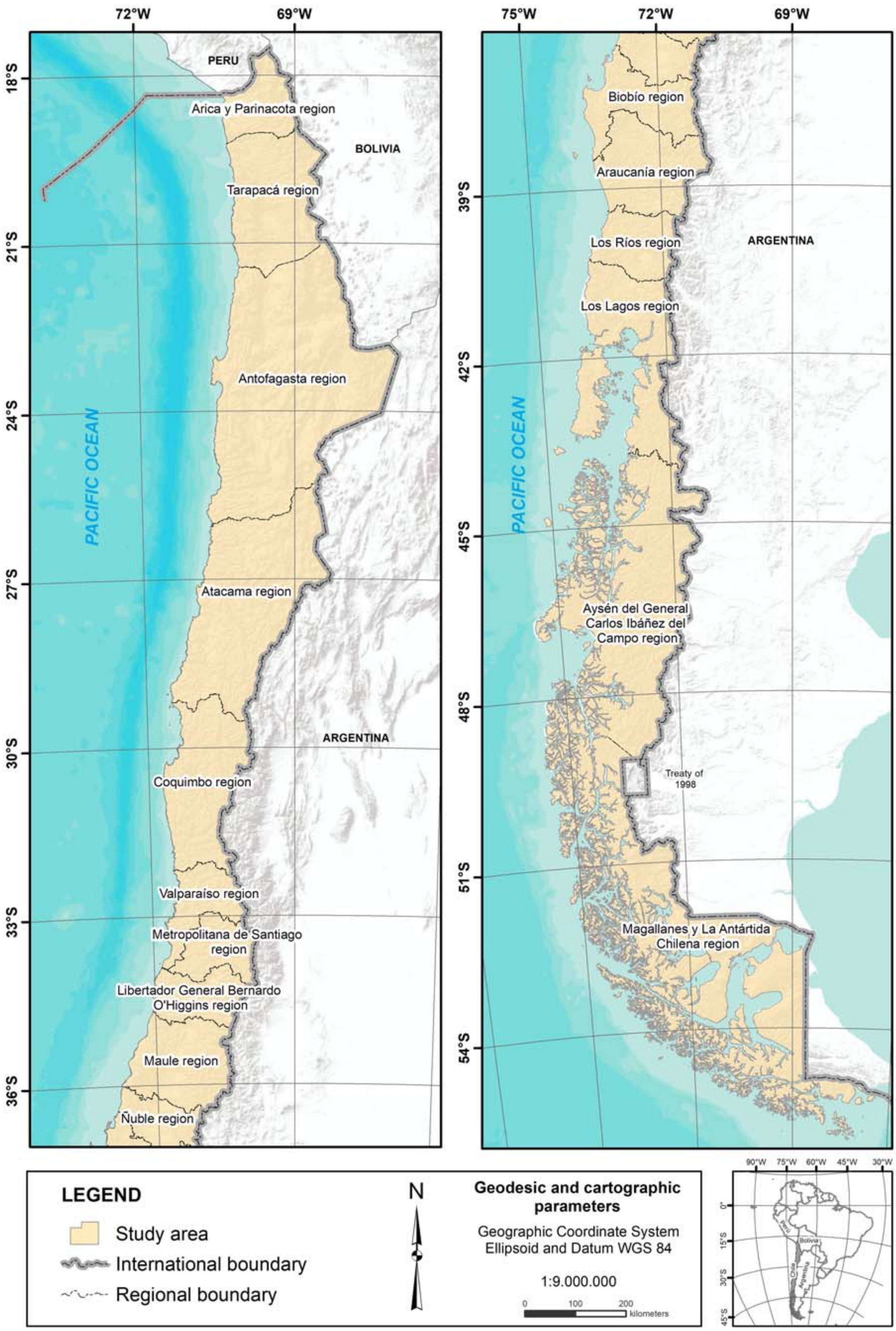

Figure 1. Study area – continental Chile.

In addition, a nomenclature was developed for each topoclimate based on three thermal- and two hydric-type variables, which describe and differentiate topoclimatic variations throughout Chile when considered together. The thermal variables considered were ADD, used to evaluate the accumulation of temperature between the northern and southern regions of the country, and summer and winter thermal amplitudes (sum_TA and win_TA), which are indicators of the continentality degree of a topoclimate (due to the moderating effect of the ocean). Regarding hydric variables, the AI was considered because it reflects the relationship between water availability and evapotranspiration, and the DP was considered to differentiate the water concentration regimes in the country. In the event that the descriptors used were not sufficient to differentiate the topoclimates, altitude (h), latitude (l), and distance to the coast (c) were also considered in the nomenclature.

The classification of the descriptive variables and the associated nomenclature was adapted from Uribe et al. (2012) and is shown in Table 1.

3. Results

3.1. Climatic and topographic zoning

3.1.1. Principal component analysis

The 26 climatic variables are represented by three main components, which account for 89.95% of the accumulated variance (Table 2). The proportion of the explained variance begins to decrease at the fourth principal component (Figure 2a). The variables that contribute the most to the first, second, and third component are WD, ETP_jul, RH_jan, RH_jul, WP, DP, SR_jan, and SR_jul; GDD, ADD, ETP_jan, CH, FFP, sum_SEV, win_SEV, TM_jan, TM_jul, TX_jan, TX_jul, TN_jan, TN_jul, WS, AI, HI_jan and HI_jul; and MAP; respectively.

The four topographic variables are represented by two principal components, which account for 94.26% of the accumulated variance (Table 2). The third and fourth components were not considered because of their low contributions to the variance (Figure 2b). The variables that contribute the most to the first and second component are convexity, slope, and roughness; and altitude, respectively.

Table 1. Classification and nomenclature of descriptive variables for the characterization of the topoclimates of Chile.

