Topoclimatic zoning of continental Chile

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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\textsuperscript{2}, whereas 46.8\% of the units have surface areas below 2,000 km\textsuperscript{2}.

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 macroareas 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
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 km² (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 (Vyas & Kumarayant, 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; Morales et 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.
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.

Figure 1. Study area – continental Chile.
(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.

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 | NtMicro |
|                     | 750–1000       | Infrathermal Infra | NtInfra |
|                     | 1000–1500      | Mesothermal Mesos | NtMesos |
|                     | 1500–2000      | Suprathermal Supra | NtSupra |
|                     | >2000          | Hyperthermal Hyper | NtHyper |
| 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 T are considered. |
| AI                  | 0–0.05         | Hyper-arid | HyAr |
|                     | 0.05–0.20      | Arid       | Ar |
|                     | 0.20–0.50      | Semi-arid  | SAr |
|                     | 0.50–0.65      | Dry Sub-humid | DSH |
|                     | 0.65–1.00      | Humid Sub-humid | HS |
|                     | 1.00–2.00      | Semi-humid | SH |
|                     | 2.00–10.00     | Humid      | H |
|                     | >10.00         | Hyper-humid | HyH |

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 accumulated variance (Table 2). The variables that contribute the most to the principal component (Figure 2a). The variables that contribute the most to the variance begins to decrease at the fourth accumulated variance (Table 2). The proportion of main components, which account for 89.95% of the accumulated variance (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.

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).

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| Statistic | Standard deviation | Variance of | Variance (%) | Cumulative variance (%) |
|-----------|--------------------|-------------|--------------|-------------------------|
| Principal component | 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% |

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 DEM of 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 km² (Table 3) and 22 of those units (22.9%) are below 1,000 km². Only one topoclimatic unit, the Magellanic Pampa, has a total surface area above 50,000 km², accounting for 6.6% of the total surface area of continental Chile. In contrast, the smallest topoclimatic unit (170.5 km²) 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 subhumid, and the coastal zone was semi-humid.
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...
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 (°C), sum_TA summer thermal amplitude (°C), win_TA winter thermal amplitude (°C), AI aridity index and DP dry period (months).

| Topoclimate Area (km²) | 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 1606.07              | 3862         | 0   | 14     | 14     | 0.07 | 9  | Micro 14e 12i Semi-arid 9 |
| 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 1345.2               | 3290         | 468 | 17     | 13     | 0.07 | 11 | Micro 17e 13i Arid 11 |
| 6 1655.5               | 3343         | 388 | 14     | 15     | 0.02 | 12 | Micro 15e 14i Hyper-arid 12 |
| 7 938.6                | 2239         | 1676| 16     | 15     | 0.01 | 12 | Micro 15e 14i Hyper-arid 12 |
| 8 453.8                | 1312         | 2169| 17     | 15     | 0.01 | 12 | Macro 17e 15i Hyper-arid 12 |
| 9 1443.6               | 477          | 2389| 10     | 9      | 0.05 | 11 | Macro 10e 9i Arid 11 |
| 10 2083                | 993          | 17  | 13     | 13     | 0.45 | 12 | Infra 17e 13i Hyper-arid 12 |
| 11 2683.66             | 1333         | 1946| 15     | 16     | 0.00 | 12 | Micro 15e 16i Hyper-arid 12 |
| 12 581.7               | 2239         | 1404| 18     | 12     | 0.03 | 12 | Micro 18e 12i Arid 12 |
| 13 2641.3              | 1998         | 1116| 14     | 15     | 0.38 | 10 | Micro 20e 15i Humid Sub-humid 10 |
| 14 22099.4             | 859          | 2186| 13     | 13     | 0.03 | 12 | Micro 20e 15i Humid Sub-humid 12 |
| 15 33664.2             | 3930         | 0   | 14     | 14     | 0.07 | 9  | Micro 14e 12i Semi-arid 9 |
| 16 3930                | 3862         | 0   | 14     | 14     | 0.07 | 9  | Micro 14e 12i Semi-arid 9 |
| 17 25873.2             | 4351         | 0   | 12     | 11     | 0.93 | 9  | Micro 12e 11i Humid Sub-humid 9 |
| 18 2004                | 1871         | 20   | 15     | 20     | 0.00 | 12 | Micro 15e 20i Hyper-arid 12 |
| 19 1305.7              | 624          | 1944| 12     | 9      | 0.08 | 11 | Micro 12e 9i Arid 11 |
| 20 15984.4             | 1041         | 1928| 12     | 12     | 0.05 | 11 | Micro 12e 11i Arid 11 |
| 21 7000.6              | 1865         | 1605| 18     | 12     | 0.02 | 12 | Micro 15e 12i Hyper-arid 12 |
| 22 581.7               | 2239         | 1404| 18     | 12     | 0.03 | 12 | Micro 15e 12i Hyper-arid 12 |
| 23 938.6               | 2239         | 1404| 18     | 12     | 0.03 | 12 | Micro 15e 12i Hyper-arid 12 |
| 24 2004                | 1871         | 20   | 15     | 20     | 0.00 | 12 | Micro 15e 20i Hyper-arid 12 |
| 25 1305.7              | 624          | 1944| 12     | 9      | 0.08 | 11 | Micro 12e 9i Arid 11 |
| 26 15984.4             | 1041         | 1928| 12     | 12     | 0.05 | 11 | Micro 12e 11i Arid 11 |
| (Continued)
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 topoclimatic zones (Main Map) were compared with those of the Agroclimatic Atlas of Chile developed by Borgel (1983). Both studies yield a longitudinal distribution of the relief types; however, Borgel’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 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.
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).

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