Descriptive variable	Classification	Nomenclature	Abbreviated Nomenclature
ADD (days)	<750	Microthermal	Micro
	750–1000	Infrathermal	Infra
	1000–1500	Mesothermal	Meso
	1500–2000	Suprathermal	Supra
	>2000	Macrothermal	Macro
Sum_TA (°C)	The degrees of thermal amplitude followed by the initial 'e' are considered.		
Win_TA (°C)	The degrees of thermal amplitude followed by the initial 'I' are considered.		
AI	0–0.05	Hyper-arid	
	0.05–0.20	Arid	
	0.20–0.50	Semi-arid	
	0.50–0.65	Dry Sub-humid	
	0.65–1.00	Humid Sub-humid	
	1.00–2.00	Semi-humid	
	2.00–10.00	Humid	
	>10.00	Hyper-humid	

3.1.2. Cluster analysis

Twenty climate clusters were identified (Figure 3), representing the climatic variability on a national scale. A marked longitudinal distribution of the climates can be observed, which is affected by the altitudinal gradient in the east–west direction. In addition, a notorious coastal strip is observed, which is associated with the coastal plains, extending from the Arica and Parinacota regions to the Araucanía region. Because the Cordillera de la Costa is less developed in the Araucanía region, the coastal plains extend toward the interior of the region (except for the Cordillera de Nahuelbuta sector). Another trait that can be identified is the presence of well-defined central and transverse valleys (the former are mainly associated with the semi-arid sector of Norte Chico; the latter exhibit Mediterranean climate of the central zone) and Andean strip, associated with high mountain climates present in the Norte Grande, which is associated with the highest altitudes in the country. In addition, a transitional climatic strip can be observed before the high mountain range sector, which corresponds to the Andean Highlands and extends into the Atacama Desert (cold desert climate).

Based on the topographic zoning, eight clusters can be identified (Figure 4), which can be used to delimit the main relief formations at the national level and topographic features, such as the central and transverse valleys associated with the Intermediate Depression and poorly developed coastal plains in the Norte Grande, due to the presence of the Farellón Costero (coastal cliff in Northern Chile). However, these coastal plains can be viewed in sectors containing the main cities of the extreme north of the country (Arica, Iquique, and Antofagasta). The Andean Plateau can also be delimited as well as the high peaks of the Norte Grande, Patagonia, and Eastern Plateau in the Magallanes Region. The latter can be differentiated from the mountain range sector and coastal area with irregular geography (numerous fjords, channels, and archipelagos). These topographic features are directly related to the climate in these areas.

Table 2. Statistical summary of the four principal component obtained from the analysis of the 26 climatic variables obtained from the Bioclimatic Atlas of Chile (Uribe et al., 2012) and the four principal component derived from the four topographic variables obtained from the DEM of continental Chile.

Principal component	Standard deviation	Variance	Variance (%)	Cumulative variance (%)
Climatic variables				
PC1	3.8518	14.8363	57.06%	57.06%
PC2	2.5639	6.5735	24,77%	81.83%
PC3	1.2215	1.4920	8.12%	89.95%
PC4	0.9795	0.9594	1.82%	91.77%
Tpographic variables				
PC1	1.6638	2.7682	69.21%	69.21%
PC2	1.0200	1.0020	25.05%	94.26%
PC3	0.4312	0.1859	4.64%	98.90%
PC4	0.2091	0.04384	1.1%	100%

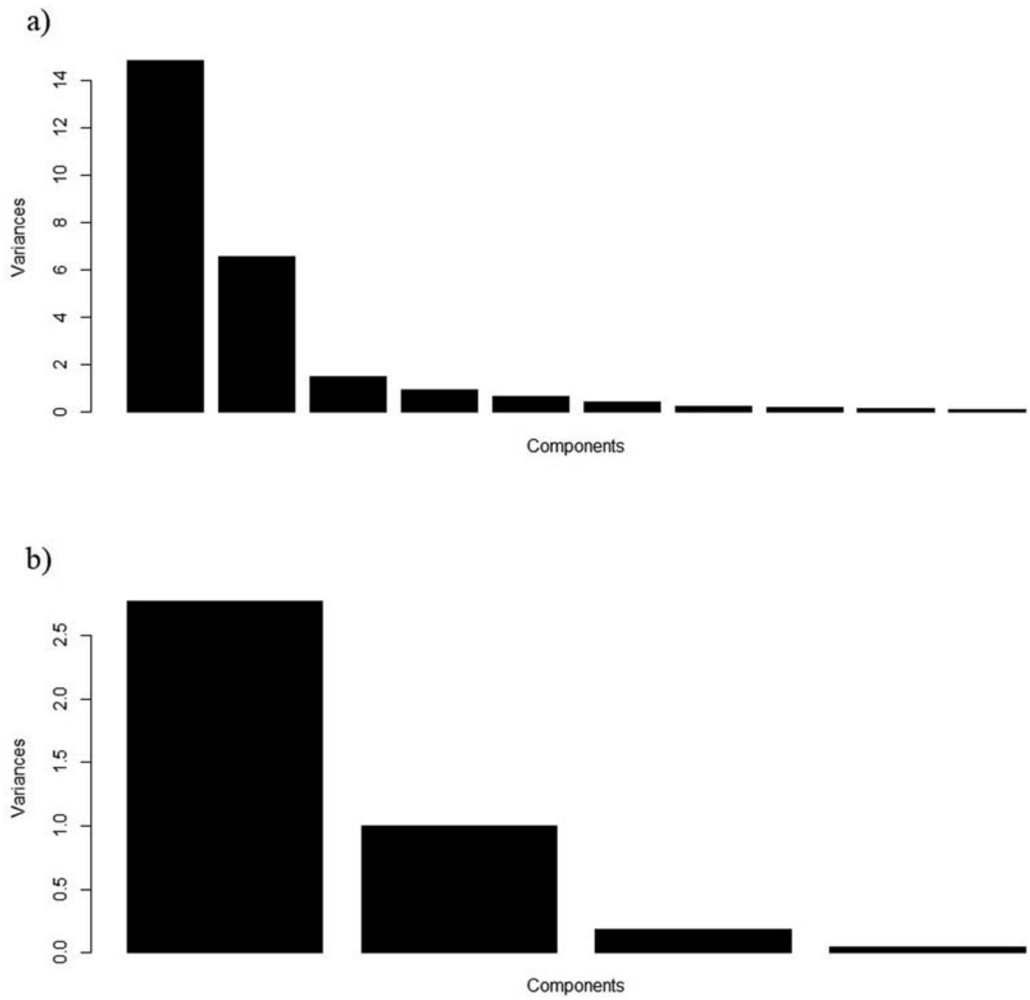

Figure 2. Sedimentation graph showing the variance of the principal component of the (a) 26 climatic variables of the Bioclimatic Atlas of Chile (Uribe et al., 2012) and (b) four topographic variables obtained from the DEM in continental Chile.

3.2. Topoclimatic zoning

A total of 96 topoclimatic areas were obtained nationwide (Main Map). Longitudinally, the greatest topoclimatic variability was identified in the foothills and mountain ranges of the country and toward inland areas, where the effect of ridge lines and mountain ranges create scenarios with greater variability for the local topoclimates. This variability differs from that of areas near the coast, which exhibit homogeneous topoclimates due to the moderating effect of the seawater on the temperature regime. At the latitudinal level, the greatest dispersion of topoclimatic units occurred in the extreme south of the country, especially in the Aysén and Magallanes regions (with the exception of the Magellanic Pampa) due to the rugged topography, which leads to highly variable topoclimatic phenomena. In the Norte Grande and central zone of the country, the topoclimatic units are uniform with respect to both extension and distribution.

It has been estimated that the total areas of 37 of the 96 homogeneous units (46.8%) are below 2,000 km^2 (Table 3) and 22 of those units (22.9%) are below 1,000 km^2. Only one topoclimatic unit, the Magellanic Pampa, has a total surface area above 50,000 km^2, accounting for 6.6% of the total surface area of continental Chile. In contrast, the smallest topoclimatic unit (170.5 km^2) was observed in the northeastern mountain range sector of the Santiago Metropolitan Region.

In northern Chile (Table 3), the topoclimates of high mountain ranges (those with altitudes above 1800 m) had the lowest temperature accumulation, followed by foothill topoclimates; while the intermediate plains areas had the highest temperature accumulation. In addition, the northern zone mainly presented an arid climate, with the exception of the Andean plateau zone and a coastal strip less than 20 km in width, which presented higher humidity.

In central Chile, mountain range topoclimates (those at altitudes higher than 1200 m) also presented lower temperature accumulation; temperature accumulation increased in the coastal area and reached its maximum values in the central valley zone. Regarding the hydric conditions of the area, mountain range topoclimates presented humid conditions, while the interior zone was humid sub-humid, and the coastal zone was semi-humid.

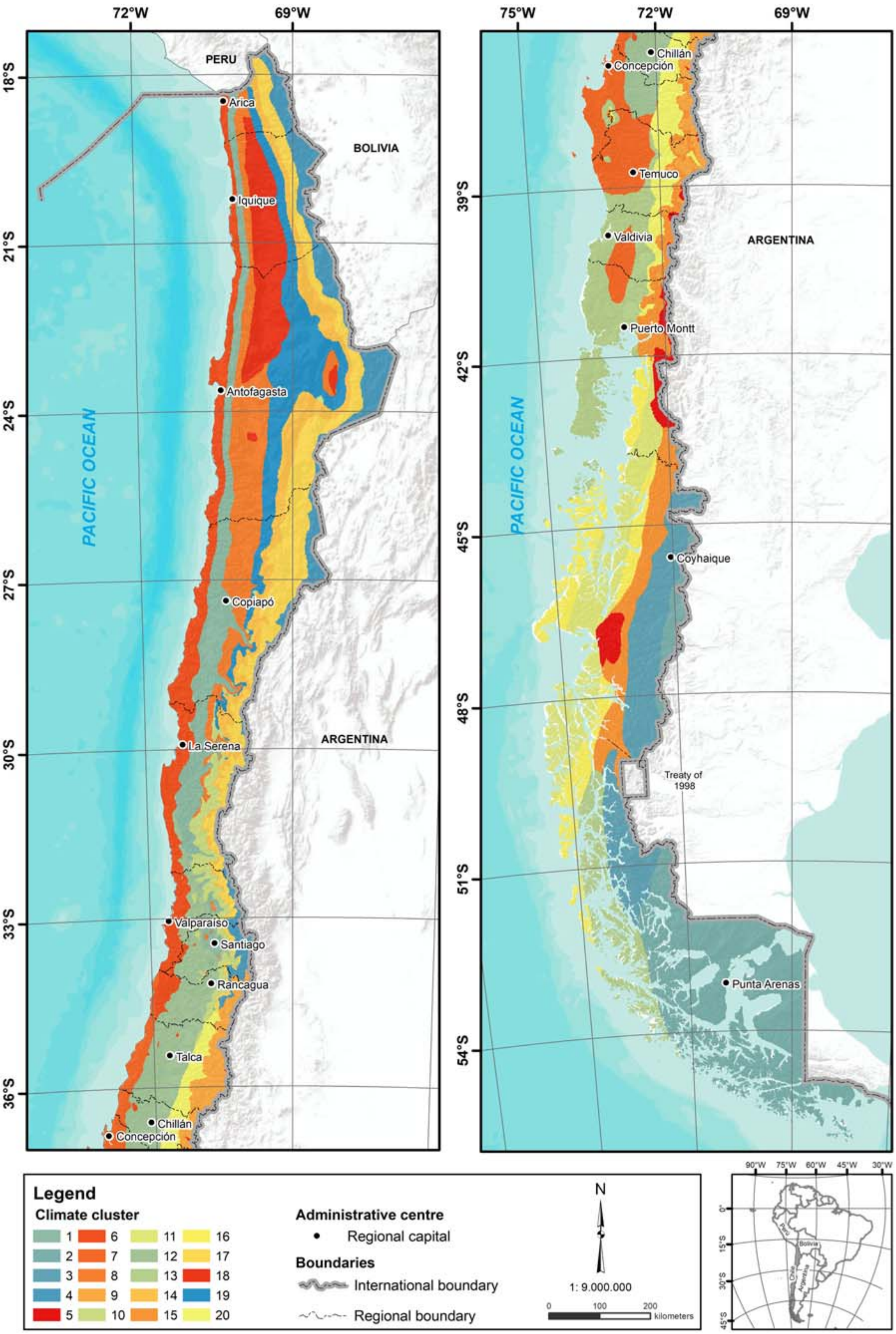

Figure 3. Climate zoning mapping of continental Chile using twenty clusters.

In southern Chile, topoclimates with low temperatures (microthermals) predominated, and a high contrast was observed between rainfall in the western and eastern areas of this region, which ranged from hyper-humid to semi-humid regimes.

4. Discussion

The methodology used for zoning was suitable for identifying the topoclimates of continental Chile. PCA has been used to address complex problems in

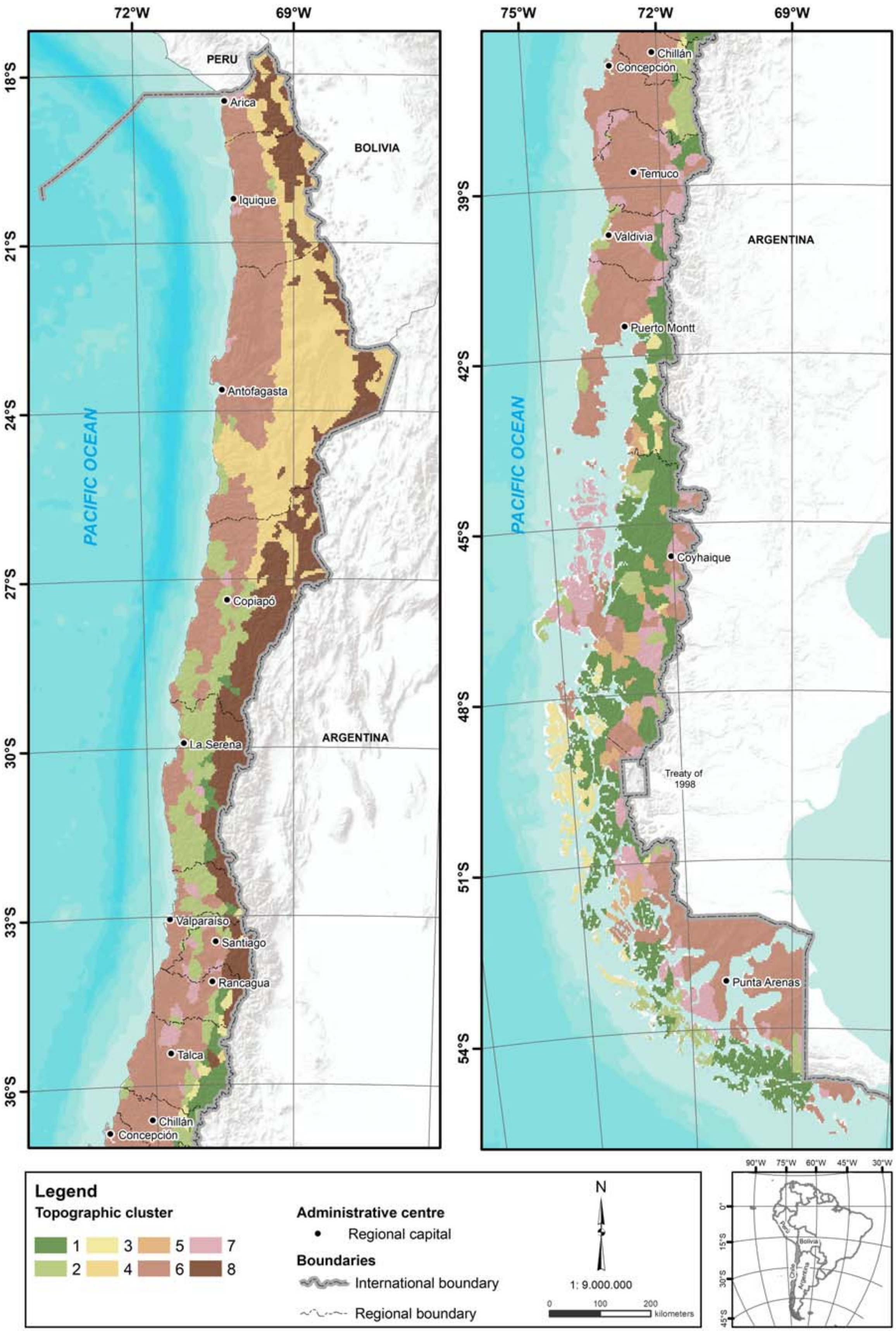

Figure 4. Topographic zoning mapping of continental Chile using eight clusters.

climatology (Reusch et al., 2005; Uddin et al., 2019). It allows the volume of information to be reduced by obtaining new uncorrelated variables. These variables retain the information that explains the maximum variability of the sample, which is fundamental for the application of CA (Rueda et al., 2016; Vyas & Kumaranayake, 2006). CA has been used to determine and map climatic zones (Mahlstein & Knutti, 2010;

Table 3. Characterization of each topoclimate obtained from the topoclimatic mapping of continental Chile, where ADD is annual degree days (days), sum_TA summer thermal amplitude (°C), win_TA winter thermal amplitude (°C), AI aridity index and DP dry period (months).

Topoclimate	Area (km^2)	Altitude (m)	ADD	sum_TA	win_TA	AI	DP	Nomenclature
1	12799.2	4242	0	10	12	0.37	9	Micro 10e 12i Semi-arid 9
2	14960.7	3862	32	14	14	0.07	12	Micro 14e 14i Arid 12
3	25873.2	4351	0	12	11	0.93	9	Micro 12e 11i Humid Sub-humid 9
4	33664.2	3930	31	14	12	0.23	10	Micro 14e 12i Semi-arid 10
5	13415.2	3290	468	17	13	0.07	11	Micro 17e 13i Arid 11
6	16357	3343	388	14	15	0.02	12	Micro 14e 15i Hyper-arid 12
7	35455.5	2655	1123	16	14	0.01	12	Meso 16e 14i Hyper-arid 12
8	9386.8	2239	1676	16	15	0.01	12	Supra 16e 15i Hyper-arid 12
9	453.8	1312	2169	17	15	0.01	12	Macro 17e 15i Hyper-arid 12
10	1443.6	747	2059	16	12	0.13	10	Macro 16e 12i Arid 10
11	1068.9	477	2389	10	9	0.05	11	Macro 10e 9i Arid 11
12	3554	2803	993	17	13	0.03	12	Infra 17e 13i Hyper-arid 12
13	26836.6	1333	1946	15	16	0.00	12	Supra 15e 16i Hyper-arid 12
14	581.7	2239	1404	18	12	0.03	12	Meso 18e 12i Hyper-arid 12
15	26141.1	392	1998	10	9	0.21	10	Supra 10e 9i Semi-arid 10
16	22099.4	859	2186	13	13	0.03	12	Macro 13e 13i Hyper-arid 12
17	917.2	1720	1431	17	14	0.00	12	Meso 17e 14i Hyper-arid 12
18	24938.2	1287	2218	16	21	0.00	12	Macro 16e 21i Hyper-arid 12
19	2500.1	2257	1784	17	18	0.00	12	Supra 17e 18i Hyper-arid 12
20	248.7	666	2501	7	9	0.00	12	Macro 7e 9i Hyper-arid 12
21	430.1	2004	1871	15	20	0.00	12	Supra 15e 20i Hyper-arid 12
22	11305.7	624	1944	12	9	0.08	11	Supra 12e 9i Arid 11
23	15894.4	1041	1928	16	12	0.05	11	Supra 16e 12i Arid 11
24	6000.6	1865	1605	18	12	0.02	12	Supra 18e 12i Hyper-arid 12
25	1510.9	2115	1976	12	13	0.00	12	Supra 12e 13i Hyper-arid 12
26	1013.9	1703	2208	10	8	0.00	12	Macro 10e 8i Hyper-arid 12
27	751.5	2306	1118	19	13	0.02	12	Meso 19e 13i Hyper-arid 12
28	235.5	1611	1649	16	11	0.07	12	Supra 16e 11i Arid 12
29	624.6	1967	1720	17	11	0.03	12	Supra 17e 11i Hyper-arid 12
30	336	1174	1601	15	13	0.11	10	Supra 15e 13i Arid 10
31	5752.5	1450	930	14	12	0.49	8	Infra 14e 12i Semi-arid 8
32	4818.7	2282	670	14	11	0.48	9	Micro 14e 11i Semi-arid 9
33	1904.9	1731	738	14	12	0.51	8	Micro 14e 12i Dry Sub-humid 8
34	803.3	2273	23	8	9	2.35	5	Micro 8e 9i Humid 5
35	7047.1	716	1483	16	10	0.41	8	Meso 16e 10i Semi-arid 8
36	253.2	1088	812	11	11	1.03	6	Infra 11e 11i Semi-humid 6
37	305.2	1362	1155	16	12	0.17	9	Meso 16e 12i Arid 9
38	253.2	273	1596	17	9	0.84	6	Supra 17e 9i Humid Sub-humid 6
39	4131.1	441	1578	16	8	0.58	7	Supra 16e 8i Dry Sub-humid 7
40	530	3431	0	9	8	2.67	5	Micro 9e 8i Humid 5
41	170.4	2292	77	12	11	1.12	6	Micro 12e 11i Semi-humid 6
42	3621	3117	6	4	7	7.88	1	Micro 4e 7i Humid 1
43	31188.5	204	1087	13	7	1.66	3	Meso 13e 7i Semi-humid 3
44	1849.2	2254	66	7	8	5.51	2	Micro 7e 8i Humid 2
45	7197.5	1999	69	10	10	6.45	1	Micro 10e 10i Humid 1
46	5183.9	1135	604	14	9	2.71	3	Micro 14e 9i Humid 3
47	2476.8	1055	461	14	8	3.45	1	Micro 14e 8i Humid 1
48	1498	1168	690	15	10	2.87	3	Micro 15e 10i Humid 3
49	3901.5	1754	35	11	8	6.93	0	Micro 11e 8i Humid 0 I
50	10564.6	633	715	15	8	2.69	2	Micro 15e 8i Humid 2
51	501.3	2716	0	3	9	12.09	0	Micro 3e 9i Hyper-humid 0
52	2784.3	827	559	15	8	3.08	1	Micro 15e 8i Humid 1
53	711.9	327	1050	11	8	1.31	4	Meso 11e 8i Semi-humid 4
54	1160.5	1314	7	11	8	6.81	0	Micro 11e 8i Humid 0
55	2139.3	1186	140	9	7	6.32	0	Micro 9e 7i Humid 0
56	30810.5	194	658	10	7	3.46	0	Micro 10e 7i Humid 0
57	8654.4	1049	28	3	6	10.18	0	Micro 3e 6i Hyper-humid 0
58	2173.1	365	1098	14	7	1.89	3	Meso 14e 7i Semi-humid 3
59	3871.1	429	620	10	6	4.05	1	Micro 10e 6i Humid 1
60	5100.5	1074	100	11	7	6.54	0	Micro 11e 7i humid 0
61	6426.5	1106	1	3	6	17.23	0	Micro 3e 6i Hyper-humid 0 I
62	22663.2	806	40	5	7	8.69	0	Micro 5e 7i Humid 0
63	1478.4	726	71	7	7	7.45	0	Micro 7e 7i Humid 0 I
64	1340.5	1478	68	14	8	5.89	0	Micro 14e 8i Humid 0
65	2065.4	1028	0	0	7	20.38	0	Micro 0e 7i Hyper-humid 0
66	1731.5	1243	0	5	7	14.18	0	Micro 5e 7i Hyper-humid 0
67	5367.6	342	512	9	5	4.35	0	Micro 9e 5i Humid 0
68	7588.3	287	133	7	4	5.68	0	Micro 7e 4i Humid 0
69	9721.3	511	271	7	6	8.13	0	Micro 7e 6i Humid 0
70	12484.9	499	286	7	6	10.37	0	Micro 7e 6i Hyper-humid 0
71	6114.2	292	237	6	5	9.05	0	Micro 6e 5i Humid 0
72	7074.5	357	238	6	5	11.97	0	Micro 6e 5i Hyper-humid 0
73	607.2	1049	3	4	5	16.54	0	Micro 4e 5i Hyper-humid 0
74	423.4	185	451	8	7	6.99	0	Micro 8e 7i Humid 0

(*Continued*)

Table 3. Continued.

Topoclimate	Area (km^2)	Altitude (m)	ADD	sum_TA	win_TA	AI	DP	Nomenclature
75	598.3	475	394	8	6	7.89	0	Micro 8e 6i Humid 0
76	1990.7	403	293	7	7	9.49	0	Micro 7e 7i Humid 0
77	8286.5	272	493	8	5	7.82	0	Micro 8e 5i Humid 0 c
78	1665.2	540	368	7	7	8.94	0	Micro 7e 7i Humid 0 h
79	3365.2	413	349	7	5	8.49	0	Micro 7e 5i Humid 0
80	19428.5	839	5	2	7	6.64	0	Micro 2e 7i Humid 0 h
81	13512.7	859	0	0	7	7.49	0	Micro 0e 7i Humid 0
82	5941.2	884	0	1	6	7.75	0	Micro 1e 6i Humid 0
83	50299.1	244	15	7	4	0.64	2	Micro 7e 4i Dry sub-humid 2
84	4472	272	479	8	5	8.99	0	Micro 8e 5i Humid 0
85	2211.9	905	19	3	8	8.82	0	Micro 3e 8i Humid 0
86	6516.7	662	6	2	7	6.00	0	Micro 2e 7i Humid 0
87	4782.6	174	330	7	5	10.86	0	Micro 7e 5i Hyper-humid 0
88	8072.3	406	83	6	3	2.13	1	Micro 6e 3i Humid 1
89	1254.5	944	0	0	8	5.06	0	Micro 0e 8i Humid 0
90	8145.3	470	86	6	4	2.74	1	Micro 6e 4i Humid 1
91	496.4	1086	0	1	8	5.74	0	Micro 1e 8i Humid 0
92	277.3	934	0	1	9	3.17	0	Micro 1e 9i Humid 0
93	21048.2	517	65	7	4	2.61	1	Micro 7e 4i Humid 1
94	1032.8	727	0	2	8	15.69	0	Micro 2e 8i Hyper-humid 0
95	3335.9	289	178	7	4	6.30	0	Micro 7e 4i Humid 0 c
96	906.4	206	127	7	3	5.50	0	Micro 7e 3i Humid 0

Nojarov, 2017). In this study, it was used to identify groups of continuous climatic and topographic data based on a grid with 1 km resolution, yielding climatic and topographic particularities at the national level. Both statistical methods are useful for the classification of climates in small areas (Cortez et al., 2020); however, they also provide consistent results in more extensive and complex territories in terms of the climate variability and relief such as in the case of Chile.

Based on the generated cartographies, Chile's climate zoning (Figure 3) obtained in this study is consistent with the Köppen climate classification presented by Rioseco and Tesser (2006). A spatial conformation of the climate was observed, with marked latitudinal and altitudinal influence and a generic distribution in several interior areas of the Norte Grande, central valleys, and Magellanic Pampa. However, the results of this study differ from those based on the Köppen climate classification with respect to the level of detail; in the present study, the zoning has a higher spatial resolution.

The updated Köppen–Geiger climate classification for Chile (Sarricolea et al., 2017) contains 25 different climatic denominations, which agree with the 20 homogeneous areas obtained in this study. Regarding the distribution, similarities were observed with respect to the identification of climatic convexity in the mountain range and foothills sectors, mainly in Norte Grande and Chico, Andean plateau sectors, cross valleys of Norte Chico, and central valleys extending from the Metropolitan region of Santiago to the Araucanía region. The main differences were observed in the extreme south of the country because the climate in the present zoning has a significant longitudinal distribution.

The zoning of continental Chile (Figure 4) yields topographic patterns similar to those obtained by Riedemann et al. (2010). However, Riedemann et al. (2010) only considered altitude as a topographic parameter. In addition, the topographic maps were compared with the geomorphological regions of Chile developed by Börgel (1983). Both studies yield a longitudinal distribution of the relief types; however, Börgel's (1983) study is more detailed in the north of Chile, whereas it is more generalized in the south. The materials and processes associated with the formation of these geomorphological regions were not considered in this study because the zoning is solely based on the relief parameters, without considering their origin.

The topoclimatic zones (Main Map) were compared with those of the Agroclimatic Atlas of Chile by Santibáñez et al. (2017), who identified agroclimatic districts using PCA and CA methodologies at the national level using only climatic variables that considered the topographic component in the model. This implies that the distribution of the topoclimatic areas of our study differs from that of agroclimatic districts. The delimitation of agroclimatic districts are considerably affected by altitude levels because the climatic variables were modeled based on a DEM. In addition, based on the aforementioned study, topoclimatic areas exhibit a more discontinuous behavior because they were intended to reflect the variability of the relief while considering additional parameters.

Mapping the climatic types of a location is important for decision-makers; it facilitates the analysis of spatial information and provides a basis for decision-making (Carver, 1991; Malczewski, 2006) regarding issues that affect the country such as the development, water scarcity, and conservation of natural resources. In addition, the methodology can be used for zoning global climate change scenarios as Chile is a country with high vulnerability (Araya-Osses et al., 2020).

5. Conclusions

Ninety-six homogeneous topoclimatic areas were identified in continental Chile. The knowledge of their spatial distribution contributes to various areas of interest and supports the zoning, planning, and management of the territory considering the current difficulties and threats that can impact natural systems and the development of productive activities.

The mapping of topoclimatic zones can be used for the analysis of other climatic processes such as the identification of zones of influence for meteorological stations, proposals of new stations in areas with little or no coverage, strengthening climatic prediction and phytosanitary alert models, and phenological crop forecasting.

6. Software

The maps were created using ESRI ArcGIS 10.4 software and the climate surfaces provided by Uribe et al. (2012). Statistical procedures were performed using the R-Studio 3.4.3 software.

7. Data availability

The datasets (digital layer of the spatial information in shapefile format) generated for this study can be found in the following repository: https://doi.org/10.34691/FK2/ULMNHV.

Open Scholarship

This article has earned the Center for Open Science badge for Open Data. The data are openly accessible at https://doi.org/10.34691/FK2/ULMNHV.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Manuel Paneque http://orcid.org/0000-0002-8731-0233

References

Antonioletti, R., Schneider, H., Borcosque, J. L., & Zarate, E. (1972). *Características Climáticas del Norte Chico (26° a 33° latitud sur)*. Instituto de Investigación de Recursos Naturales.

Araya-Osses, D., Casanueva, A., Román-Figueroa, C., Uribe, J. M., & Paneque, M. (2020). Climate change projections of temperature and precipitation in Chile based on statistical downscaling. *Climate Dynamics*, *54*(9-10), 4309–4330. https://doi.org/10.1007/s00382-020-05231-4

Beguería, S., & Lorente, A. (1999). Distribución espacial del riesgo de precipitaciones extremas en el Pirineo aragonés occidental. *Geographicalia*, *37*, 17–36. https://doi.org/10.26754/ojs_geoph/geoph.1999371398

Bell, V., Kay, A., Jones, G., & Moore, J. (2007). Development of a high resolution grid-based river flow model for use with regional climate model output. *Hydrology and Earth System Sciences Discussions*, *11*(1), 532–549. https://doi.org/10.5194/hess-11-532-2007

Böhner, J., & Antonić, O. (2009). Land-surface parameters specific to topo-climatology. *Developments in Soil Science*, *33*, 195–226. https://doi.org/10.1016/S0166-2481(08)00008-1

Börgel, R. (1983). *Geomorfología. Colección Geografía de Chile, Tomo II*. Instituto Geográfico Militar.

Canu, S., Rosati, L., Fiori, M., Motroni, A., Filigheddu, R., & Farris, E. (2015). Bioclimate map of Sardinia (Italy). *Journal of Maps*, *11*(5), 711–718. https://doi.org/10.1080/17445647.2014.988187

Caroca, C., Santibáñez, P., Santibáñez, F., Ruiz, R., Campos, C., & Bravo, R. (2015). *Estudio de la Cobertura Actual y Futura de la Red Agroclimática Nacional. Serie de Estudios Para la Innovación FIA*. Fundación para la Innovación Agraria.

Carver, S. J. (1991). Integrating multi-criteria evaluation with geographical information systems. *International Journal of Geographical Information System*, *5*(3), 321–339. https://doi.org/10.1080/02693799108927858

Castro, L., Carvajal, T., & Ávila, A. (2012). Análisis de clúster como técnica de análisis exploratorio de registros múltiples en datos metereológicos. *Ingeniería de Recursos Naturales y del Ambiente*, *11*, 11–20. Retrieved from https://www.redalyc.org/articulo.oa?id=231125817001

Cortez, D., Padilla, R., Herrera, S., Uribe, J. M., & Paneque, M. (2020). Topoclimatic zoning and representative areas as determined by an automatic weather station (AWS) network in the Atacama region, Chile. *Atmosphere*, *11*(6), 611. https://doi.org/10.3390/atmos11060611

De la Fuente, S. (2011). *Análisis Conglomerados. Facultad de Ciencias Económicas y Empresariales*. Universidad Autónoma de Madrid.

Demey, J., Adams, M., & Freites, H. (1994). Uso del método de análisis de componentes principales para la caracterización de fincas agropecuarias. *Agronomía Trop*, *44*(3), 475–497. Retrieved from http://www.sian.inia.gob.ve/revistas_ci/Agronomia%20Tropical/at4403/Arti/demey_j.htm

Errázuriz, A. M., González, J. I., Henríquez, M., Cereceda, P., González, M., & Rioseco, R. (1998). *Manual de Geografía de Chile* (3rd ed.). Editorial Andrés Bello.

Felicísimo, A. (1994). *Modelos Digitales del Terreno. Introducción y Aplicaciones en las Ciencias Ambientales*. Pentalfa.

Gaete, G., Espinoza, C., & Muñoz, A. (2006). *Manual de Geografía de Chile*. Facultad de Humanidades. Departamento de Filosofía y Ciencias Sociales. Universidad de Playa Ancha de Ciencias de la Educación.

Garreaud, R. (2011). *Cambio Climático: Bases Físicas e Impactos en Chile. Revista Tierra Adentro-INIA*. Departamento de Geofísica. Universidad de Chile.

Gil, A., & Olcina, J. (2017). *Tratado de Climatología. Instituto Interuniversitario de Geografía*. Publicaciones de la Universidad de Alicante.

Giorgi, F., Francisco, R., & Pal, J. (2003). Effects of a subgrid-scale topography and land use scheme on the simulation of surface climate and hydrology. Part I: Effects of temperature and water vapor disaggregation. *Journal of Hydrometeorology*, *4*(2), 317–333. https://doi.org/10.1175/1525-7541(2003)4<317:EOASTA>2.0.CO;2

Hartigan, J. A., & Wong, M. A. (1979). Algorithm AS 136: A k-means clustering algorithm. *Journal of the Royal*

Statistical Society. Series C (Applied Statistics), *28*(1), 100–108. https://doi.org/10.2307/2346830
Juliá, C., Montecinos, S., & Maldonado, A. (2008). Características Climáticas de la Región de Atacama. In F. Squeo, G. Arancio, & J. R. Gutiérrez (Eds.), *Libro Rojo de la Flora Nativa y de los Sitios Prioritarios para su Conservación: Región de Atacama* (pp. 25–42). Ediciones Universidad de La Serena.
Leung, L. R., Mearns, L. O., Giorgi, F., & Wilby, R. L. (2003). Regional climate research: Needs and opportunities. *Bulletin of the American Meteorological Society*, *84*(1), 89–95. https://doi.org/10.1175/BAMS-84-1-97
Mahlstein, I., & Knutti, R. (2010). Regional climate change patterns identified by cluster analysis. *Climate Dynamics*, *35*(4), 587–600. https://doi.org/10.1007/s00382-009-0654-0
Malczewski, J. (2006). GIS-based multicriteria decision analysis: A survey of the literature. *International Journal of Geographical Information Science*, *20*(7), 703–726. https://doi.org/10.1080/13658810600661508
Meza, L. (2014). *Incorporación de la Gestión de Riesgo Agroclimático en el sector Silvoagropecuario de Chile. Experiencia de cooperación de la FAO (UTF/CHI/028).* Organización de las Naciones Unidas para la Alimentación y la Agricultura.
Morales, L., Canessa, F., Mattar, C., Orrego, R., & Matus, F. (2006). Caracterización y zonificación edáfica y climática de la Región de Coquimbo, Chile. *Revista de la Ciencia del Suelo y Nutrición Vegetal*, *6*(3), 52–74. https://dx.doi.org/10.4067/S0718-27912006000300005
Morales, C. R., Quero, A., Pérez, J., Hernández, A., & Le-Blanc, O. (2008). Caracterización morfológica de poblaciones nativas de pasto banderita [Bouteloua curtipendula (Michx.) Torr.] en México. *Agrociencia*, *42*(7), 767–775. Retrieved from http://www.scielo.org.mx/scielo.php?pid=S1405-31952008000700003&script=sci_arttext
Nojarov, P. (2017). Genetic climatic regionalization of the Balkan Peninsula using cluster analysis. *Journal of Geographical Sciences*, *27*(1), 43–61. https://doi.org/10.1007/s11442-017-1363-y
Novoa, J., Tracol, Y., & López, D. (2008). Paisajes Eco-Geográficos de la Región de Atacama. In F. Squeo, G. Arancio, & J. R. Gutiérrez (Eds.), *Libro Rojo de la Flora Nativa y de los Sitios Prioritarios para su Conservación: Región de Atacama* (pp. 13–24). Ediciones Universidad de La Serena.
Núñez-Colín, C., & Escobedo, D. (2011). Uso correcto del análisis clúster en la caracterización de germoplasma vegetal. *Agronomía Mesoamericana*, *22*(2), 415–427. https://doi.org/10.15517/am.v22i2.8746
OMM (Organización Meteorológica Mundial). (2011). *Documento Técnico N° 100.* Organización Meteorológica Mundial. Ginebra, Suiza. 128 pp.
Peña, D. (2002). *Análisis de Datos Multivariantes*. McGraw-Hill.
Pino, M., & Mulsow, S. (1983). Distribución de faces granulométricas en el estuario del Río Queule, IX región: Un análisis de componentes principales. *Revista Geológica de Chile*, *18*, 77–85. Retrieved from http://www.andeangeology.cl/index.php/revista1/article/view/815
Reusch, D. B., Alley, R. B., & Hewitson, B. C. (2005). Relative performance of self-organizing maps and principal component analysis in pattern extraction from synthetic climatological data. *Polar Geography*, *29*(3), 188–212. https://doi.org/10.1080/789610199
Riedemann, E., Plá, F., Correa, H., Arévalo, V., Widow, J., & Romero, E. (2010). *Atlas de Chile y el Mundo*. Editorial Bibliográfica Internacional Limitada.
Rioseco, R. & Tesser, C. (2006). Cartografía Interactiva de los Climas de Chile. Chile: Instituto de Geografía, Pontificia Universidad Católica de Chile. Retrieved 2020, 07 July from http://www.uc.cl/sw_educ/geografia/cartografiainteractiva/
Rodríguez, M., & Menzonet, Y. (2004). Definición de la época de incendios forestales en un contexto multivariado. *Revista FLORESTA*, *34*(2), 137–143. http://dx.doi.org/10.5380/rf.v34i2.2385
Romero, H., & Vinagre, J. (1985). Topoclimatología de la cuenca del río Mapocho. *Investigaciones Geográficas*, *32*(32), 3–30. https://doi.org/10.5354/0719-5370.1985.27689
Rueda, J., Elles, C., Sánchez, E., González, A. L., & Rivillas, G. (2016). Identificación de patrones de variabilidad climática a partir de análisis de componentes principales, Fourier y clúster k-medias. *Tecnura*, *20*(50), 55–68. Retrieved from http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0123-921X2016000400004&lng=en&nrm=iso&tlng=es
Santibáñez, F., Santibáñez, P., Caroca, C., & González, P. (2017). *Atlas Agroclimático de Chile*. Universidad de Chile. Santiago, Chile.
Sarricolea, P., Herrera-Ossandon, M. J., & Meseguer-Ruiz, O. (2017). Climatic regionalisation of continental Chile. *Journal of Maps*, *13*(2), 66–73. https://doi.org/10.1080/17445647.2016.1259592
SUBDERE (Subsecretaría de Desarrollo Regional y Administrativo). (2017). *División Político Administrativa de Chile*. Ministerio del Interior y Seguridad Pública.
Uddin, M. N., Islam, A. S., Bala, S. K., Islam, G. T., Adhikary, S., Saha, D., Hake, S., Fahad, M. G. R., & Akter, R. (2019). Mapping of climate vulnerability of the coastal region of Bangladesh using principal component analysis. *Applied Geography*, *102*, 47–57. https://doi.org/10.1016/j.apgeog.2018.12.011
UNGRD (Unidad Nacional para la Gestión del Riesgo de Desastres). (2014). Documento de priorización de líneas estratégicas y zonas de intervención en gestión del riesgo de desastres en Colombia. 2014-2018. Sistema Nacional de Gestión del Riesgo de Desastres. Bogotá, Colombia. 37 pp.
Uribe, J. M., Cabrera, R., De la Fuente, A., & Paneque, M. (2012). *Atlas Bioclimático de Chile*. Universidad de Chile.
Vicente-Serrano, S. M., El Kenawy, A., Azorin-Molina, C., Chura, O., Trujillo, F., Aguilar, E., Martín-Hernández, N., López-Moreno, J. I., Sánchez-Lorenzo, A., Moran-Tejeda, E., Revuelto, J., Ycaza, P., & Friend, F. (2016). Average monthly and annual climate maps for Bolivia. *Journal of Maps*, *12*(2), 295–310. https://doi.org/10.1080/17445647.2015.1014940
Vilá, R., Rubio, M. J., Berlanga, V., & Torrado, M. (2014). Cómo aplicar un clúster jerárquico en SPSS. *Revista d'Innovació i Recerca en Educació*, *7*(1), 113–127. Retrieved from https://revistes.ub.edu/index.php/REIRE/article/view/reire2014.7.1717/17688
Vyas, S., & Kumaranayake, L. (2006). Constructing socio-economic status indices: How to use principal components analysis. *Health Policy and Planning*, *21*(6), 459–468. https://doi.org/10.1093/heapol/czl029
Wagstaff, K., Cardia, C., Rogers, S., & Schrödl, S. (2001). Constrained k-means clustering with background knowledge. *Proceedings of the Eighteenth International Conference on Machine Learning*, ICML, Williamstown, MA, USA, 28 June–1 July, 577–584. Retrieved from https://web.cse.msu.edu/~cse802/notes/ConstrainedKmeans